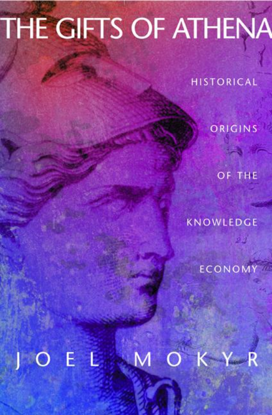
THE GIFTS OF ATHENA

HISTORICAL ORIGINS OF THE KNOWLEDGE ECONOMY



JOEL MOKYR

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Historical Origins of the Knowledge Economy

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Dedicated to

Eric L. Jones,

David S. Landes,

Douglass C. North,

Nathan Rosenberg

Whose wisdom and scholarship
have instructed and inspired me

There hath not been wanting in all ages and places great numbers of men whose genius and constitution hath inclined them to delight in the inquiry into the nature and causes of things, and from those inquirys to produce somewhat of use to themselves or mankind. But their Indeavours having been only single and scarce[ly] ever united, improved, or regulated by Art, have ended only in some small inconsiderable product hardly worth naming. But though mankind have been thinking these 6000 years and should be soe six hundred thousand more, yet they are and would be ... wholly unfit & unable to conquer the difficultys of natural knowled[ge]. But this newfound world must be conquered by a Cortesian army, well-Disciplined and regulated, though their numbers be but small.

—Robert Hooke, 1666

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Preface

It was said of the mythological Greek king Cecrops that he founded a new city on the Acropolis in Attica and that he promised to name it after the god who would give the young town the most attractive gift. Poseidon, the god of the oceans, struck a rock, and out came a stream of clear water. Upon tasting it, however, Cecrops found the water to be brackish. The goddess of knowledge and wisdom, Athena, then approached him with a more valuable gift: the olive tree. The rest, maybe, is history.

The development of the connection between knowledge and the exploitation of natural regularities and resources is the stuff of the history of technology. This book is about the proposition that what people knew about their physical environment was of great importance to them and became increasingly so in recent centuries. It is about the history of economic growth, but far more than that, it is the history of economic welfare, of longer, healthier, and more secure lives, of more leisure and material comfort, of reducing mortality, morbidity, pain, and sorrow. Knowledge can also be abused and was so in the twentieth century on a monstrous scale. Technology has the capacity to wipe out life on the planet and to provide enormous leverage to few individuals. Never before, to paraphrase Churchill's hackneyed phrase once again, have so few had the power to cause so much damage to so many. Either way, no one will dispute that our material world is not what it used to be, and that what we know—more than anything else—has brought about this transformation.

This book is based on essays I published in the late 1990s and on lectures I have given at a variety of institutions and conferences. In the course of that work I have incurred enormous debts, not all of which I can fully acknowledge. Above all, I am indebted to the four scholars whose personal friendship and written scholarship have been an endless source of support and to whom this book is dedicated. The members of my two Northwestern University home departments have helped and inspired me in many different ways. More than any person, the late Jonathan R. T. Hughes and his equally lamented wife Mary Gray Hughes have been irreplaceable and I still miss them, every day. Among the living, the continuous conversation with many Northwestern colleagues has kept my mind turning and my reading lists long. I will mention by name Kenneth Alder, Louis Cain, Joseph Ferrie, Robert J. Gordon, David Hull, Wolfram Latsch, Moshe Matalon, Peter Murmann, and Stanley Reiter. Among my many former and present students who have contributed materially to my thinking and writing, I should single out the indefatigable Peter B. Meyer, who read large parts of the manuscript and suggested innumerable improvements, and acknowledge Maristella Botticini, Federico Ciliberto, Dario Gaggio, Thomas Geraghty, Avner Greif, Lynne Kiesling, Hilarie

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Outside Northwestern, the list is necessarily incomplete, but I have for many decades been fortunate to count as my friends the formidable intellects of Maxine Berg, Louis Cain, Paul A. David, Jan DeVries, Avner Greif, Deirdre McCloskey, Jacob Metzer, Cormac Ó Gráda, and Kenneth Sokoloff. Many other individuals have helped me with suggestions, advice, data, comments, and reflections. An inevitably incomplete list must include Daron Acemoglu, Kenneth Arrow, Joerg Baten, Tine Bruland, Steve Durlauf, Richard Easterlin, Jan Fagerberg, Nancy Folbre, Oded Galor, Renato Giannetti, Jack A. Goldstone, Timothy Guinnane, Daniel Headrick, Carol Heim, Elhanan Helpman, Benjamin Acosta Hughes, Thomas P. Hughes, Margaret C. Jacob, Barbara Karni, Haider Khan, Janice Kinghorn, Yoav Kislev, Timur Kuran, Naomi Lamoreaux, Richard Langlois, Ned Lebow, Richard G. Lipsey, John McDermott, Patricia Mokhtarian, Richard Nelson, Patrick O'Brien, Keith Pavitt, Craig Riddell, Arie Rip, Philip Tetlock, Ross Thomson, Manuel Trajtenberg, Nick Von Tunzelmann, Ulrich Witt, and John Ziman.

A number of research assistants read large chunks of this manuscript in a desperate attempt to make sense out of a seemingly chaotic series of requests for library books and papers. They are Elizabeth Brown-Inz, Amit Goyal, Shilpa Jatkar, Steve Nafziger, and Michael Piafsky. During the various stages of writing, I benefitted from the hospitality of the University of Manchester, where I served as John Simon Professor in 1996; the Center for the Study of Economies in the Long Run at Washington University, which I visited in 1997; the Minerva Center of the Hebrew University of Jerusalem, which I visited in 1999; and the Center for Advanced Studies in the Behavioral Sciences at Stanford, where I am currently a fellow, with the financial support provided by the William and Flora Hewlett Foundation, grant 2000-5633. Thanks are due to the Leonard Hastings Schoff Publication Fund of the Columbia University Seminars for financial support. I also benefitted from many comments at the All University of California Economic History Conference at Scripps College in March 2002. Two chapters were delivered as the Kuznets Lectures at Yale University in November 2001, and I am grateful to Yale University for its hospitality and generosity, as well as for four wonderful years of graduate school in the early 1970s.

At Princeton University Press, I have for many years had the pleasure

with working with Peter Dougherty. No author can wish for a more supportive editor. Kathleen Much and Janet Mowery did a wonderful job copyediting my often opaque prose.

These debts pile up, and I cannot hope to repay them in a finite lifetime. Yet none of them is greater than the one I owe to Margalit B. Mokyr, my wife and companion for more than three decades, and without whom nothing would have been worth accomplishing.

Menlo Park, California
December 2001

The Gifts of Athena

Chapter 1

Technology and the Problem of Human Knowledge

Introduction

The growth of human knowledge is one of the deepest and most elusive elements in history. Social scientists, cognitive psychologists, and philosophers have struggled with every aspect of it, and not much of a consensus has emerged. The study of what we know about our natural environment and how it affects our economy should be of enormous interest to economic historians. The growth of knowledge is one of the central themes of economic change, and for that reason alone it is far too important to be left to the historians of science.

Discoveries, inventions, and scientific breakthroughs are the very stuff of the most exciting writing in economic history. In what follows, my approach relies heavily on the history of science, but it differs from much current writing in that it addresses squarely the issues of modern economic growth. Through most of human history—including the great watershed of the Industrial Revolution—new knowledge appeared in a haphazard and unpredictable manner, and economic history is thus subject to similar contingencies. It therefore needs a special approach if it is to come to grips with modern economic growth, one that will take into consideration the untidy nature of the historical processes that created modern economic civilization of the past quarter-millennium.

In this book I am not explicitly concerned with "modernization," a terms that has fallen on hard times. Economic modernization is associated with industrialization, yet economic performance improved in services and agriculture. This book does not consider such "modernist" trends as urbanization, the rise of a powerful and centralized state, the increase in political freedom and participation, and the growth in literacy and education. It starts from the basic and mundane observation that economic performance, our ability to tease out material comforts from niggardly nature, has improved immensely in the past two centuries.

The relationship between economic performance and knowledge seems at first glance obvious if not trite. Simply put, technology is knowledge, even if not all knowledge is technological. To be sure, it is hard to argue that differences in knowledge alone can explain the gaps in income between the prosperous West and poor nations elsewhere. If that were all that differed, surely knowledge would flow across boundaries. Yet nobody would seriously dispute the proposition that living standards today are higher than in the eleventh century primarily because we know more than medieval peasants. We do not say that we are smarter (there is little evidence that we are), and we cannot even be sure that we are richer than we used to be because we are better educated (although of course we are). The central phenomenon of the modern age is that as an aggregate we know more. New knowledge developed in the past three centuries has created a great deal of social conflict and suffering, just as it was the origin of undreamed-of wealth and security. It revolutionized the structures of firms and households, it altered the way people look and feel, how long they live, how many children they have, and how they spend their time. Every aspect of our material existence has been altered by our new knowledge.

But who is "we"? What is meant by a society "knowing" something, and what kind of knowledge really matters? For the economic historian, these propositions prompt further questions. *Who* knew that which was "known"? What was done with this knowledge? How did people who did not possess it acquire it? In short, the insights of economic theory need to be coupled with the facts and narratives of the history of science and technology.

Useful Knowledge: Some Definitions

I am neither qualified nor inclined to deal with the many subtleties of epistemology and cognitive science that a thorough treatment of knowledge as a historical force requires. Instead this book takes a simple and straightforward approach to knowledge and its role in technological and economic change. It asks how new knowledge helped create modern material culture and the prosperity it has brought about.

What kind of knowledge do I have in mind? My interest in what follows is confined to the type of knowledge I will dub *useful* knowledge. The term "useful knowledge" was used by Simon Kuznets (1965, pp. 85–87) as the source of modern economic growth. One could debate at great length what "useful" means.[1] In what follows, I am motivated by the centrality of technology. Because technology in its widest sense is the manipulation of nature for human material gain, I confine myself to knowledge of natural phenomena that exclude the human mind and social institutions. Jewish tradition divides all commands into commands that are between a person and *makom* (literally "place," but actually the deity) and between a person and *chavayro* (other people). In epistemology such distinctions are hazardous, yet it seems to me that roughly speaking there is a kind of knowledge accumulated when people observe natural phenomena in their environment and try to establish regularities and patterns in them. This knowledge is distinct from knowledge about social facts and phenomena. To be sure, a great deal of important knowledge, including economic knowledge, involves people and social phenomena: knowledge about prices, laws, relationships, personalities, the arts, literature, and so on. I should add right away that some "technologies" are based on the regularities of human behavior (e.g., management science and marketing) and therefore might be considered part of this definition. It could also be argued that economic knowledge (e.g., about prices or rates of return on assets) should be included, as it is necessary for efficient production and distribution. Despite some gray areas, in which the two overlap, I shall maintain this definition. Hence useful knowledge throughout this book deals with natural phenomena that potentially lend themselves to manipulation, such as artifacts, materials, energy, and living beings.

Economists often make a distinction between the growth of the stock of useful best-practice knowledge and its effective diffusion and utilization by all economies that have access to it.[2] Their work is concerned with the latter; what follows is primarily about the former. The complementarity between the two is obvious. The idea that changes in useful knowledge are a crucial ingredient in economic growth seems so self-evident as to make elaboration unnecessary, were it not that with some notable exceptions—especially the work of the Stanford school embodied in the work of Nathan Rosenberg and Paul David—economists rarely have dealt with it

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[1] Kuznets (1965) uses the term interchangeably with "tested" knowledge that is potentially useful in economic production. In what follows below, this definition is too restrictive. There is of course no universally accepted definition of what "testing" means; any testing procedure is a social convention at the time. Moreover, in order to be "useful," knowledge does not have to be "tested"; indeed it does not have to be "true" (that is, conform to today's beliefs). Machlup (1980–84, Vol. 2, p. 10) discusses the slippery distinction between useful and useless knowledge and suggests that "useful" might be akin to "practical" or capable of making contributions to material welfare.

[2] For a recent example see Parente and Prescott (2000). The literature is surveyed by Ruttan (2001).

explicitly. Even the "New Growth Theory," which explicitly tries to incorporate technology as one of the variables driven by human and physical capital, does not try to model the concept of useful knowledge and its change over time explicitly. Much in the tradition of A. P. Usher (1954), what I propose here is to look at technology in its intellectual context.

A Theory of Useful Knowledge

Useful knowledge as employed throughout the following chapters describes two types of knowledge. One is knowledge "what" or *propositional* knowledge (that is to say, beliefs) about natural phenomena and regularities.[3] Such knowledge can then be applied to create knowledge "how," that is, instructional or *prescriptive* knowledge, which we may call techniques.[4] In what follows, I refer to propositional knowledge as Ω-knowledge and to prescriptive knowledge as λ-knowledge. If Ω is *episteme*, λ is *techne*. This distinction differs in important respects from the standard distinctions between science and technology that have produced a vast literature but has increasingly come under scrutiny. It is also different from the distinction between "theory" and "empirical knowledge."

Who are the people who "know"? Knowledge resides either in people's minds or in storage devices (external memory) from which it can be retrieved.[5] From the point of view of a single agent, another's mind is a storage device as well. The "aggregate" propositional knowledge in a society can then be defined simply as the *union* of all the statements of such knowledge contained in living persons' minds or storage devices. I call this set Ω. A discovery then is simply the addition of a piece of knowledge hitherto not in that set.[6] Society "knows" something if at least one

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[3] This is akin to what Arora and Gambardella (1994) refer to as "abstract and generalized knowledge," yet it need not be either abstract or generalized. A list of the times of sunset and sunrise, for example, would be propositional knowledge because it describes a natural regularity.

[4] Scheffler (1965, p. 92) has suggested the term "procedural knowledge" for a distinction much like the one I propose here. Much of the epistemological literature is concerned with the people who possess this knowledge, not with the knowledge itself, or with any clear-cut concept of "social" or "aggregate" knowledge. "Knowing how" represents the possession of a skill, a trained capacity, a competence, or a technique. For the purpose of the arguments here, I am mostly interested in the characteristics of the object that people who "know how" possess, that is, the content of whatever it is that lies beneath the economist's notion of the isoquant.

[5] The dimensionality of this set is a problem I shall set aside here. Reiter (1992) defines a megaset E as all the possible sentences that can be constructed by combining all symbols in the language (including mathematical symbols) and the knowledge of each individual is a subset of E.

[6] Formally, if Ω is the union of all the individual sets of knowledge contained in either minds or storage devices, diffusion and learning would concern the *intersection* of these sets. The larger the number of elements in all intersections, the larger the *density* of Ω.

individual does. In this kind of model the social nature of knowledge is central: learning or diffusion would be defined as the transmission of existing knowledge from one individual or device to another.[7] Similarly, I will refer to the union of all the techniques known to members of society or in accessible storage devices as the set λ.

The idea underlying this book is the proposition that Ω-knowledge serves as the support for the techniques that are executed when economic production takes place. For an inventor to write a set of instructions that form a technique, something about the natural processes underlying it must be known in this society. Before I can elaborate on this relationship, a few more details about the nature of Ω and λ should be clarified.

What is propositional knowledge? It takes two forms: one is the observation, classification, measurement, and cataloging of natural phenomena. The other is the establishment of regularities, principles, and "natural laws" that govern these phenomena and allow us to make sense of them. Such a definition includes mathematics insofar as mathematics is used to describe and analyze the regularities and orderliness of nature.[8] This distinction, too, is not very sharp, because many empirical regularities and statistical observations could be classified as "laws" by some and "phenomena" by others. Useful knowledge includes "scientific" knowledge as a subset.

Science, as John Ziman (1978) has emphasized, is the quintessential form of public knowledge, but propositional knowledge includes a great deal more: practical informal knowledge about nature such as the properties of materials, heat, motion, plants, and animals; an intuitive grasp of basic mechanics (including the six "basic machines" of classical antiquity: the lever, pulley, screw, balance, wedge, and wheel); regularities of ocean currents and the weather; and folk wisdoms in the "an-apple-a-day-keeps-the-doctor-away" tradition. Geography is very much part of it: knowing where things are is logically prior to the set of instructions of how to go from here to there. It also includes what Edwin Layton (1974) has termed "technological science" or "engineering science" and Walter Vincenti (1990) has termed "engineering knowledge," which is more formal than folk wisdom and the mundane knowledge of the artisan, but less than

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[7] George Santayana defined science as "common knowledge, refined and extended...with its deductions more accurate" (Ziman, 1978, p. 8). Science differs from other parts of Ω-knowledge in that it is purposefully shared, that formal credit is assigned according to priority, that its propositions are tested by consensuality (that is, that they have to be agreed upon before they are accepted), and that it tries to minimize the tacit component by elaborating its materials, methods, assumptions, and techniques.

[8] As Alfred Crosby (1997, p. 109) notes, "measurement is numbers and the manipulation of numbers means mathematics." The great mathematician David Hilbert is reputed to have remarked that there is nothing more useful than a good mathematical theory (cited in Casti, 1990, p. 33).

science. Engineering knowledge concerns not so much the general "laws of nature" as the formulation of quantitative empirical relations between measurable properties and variables, and imagining abstract structures that make sense only in an engineering or a chemical context, such as the friction-reducing properties of lubricants or simple chemical reactions(Ferguson, 1992, p. 11).[9] The focus on whether "science" or "theory" served as a basis of technology before 1850 has been a source of confusion to economic historians concerned with the intellectual roots of economic change, as I argue below.

It seems pointless, furthermore, to argue about whether components of Ω are "correct" or not. Theories and observations about nature may have been of enormous practical influence and yet be regarded today as "incorrect." As long as they are believed to be true by some members of society, they will be in Ω. Hence Ω can contain elements of knowledge that are mutually inconsistent. For centuries, techniques in use were based on pieces of Ω that are no longer accepted, such as the humoral theory of disease or phlogiston chemistry, yet that hardly lessens their historical significance. Knowledge can be in dispute and speculative, or it can be widely accepted, in which case I will call it "tight." Tightness is a measure of consensualness of a piece of knowledge. It depends on the effectiveness of justification, the extent to which rhetorical conventions accepted in a society persuade people that something is "true," "demonstrated," or at least "tested." Tightness is a function of the ease of verifiability, and it determines the confidence that people have in the knowledge and—what counts most for my purposes—thus their willingness to act upon it. Such rhetorical conventions can vary from "Aristotle said" to "the experiment demonstrates" to "the estimated coefficient is 2.3 times its standard error." These rhetorical rules are pure social constructs, but they are not independent of how and why knowledge, including "useful" knowledge, grows over time.

Tightness has two dimensions: confidence and consensus. The tighter a piece of knowledge is, the more certain the people who accept it are of their beliefs, and the less likely it is that many people hold views inconsistent with it. Flat Earth Society members and those who believe that AIDS can be transmitted by mosquito bites may be few in number, but many Americans still do not believe in the Darwinian theory of evolution and believe in the possibility of predicting human affairs by looking at the

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[9] Ziman asks if there is such a thing as a "science" of papermaking (1978, p. 178). The answer must be that the history of papermaking technology, at least until the twentieth century, owed little to science but a great deal to pieces of Ω-knowledge that described such things as the properties of rags, the mechanical elements of cutting them, their tendency to dry, and the qualities of different bleaching pulp. It is hard to call this science, yet without this knowledge the techniques of papermaking would not have advanced much since they were imported from China.

stars. On this point it is hard to disagree with the thrust of the postmodernist critiques of rationalist accounts of the history of useful knowledge: truth is to a large extent what society believes on the basis of what authorities and experts tell the rest is the truth. Hence questions of politics (for example, who appoints these authorities and experts, and who sets their research agenda) permeate the search for useful knowledge and its deployment.

In the end, what each individual knows is less important than what society as a whole knows and can do. Even if very few individuals in a society know quantum mechanics, the practical fruits of the insights of this knowledge to technology may still be available just as if everyone had been taught advanced physics. For the economic historian, what counts is *collective* knowledge. But collective knowledge as a concept raises serious aggregation issues: how do we go from individual knowledge to collective knowledge beyond the mechanical definitions employed above?

Progress in exploiting the existing stock of knowledge will depend first and foremost on the efficiency and cost of *access* to knowledge. Although knowledge is a public good in the sense that the consumption of one does not reduce that of others, the private costs of acquiring it are not negligible, in terms of time, effort, and often other real resources as well (Reiter, 1992, p. 3). When the access costs become very high, it could be said in the limit that social knowledge has disappeared.[10] Language, mathematical symbols, diagrams, and physical models are all means of reducing access costs. Shared symbols may not always correspond with the things they signify, as postmodern critics believe, but as long as they are shared they reduce the costs of accessing knowledge held by another person or storage device.

What makes knowledge a cultural entity, then, is that it is distributed to, shared with, and acquired from others; if that acquisition becomes too difficult, Ω-knowledge will not be accessible to those who do not have it but are seeking to apply it. Between the two extreme cases of a world of "episodic knowledge" as it is said to exist among animals and a world in which all knowledge is free and accessible at no cost, there is a reality in

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[10] This cost function determines how costly it is for an individual to access information from a storage device or from another individual. The *average* access cost would be the average cost paid by all individuals who wish to acquire the knowledge. More relevant for most useful questions is the *marginal* access cost, that is, the *minimum* cost for an individual who does not yet have this information. A moment reflection will make clear why this is so: it is very expensive for the average member of a society to have access to the Schrödinger wave equations, yet it is "accessible" at low cost for advanced students of quantum mechanics. If someone "needs" to know something, he or she will go to an expert for whom this cost is as low as possible to find out. Much of the way knowledge has been used in recent times has relied on such experts. The cost of finding them experts and retrieving knowledge thus determines marginal access costs. Equally important, as we shall see, is the technology that provides access to storage devices.

which some knowledge is shared, but access to it requires the person acquiring it to expend real resources. Access costs depend on the technology of access, the trustworthiness of the sources, and the total size of Ω; the larger Ω, the more specialization and division of knowledge is required. Experts and special sources dispensing useful information will emerge, providing access. Information technology (IT) is exactly about that. Given that access costs vary across economies, it is an oversimplification to assume that the stock of usable knowledge is common and freely available to all countries.

The inventions of writing, paper, and printing not only greatly reduced access costs but also materially affected human cognition, including the way people thought about their environment.[11] But external memory came at a cost in that it codified and in some cases crystallized useful knowledge and gave it an aura of unassailability and sanctity that sometimes hampered the continuous revision and perfection. All the same, the insight that the invention of external storage of information is much like networking a computer that previously was stand-alone has some merit. Elizabeth Eisenstein (1979) has argued that the advent of printing created the background on which the progress of science and technology rests. In her view, printing created a "bridge over the gap between town and gown" as early as the sixteenth century, and while she concedes that "the effect of early printed technical literature on science and technology is open to question" she still contends that print made it possible to publicize "socially useful techniques" (pp. 558, 559).

Much of the likelihood that knowledge will be transmitted depends on the social organization of knowledge, storage technology, and who controls access to it. Knowledge, however, is transmitted over time as well as among individuals. If propositional knowledge is controlled by an imperial bureaucracy, as was the case in China, or a small aristocratic elite, as was the case in classical civilization, much of it can be lost or made inaccessible. If access costs are low, the likelihood of losing an existing "piece" of knowledge is small, and the search for new knowledge will be less likely to reinvent wheels. Access costs thus determine how likely it is that Ω will expand—that is, that new discoveries and knowledge will be added—because the lower access costs are, the more knowledge will be cumulative.

The much heralded "IT revolution" of our own age is not just about the fact that we know more (and different) things, but that the flows of information in and out of agents' minds are much more rapid. The con-

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[11] The invention of "external storage systems" has been credited by Merlin Donald (1991, pp. 308–12, 356) as the taproot of modern technological culture.

tinuous exchange of useful knowledge between the minds of agents and between agents and storage devices has become much faster and cheaper since the early 1990s. Access costs, however, depend not just on technological variables. They also depend on the *culture* of knowledge: if those who possess it regard it as a source of wealth, power, or privilege, they will tend to guard it more jealously. Secrecy and exclusionary practices are, of course, artificial ways to increase access costs. To be sure, language, notation, and jargon were also barriers to access (as they are today), but "popularized" versions of scientific books became necessary if scientists were to reach their paying audiences and patrons. There is the further issue of the "sociology of knowledge": in some societies the people who "know" are quite different from those who "do," that is, those who are active in the field and on the shop floor. How do these groups overlap and what kind of communication exists between them?

An evolutionary approach can help us clarify our thinking about useful knowledge, although analogies with biology and genetics have to be pursued with caution (Mokyr, 1998a, 2000d). Much like DNA, useful knowledge does not exist by itself; it has to be "carried" by people or in storage devices. Unlike DNA, however, carriers can acquire and shed knowledge so that the selection process is quite different. This difference raises the question of how it is transmitted over time, and whether it can actually shrink as well as expand. All carriers have finite lives and thus need to reproduce themselves in some fashion. The existence of nonliving carriers does expedite this transmission, but some crucial components cannot be codified or stored in devices that require codification. This "tacit" knowledge therefore dies with its live carrier unless it is passed on to the next generation. In principle there is nothing to stop knowledge from being lost altogether or becoming so expensive to access that for all practical purposes it might as well be.

The actual structure of Ω is self-referential: a great deal of knowledge consists of knowing that something is known and knowing how to find it. In almost Socratic fashion, it is a hallmark of an innovative producer to know what he or she does not know but is known to someone else, and then to try to find out. Beyond that, of course, society by definition faces a finite set of Ω: there are things that are knowable but are not known by any member of society. It is this finiteness that trivially constrains what each historical society could do, and increments in Ω open doors hitherto closed. Opening such doors does not guarantee that anyone will choose to walk through them, and the economic history of useful knowledge must concern itself with both issues if it is to make progress in understanding economic growth.

What properties of the set of prescriptive knowledge matter for my story? Techniques are the fundamental unit of the technological knowledge set. They are sets of executable instructions or recipes for how to manipulate nature, much like Richard Nelson and Sidney Winter's (1982) "routines." When these instructions are carried out in practice, we call it production, and then they are no longer knowledge but action.[12] It is comparable to DNA instructions being "expressed." Much like instructions in DNA, the lines in the technique can be either "obligate" (do X) or "facultative" (if Y, do X). For more complex techniques, nested instructions are the rule.

The instructions in the λ-set, like all knowledge, reside either in people's brains or in storage devices. They consist of designs and instructions for how to adapt means to a well-defined end, much like a piece of software or a cookbook recipe.[13] Elements of λ consist of "do loops" replete with "if-then" statements instructing one how to carry out activities that broadly constitute what we call "production." They can all be taught, imitated, communicated, and improved upon. A "how-to" manual is a codified set of techniques. An addition to the λ set of a society would be regarded as an "invention" (although the vast majority of them would be small incremental changes unrecorded by patent offices or history books).

Not all techniques are explicit, codified, or even verbalized. But even those that are are rarely complete, and much is left to be interpreted by the user. Thus riding a bicycle or playing a musical instrument consists of neuromuscular movements that cannot be made entirely explicit.[14] It should be obvious that in order to read such a set of instructions, readers need a "codebook" that explains the terms used in the technique (Cowan and Foray, 1997). Even when the techniques are explicit, the codebook may not be, and the codebook needed to decipher the first codebook and the next, and so on, eventually must be tacit. Sometimes instructions are

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[12] "Production" should be taken to include household activities such as cooking, cleaning, childcare, and so forth, which equally require the manipulation of natural phenomena and regularities.

[13] Reiter (1992, p. 13) employs the same concept. A technique, in his view, is like a cookbook recipe that contains four elements: (1) a description of the final product and its characteristics; (2) a list of ingredients and intermediate inputs; (3) the actual commands and suggestions on how to carry it out; and (4) an assurance that the recipe works. Arguably, part (4) properly belongs in Ω, since the statement that a technique works is, properly speaking, a natural regularity.

[14] Many techniques have elements and refinements that can only be stored in people's minds and transmitted, if at all, by personal contact. Some of them are "knacks" that are uncodifiable and defy any formalization; if they are valuable enough, they yield large rents to their carrier. Thus the skills of basketball- or violin-playing can be codified and taught, but the techniques applied by Michael Jordan or Itzhak Perlman are clearly not wholly transmissible.

"tacit" even when they could be made explicit but it is not cost-effective to do so. Much like elements of Ω, the elements of λ require carriers to be "expressed" (that is, used) and transmitted over time and across space. Each society has access to some metaset of feasible techniques, a monstrous compilation of blueprints and instruction manuals that describe what society can do. What these techniques looked like in the more remote past is often hard to pin down.[15] All the same, they existed. From that set, economic decision-makers, be they households, peasants, small-scale craftsmen, or large corporations, select the techniques actually used. This choice is the technological analogue of natural selection, and since Nelson and Winter first enunciated it in 1982 it has remained the best way to describe and analyze technology and technological change.

Naturally, only a small subset of λ is in use at any point in time. How society "selects" some techniques and rejects others is an important question that I will return to later in this book. Techniques, too, need to be passed on from generation to generation because of wear and tear on their carriers. Much learning happens within families or in a master-apprentice relationship. Despite the codifiability of many techniques, direct contact between teacher and pupil seemed, at least until recently, indispensable. Techniques are in many instances written in shorthand and economize on cognition. To transmit such action requires some form of codification, language, or symbols. The techniques in λ are, of course, "representations within the brain," as Brian Loasby notes (1999, p. 64), and the knowledge that "*this* is how you do that" is twice removed from the audience: first by the ability of the knower to map what he does into his own brain, and then by his ability to cast it in a language common with the audience. People can learn vertically, but also from one another through imitation.

Much like Ω-knowledge, λ-knowledge is stored in people's minds or in external memory. External memory takes the form of technical manuals and cookbooks, which need to be decoded by the user before the techniques they describe can be carried out effectively. But unlike Ω-knowledge, a great deal of the λ-knowledge is stored in the artifacts themselves. Looking at a piano for the first time, most people will realize that by pressing the keys they can generate music. On the other hand, the knowledge of how to make an artifact rather than use it is rarely obvious from the artifact itself, and reverse engineering requires a great deal of prior knowledge. Usually the information contained in the artifact itself is not sufficient even for purposes of usage, but it is often complementary to the

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[15] Hall points out that the historian finds it very difficult to identify λ from early records, because past shipwrights, toolmakers, and other artisans left few records of their "instructions," and inferring these from the end-products can be misleading (1978, p. 96).

knowledge attained from other external memory devices. Even those two are usually inadequate, and a great deal of tacit knowledge has to be transmitted through personal contact and imitation. Hence the long postdoctoral training periods required for would-be scientists whose work involves highly complex techniques that cannot be learned from books and journals alone.

Techniques, too, can be "tight" in the sense that their results are readily observed and compared with alternatives. Decision-makers may decide to adopt or not to adopt an untight technique by comparing the costs associated with type I errors (incorrectly accepting a wrong hypothesis) and type II errors (incorrectly rejecting a true hypothesis). We may not be sure that the hypothesis that eating raw cabbage prevents bowel cancer is correct, but the costs of not adopting the technique in case it is true may seem to some to be very much higher than the cost of adopting it when it is not. This kind of technological "Pascal's wager" applies to many untight techniques.

Is the distinction between propositional Ω-knowledge and prescriptive λ-knowledge meaningful? Both reflect some form of useful knowledge and thus are subject to the same kinds of difficulties that the economics of knowledge and technology encounters. An addition to Ω is a *discovery,* the unearthing of a fact or natural law that existed all along but that was unknown to anyone in society. An addition to λ is an *invention,* the creation of a set of instructions that, if executed, makes it possible to do something hitherto impossible. Michael Polanyi points out that the difference boils down to observing that Ω can be "right or wrong" whereas "action can only be successful or unsuccessful."(1962, p. 175)[16] Purists will object that "right" and "wrong" are judged only by socially constructed criteria, and that "successful" needs to be defined in a context, depending on the objective function that is being maximized.[17] Yet even with these

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[16] Polanyi fails to recognize the important historical implications of the two kinds of knowledge and maintains that "up to [1846] natural science had made no major contribution to technology. The Industrial Revolution had been achieved without scientific aid" (p. 182). However, the implicit definition he uses for Ω implies a much larger entity than formal science and includes much informal and folk knowledge. In addition to "pure science," he includes an intermediate set of inquiries that are "systematic technology" and "technically justified science." Moreover, his set of propositional knowledge must include even less formal elements when he points out that "technology always involves the application of some empirical knowledge... our contriving always makes use of some anterior observing"(Polanyi, 1962, p. 174). If so, the role of propositional knowledge of some kind in the development of technology must have been important long before modern science came into its own.

[17] Thus Carroll-Burke finds the distinction to be "weak" (2001, p. 619, n. 50). This judgment ignores that such distinctions and definitions can only be assessed if they help us answer the questions we pose. Here I am interested above all in the question of the effect of knowledge on material well-being, a topic that much constructivist scholarship seems to regard as

criteria, and the possibility of disagreement or an "undecided" verdict, the difference seems obvious. The planet Neptune and the structure of DNA were not "invented"; they were already there prior to discovery, whether we knew it or not. The same cannot be said about diesel engines or aspartame. Polanyi notes that the distinction is recognized by patent law, which will patent inventions (additions to λ) but not discoveries (additions to Ω).

The distinction between Ω and λ parallels the distinction made famous by Gilbert Ryle (1949), who distinguished between knowledge "how" and knowledge "what." Ryle rejected the notion that one can meaningfully distinguish *within a single individual* knowledge of a set of parameters about a problem and an environment from a set of instructions derived from this knowledge that directs an individual to take a certain action. Yet what may not be true for an individual is true for society as a whole: for a technique to exist, it has to have *an epistemic base* in Ω. In other words, somebody needs to know enough about a natural principle or phenomenon on which a technique is based to make it possible.[18] How much "enough" is depends on the complexity of the technique and other factors. Some techniques can be designed with minimal knowledge and are invented serendipitously, often while their inventor is looking for something else. A single subset of Ω can serve as the epistemic base for many techniques, thus providing for a kind of increasing returns (Langlois, 2001).[19] At the same time, most techniques normally involve many different elements in Ω.

As an illustration, consider the imaginary village proposed by Rachel Laudan (1984), which suffers from the regular flooding of its homes. One response of the villagers could be the invention of dams, but they might just as well decide to move to higher ground. How do we predict what actually happens? The building of a dam requires at least one person who possesses the understanding—however intuitive—of the basic regularities of hydraulics and the properties of earth. A minimum has to be known before a technique can be created. The likelihood that a laptop computer would be

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uninteresting. Carroll-Burke himself admits that certain "epistemic engines" (devices that measure and quantify observations of nature) "embed the abstractions of 'knowing what' into the practices of 'knowing how'" (p. 602).

[18] Strictly speaking, even if Ω is the null set, some elements in λ *could* exist. A beaver's technique of building dams or bees' ability to construct hives are techniques that have no demonstrable basis in anything we could define as useful knowledge.

[19] Machlup maintains that the difference in essential meaning is categorical: knowing that means that one confidently believes that something is so and not otherwise, whereas knowing how refers to a capability of doing something (1982, p. 31). Layton remarks that "'knowing' and 'doing' reflect the fundamentally different goals of communities of science and technology" (1974, p. 40).

developed in a society with no knowledge of computer science, advanced electronics, materials science, and whatever else is involved is nil.[20]

To repeat: the relationship between Ω and λ is that each element in λ—that is, each technique—rests on a known set of natural phenomena and regularities that support it. It is not necessary for many people to have access to the epistemic base, but the people writing the instructions must be among them. The historical significance of the epistemic base is not just that there is a minimum base without which techniques cannot be conceived. It is also that the wider and deeper the epistemic base on which a technique rests, the more likely it is that a technique can be extended and find new applications, product and service quality improved, the production process streamlined, economized, and adapted to changing external circumstances, and the techniques combined with others to form new ones.[21] When an existing technique needs to be extended or adapted to different circumstances, the content and extent of the epistemic base become important, and the practitioners return to the "theorists." Trial and error might work, of course, but it is more uncertain, slower, and more expensive. If someone, somewhere, knows the regularities and natural laws that make the technique work, that knowledge can be invoked or that expert can be consulted.

Furthermore, it is not necessary that the person actually carrying out the technique possess the supporting knowledge: I typed these lines on a computer even though I have only rudimentary knowledge of the physical and mathematical rules that make my computer work. It is likely that the workers who put together my laptop did not possess this knowledge either. To distinguish the knowledge needed to invent and design a new technique from that needed to execute it, I shall refer to the latter as *competence.* Competence is defined as the ability of agents to carry out the instructions in λ. The codified knowledge in the instructions still needs to be decoded, and in part competence consists of the ability to do the decoding, or if a codebook is supplied, to decode the codebook. Tacit knowledge is needed for obtaining inexpensive and reliable access to the codified instructions. Familiarity with the artifacts and substances used in executing the

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[20] Vincenti (1990, pp. 207–25) provides a detailed description of the kinds of knowledge that underlie engineering designs.

[21] This argument was well formulated by William Rankine, the great Scottish engineer, in 1859, when he noted that normal progress consists of "amendments in detail of previously existing examples." However, when the laws on which machines operate have been reduced to a science, practical rules are deduced "showing not only how to bring the machine to the condition of greatest efficiency...but also how to adapt it to any combination of circumstances" (Rankine, 1873, p. xx).

instructions is assumed when the instructions are formulated. Moreover, no set of instructions in λ can ever be complete. It would be too expensive to write a complete set of instructions for every technique. Judgment, dexterity, experience, and other forms of tacit knowledge inevitably come into play when a technique is executed. Another element of competence is the solution of unanticipated problems that are beyond the capability of the agent: knowing whom (or what) to consult and which questions to ask is indispensable for all but the most rudimentary production processes.[22]

The epistemic base of a technique does not have to be invoked consciously each time the technique is carried out. Much of it is embodied in the artifacts used, and the instructions themselves rarely need to explain *why* the recommendations work. Nor does every user have to possess the entire competence involved in operating the technique. The nature of *social knowledge* is that such knowledge is not necessary for everyone concerned. Hence the assumption, often made by economists, that the stock of technical knowledge is accessible to all economies seems reasonable. It seems plausible that competence—the capability to deploy a technique—is usually easier to access than the epistemic base. Thus even in countries where only a few people understand the finer points of electronics and microbiology, CD players and antibiotics can be produced and used. Yet how effectively techniques are deployed may differ a great deal from society to society even if the artifacts are identical, because competence depends on tacit knowledge and cultural traits that may differ systematically.

It should also be kept in mind that, for logical consistency, Ω contains such elements as "technique λ_i exists and works satisfactorily." After all, *strictu sensu* these statements are natural regularities. Hence the diffusion of techniques in λ depends on the characteristics of Ω. If access costs are low, producers may readily find out what kinds of techniques are available and how to get to them. Techniques are related to the artifacts they employ, but otherwise artifacts as such are not central. The techniques relating to a piano are sets of instructions for how to build one, how to play one, how to tune one, and how to move one into an apartment.

The Historical Evolution of Useful Knowledge

Where do the two types of knowledge come from, and how do they change over time? The Ω set is in part the result of purposeful search in the

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[22] Teece et al. (1994) correctly point out that the firm's "competence" includes some skills complementary to purely technical capacities such as knowledge of markets, sources of supply, finance, and labor management.

past for useful regularities, but a lot results simply from curiosity, an essential human trait without which no historical theory of useful knowledge makes sense. Hence, a very large part of Ω does not serve any useful purpose and does not serve as the epistemic base of any technique. Donald Stokes (1997) refers to this research as "Bohr's quadrant" (where the research into fundamental regularities is driven by purely epistemic motives) in contrast to Pasteur's quadrant (where the research is still "basic" but the underlying motive is use-driven). Historically, the development of Ω was sensitive to signals emitted by the economy and the polity regarding pieces of knowledge that society valued highly. Such signals of course did not always lead to results, and the history of useful knowledge remains a tale of contingency and accidents. The constraint on the menu of prescriptive knowledge available to society is above all, historical. At any moment, social knowledge is bounded, and much as in evolutionary systems, it cannot change too much at one time.

What about prescriptive knowledge? I have argued elsewhere that the relationship between Ω and λ is in some ways akin to the relationship between genotype and phenotype (Mokyr, 1998a). Not every gene ends up coding for a protein, but for any phenotype to emerge, some basis for it has to exist in the genome. But much like parts of the DNA that do not code for any protein, some exogenous change in the environment may bring about the activation of hitherto dormant useful knowledge. Similarly, techniques exist that are known but currently not used, but which could be brought back with the right kind of stimulus. Economists familiar with isoquants will find that conclusion familiar. The basic structure of the model is described in figure 1.

The diagram illustrates the basic setup of the model: an existing body of Ω-knowledge "maps" into a set of instructions that determines what this economy *can* do. This is the set of feasible techniques, sometimes known among economists as "the book of blueprints." Among these feasible techniques, a few are selected for actual execution, here denoted as λ^*.

The set Ω maps into λ and thus imposes a constraint on it much as the genotype maps into the phenotype and constrains it without uniquely determining it. The obvious notion that economies are limited in what they can do by their useful knowledge bears some emphasizing simply because so many scholars believe that if incentives and demand are right, somehow technology will follow automatically. Even a scholar as sophisticated as

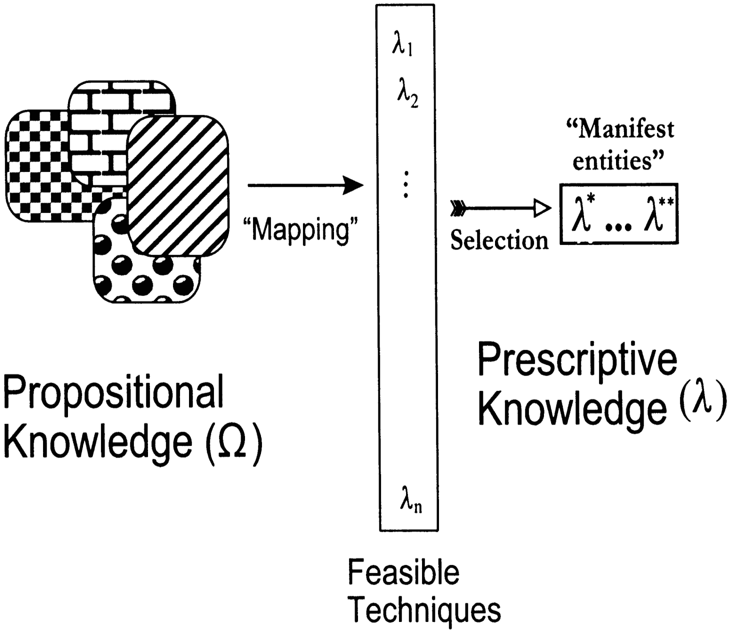

Figure 1: Propositional and Prescriptive Knowledge

Eric Jones believes that "technology seems to offer 'free lunches' but its spectacular gains are really secondary; they are attainable by any society that invests in institutions to encourage invention and enterprise" (2002, ch. 3, p. 20). Yet throughout history things that were knowable but not known were the chief reason why societies were limited in their ability to provide material comforts. Certain societies, including in all likelihood our own, did not have access to some feasible techniques that would have benefited them a great deal because they lacked a base in Ω. Medieval Europe could not design a technique describing the ocean route to Australia or produce antibiotics against the Black Death. Our own societies have been unable to tame nuclear fusion and make effective antiviral agents because we do not know enough about high-energy physics and virology. Nonetheless, we cannot be sure that such knowledge will never exist; all that matters is that we do not have it.

At the same time, the existence of some piece of Ω-knowledge that could serve as an epistemic base does not guarantee that any mapping will occur into λ. As noted above, the existence of a knowledge base creates opportunities but does not guarantee that they will be taken advantage of.

Hellenistic civilization created Ptolemaic astronomy but never used it, apparently, for navigational purposes; nor did their understanding of optics translate into the making of binoculars or eyeglasses. What matters, clearly, is culture and institutions. Culture determines preferences and priorities. All societies have to eat, but cultural factors determine whether the best and the brightest in each society will tinker with machines or chemicals, or whether they will perfect their swordplay or study the Talmud. Institutions set the incentive and penalty structure for people who suggest new techniques. They also determine in part the access costs to Ω by people who are active in production. The mapping function depicted in figure 1 remains one of the more elusive historical phenomena and is the key to explanations of "invention" and "technological creativity." What has not been sufficiently stressed, however, is that changes in the size and internal structure of Ω can themselves affect the chances that it will be mapped and determine the nature of the techniques that will emerge.

How and when does Ω provide the epistemic bases for technology? For people to create a new technique, they have to believe that the underlying propositional knowledge is likely to be correct. The mapping of the route around the globe was based on the belief that the earth was round, much as aseptic methods are based on the belief that bacteria cause infectious diseases. The tightness of the knowledge in Ω also determines the extent to which people are willing to employ the techniques that are based on it. This is particularly relevant when the outcome of a technique cannot be assessed immediately. Many techniques can be selected by individuals on the basis of readily measured characteristics: laser printers are preferred to dot matrix printers for the same reasons air-conditioning is preferred to room-fans. But in many other cases the judgment is difficult: Does broccoli consumption reduce the risk of cancer? Do nuclear power plants harm the environment more than fossil fuel-burning generators? In those cases, people might choose the technique that is based on the tighter Ω. Hence more people choose antibiotics over homeopathic medicine or Christian Science when they suffer from a disease whose etiology is well understood. Techniques may be "selected" because they are implied by a set of knowledge that is gaining acceptance.

As noted, the epistemic base of techniques can be narrow or wide. In this respect the analogy with the genotype breaks down. If it is very wide, so that a great deal is known about the underlying processes, in the limit inventions become increasingly deterministic, since society can invent whatever it needs. When the Ω set is relatively small and the epistemic base is narrow, solutions to well-defined problems are often prohibitively costly or impossible. For instance, if it were realized that infectious disease is associated with unclean water but not what exactly it is in the water that causes disease, people might have to purchase expensive drinks or bring the water from afar instead of, say, boiling or chlorinating it. In the age before metallurgy, high-quality steel production was feasible but extremely labor-intensive and costly.[23] Whatever progress was made in such a society depended on mostly accidental and stochastic inventions or costly searches based on buckshot experimentation. The narrower the epistemic base in Ω of a particular technique, the less likely it is to keep growing and expanding after its first emergence, because further expansion would demand even more fortuitous events. In the absence of an understanding of why and how a technique operates, further improvements run quickly into diminishing returns. In the limiting case, the base of a particular technique is so narrow that all that is known (and is thus contained in Ω) is the trivial element that "technique *i* works." These techniques, which might be called "singleton techniques" (because their domain is a singleton), usually emerged as the result of serendipitous discoveries.

A central argument of this book is that much technological progress before 1800 was of that nature. Although new techniques appeared before the Industrial Revolution, they had narrow epistemic bases and thus rarely if ever led to continued and sustained improvements. At times these inventions had enormous practical significance, but progress usually fizzled out after promising beginnings. Such techniques are also less flexible and adaptable to changing circumstances, a problem that is particularly acute in medicine (Mokyr, 1998b).[24] The more complex a technology, the less likely that a singleton technique will be discovered by luck. To be sure, pure singleton techniques are rare. More often the epistemic base was very narrow, just broad enough to create the "prepared minds" that Pasteur said fortune favored. A great deal of present-day industrial research and development still has room for serendipity and contains an element of "try every bottle on the shelf." When a compound is discovered that works for

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[23] Gerry Martin (2000) notes that the quench hardening of steel was known to the Japanese but that they knew nothing of carbon or iron and had no clue to how it worked. Innovation in such societies, he notes, is "extremely risky and unacceptably expensive."

[24] Hall (1978, p. 97) argues that a shipwright who knows "how" to build a ship without having any knowledge of the underlying rules would not be able to build a whole series of different ships. Thus Jenner's 1796 discovery of the vaccination process, one of the most successful singleton techniques in history, led to no further vaccinations until the triumph of the germ theory, and smallpox flare-ups due to ignorance and improper use of vaccinations were common till the end of the nineteenth century. The correct use of fertilizer in agriculture in ancient times improved but slowly until the development of organic chemistry by Justus von Liebig and his followers and the systematic experimentation of John Bennet Lawes and J. H. Gilbert at Rothamsted after 1840.

a particular purpose, the fine details of its modus operandi often emerge much later.[25]

Techniques that have narrow or negligible bases in Ω, however, tend also to be untight. Their inventors encounter more difficulty persuading the public to use them, if only because something might be more believable if it is known not only that it seems to work but also why. This tightness depends on other factors as well: if the technique is demonstrably superior, a narrow base in Ω may have little effect on its acceptability (as was surely the case with Jenner's invention of smallpox vaccination). The tightness of a demonstrably superior technique may reinforce confidence in an untight piece of Ω that serves as its epistemic base.

The widening of epistemic bases after 1800 signals a phase transition or regime change in the dynamics of useful knowledge. Of course, this did not happen throughout the economy. The rate at which it happened differed from activity to activity and from technique to technique. But any reading of the technological history of the West confirms that, sooner or later, this growth in useful knowledge became the moving force in economic change. In chapters 2 and 3, I document this process in some detail.

Moreover, unlike what happens in biology, λ can produce a feedback into Ω. As we shall see, this feedback is of considerable historical importance. The simplest case occurs when a technique is discovered serendipitously and the fact that it works is registered into the realm of Ω. The growth of Ω might then be further stimulated by this addition, since it is often provoked by new and unexplained phenomena, including the operation of a new technique. But changes in techniques also open up new opportunities, and technical developments in instruments and laboratory methods make new research possible. Finally, technological success inspires confidence in the Ω-knowledge underlying the techniques. This leads to further expansion of the epistemic base and to improvements and extensions of the techniques. The historical development of this mutual reinforcement between Ω and λ differs from case to case, but at least since the middle of the nineteenth century there has been a gradual if incomplete shift toward a priority of Ω.

Positive feedback from λ to Ω, then, can lead to virtuous cycles much more powerful than can be explained by technological progress or scientific

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[25] As *The Economist* puts it in its Millennium Special Issue, before Carl Djerassi drugs were developed in a "suck it and see" fashion: either their mode of action remained unknown, or it was elucidated only after their discovery (*The Economist,* Jan. 1, 2000, p. 102).

progress separately.[26] The process is self-sustaining because the two types of knowledge are complementary in the technical sense that a growth in one increases the marginal product of the other (Milgrom, Qian, and Roberts, 1991). If there is sufficient complementarity between an upstream process (Ω) and a downstream process (λ) in the system, persistent, self-reinforcing economic change can occur even without increasing returns. It should be added that λ itself can also show persistent dynamics, in that new technology leads directly to further inventions that introduce local improvements and "debug" the techniques. Without a corresponding growth in the epistemic base, however, such episodes have tended in the past to converge to a higher level of technology but did not lead to a self-sustained cumulative growth in which knowledge spins out of control. The overall idea is demonstrated in figure 2. The successive sets of Ω not only grow but provide wider and wider epistemic bases (checkered areas) for λ, which in turn lead to increased sets of Ω.

The idea of an epistemic base seems useful in other contexts as well. The existence of an Ω-set that serves as the epistemic base for possible new techniques, coupled to the public and open nature of Ω-knowledge, explains to a great extent the well-documented duplication-of-invention phenomenon that has often been marshaled as evidence for the importance of demand as a stimulus to innovation. It is more likely that separate inventors, even when they work in secrecy, will draw on a common body of known knowledge, to which others have access.

Useful Knowledge and the Social Sciences

The reader may well ask why a theory of useful knowledge is needed at all. Modern social scientists have treated useful knowledge in different and sometimes incompatible ways. For example, economists and economic historians influenced by New Growth Theory, in which the sources of economic growth are "endogenous," regard technology and knowledge as "produced by the system," that is, as outputs of a knowledge-creating production process that is governed by rational economic decision-making, even if it is recognized that some of the properties of knowledge as a commodity are unusual. This approach has led to a large literature on the economics of technological change and its ramifications for the theory of

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[26] Historians of Science such as Layton (1971, 1974) and Price (1984a) have long emphasized the intricacies of the interactions between science and technology, but have not fully realized that fairly small changes in the parameters can move the entire system from one that is homeostatic and relatively controlled, to a "supercritical region" in which the rate of change keeps accelerating.

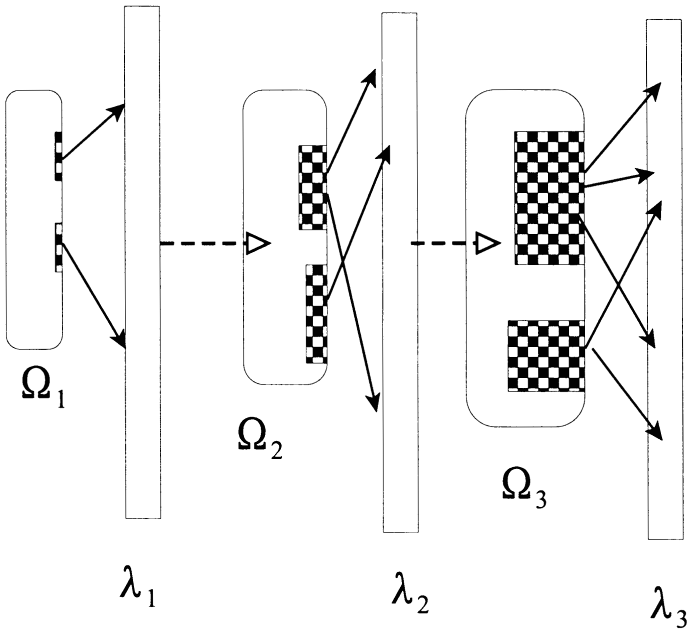

Figure 2: Feedback between Propositional and Prescriptive Knowledge

growth, the economics of education, human capital, and research and development.[27] The exact function that turns "research" into new knowledge is unknown, and if it itself changes over time, the model cannot explain historical trends.

Economists know, of course, that novel ideas and knowledge are expensive to generate but cheap to use once generated, that they create spillovers and externalities to other areas of knowledge, that they tend to create competitive equilibria that are not efficient, that they often create economies of scale, that they bias the contribution of capital to output, that they create a great deal of uncertainty, and so on. Treating knowledge as just another commodity (or, from the point of view of the firm, as just another input with is obviously fraught with pitfalls, yet in a competitive free-market system it would be equally irresponsible to ignore that new technology and useful knowledge have some commodity-like attributes and

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[27] For a magisterial and encompassing survey of this literature, see Ruttan (2001). The more theoretical aspects of endogenous growth theory are summarized in Aghion and Howitt (1997).

that the people producing it are on the whole as self-interested and capitalistic as anyone else.[28] Yet what this literature cannot deal with very well is the efficiency of the knowledge production function, that is, the ease with which efforts are transformed into invention.

In the literature of economics, the modern theory of endogenous growth is not the first to point to human knowledge as the issue at center stage in long-term economic development. To be sure, the issue has always been treated rather gingerly by writers who were somewhat outside the mainstream of economics but felt intuitively that the production and consumption of knowledge mattered.[29] In 1972 G. L. S. Shackle took the economics profession to task for largely ignoring what economic agents know and what they do not know.[30] His followers have continued in this vein. Scholars working in the field of evolutionary economics have dealt with the matter in great detail and with considerable success (e.g., Arora and Gambardella, 1994; Langlois, 2001; Loasby, 1999; Metcalfe, 1998a and 1998b; Nelson, 2000; Nelson and Nelson, 2002; Saviotti, 1996). Oddly, however, neither the "new" growth theory nor the extensive literature associated with the evolutionary approach has made much of an effort to use their tools in an attempt to come to grips with the fundamental problems that come up in the growth of useful knowledge and how they impinge on the major issues in economic history. Of course, not all economists are equally guilty: in his massive but incomplete trilogy Fritz Machlup (1980–84) attempted to face squarely the philosophical issues of human knowledge as they appear to the economist. Since then, economists have tried off and on to deal with the concept and reconcile it with the axioms and methods of economics (e.g., Reiter, 1992; Cowan, David, and Foray, 1999; Nelson and Nelson, 2002). Another approach has been to postulate how people behave in the absence of perfect knowledge through bounded rationality (e.g., Simon, 1996). My indebtedness to this literature

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[28] For a full treatment of innovation from this point of view, see Baumol (2002): "At heart, novel technology is simply another (durable) input into the production process, one that permits better products to be produced or that enables better processes to be used" (p. 80).

[29] In a classic article, Hayek (1945) noted the importance of knowledge in society but deals largely with *economic* knowledge such as prices and costs, which does not overlap much with the knowledge I am concerned with below.

[30] Shackle opens his book with a resounding indictment: "When the time came to invent economic theory...*knowledge* and *novelty*, the essential counter-point of conscious being, was given only a casual and subsidiary role. Un-knowledge, the aboriginal state of man...was simply disregarded and tacitly abolished by unthinking implication. The question of knowledge, of what is and can be known, the governing circumstance and condition of all deliberative action, was assumed away in the very theories of deliberative action" (Shackle, 1972, p. 3).

is enormous. So far, however, it has not made a systematic attempt to apply its insights to long-term economic growth.

Economic historians work from the assumption that some knowledge transcends specific social contexts. Nature poses certain challenges and constraints that matter to the human material condition, and overcoming these constraints is what technology is all about. To overcome them, we need to *know* things. Bodies of knowledge reflect matters with certain self-evident properties that are not historically contingent themselves. The exact form and language of knowledge, the way it was acquired, diffused, assessed, and utilized, were all historically contingent and differed from society to society. However, the assumption that the speed of sound, the human digestive system, the rules of genetic inheritance, and the laws of thermodynamics are themselves *not* socially constructed has remained axiomatic among economic historians.

In recent years, a large number of scholars of a more cultural bend have criticized these positions. For the purposes of this book—as for the purposes of science and technology itself—the philosophical position that knowledge is purely a matter of "conversation" and politics and does not reflect reality or mirror nature is unhelpful. If it were true, the "performativity" of technology—as one social constructivist has hideously termed it (Lyotard, 1984, pp. 41f)—would itself remain unexplained. All the same, the influence of this way of thinking about the history of useful knowledge is undeniable. Little can be gained by phrasing the progress of useful knowledge in terms of ever-diminishing deviations from the true knowledge as revealed to us. In its more extreme forms, the radical "social construction" approach to the history of science and technology denies any kind of knowledge that is definable outside the power structure of a society and insists that such knowledge is wholly contextualized and socially constructed to serve political ends. It dismisses economic growth and modernization as legitimate topics of research and denies the relevance of technological progress as the defining trend of recent history. On at least two fronts, I must acknowledge my debts to these scholars.

One is that there is no pretense that useful knowledge today represents the last word, only the latest. We may be persuaded that phlogiston physics and humoral medicine are "wrong" to the point of amusement, but honest scholars must acknowledge that future scientists may well think in the same way of best-practice knowledge *anno* 2002. The standards by which we accept or reject certain propositions are themselves "socially constructed," and it seems no more than proper not to claim too much for useful knowledge as a way of "understanding" the world.

To be a bit more precise, nothing in technological knowledge requires the *understanding* of nature. There is, in fact, a great deal of debate over what explanation and understanding mean. Wittgenstein famously remarked that "the illusion that the so-called laws of nature are explanations of natural phenomena" was at the basis of the modern view of the world. Whether it is an illusion or not depends on what is meant by "explaining." Some natural phenomena are regularities, some are accidents. Much modern science is about distinguishing the two, as Steven Weinberg (2001) has pointed out, but even accidents are subject to certain constraints and order. The useful knowledge in Ω consists of a catalog of phenomena, the patterns that can be distinguished in their occurrence, the regularities that govern their behavior, and the basic principles that govern these regularities. Useful knowledge, however, rarely contains an explanation *why* these principles exist as they do. We know, for instance, that the behavior of particles and waves is governed by Planck's constant, but we have no way of explaining *why* it is equal to $6.6260755 \times 10^{-34}$ joule-second. The point is that for the application of quantum mechanics, the answer does not matter much. For most purposes knowing that radiation such as light is emitted, transmitted, and absorbed in quanta, determined by the frequency of the radiation and the value of Planck's constant, is enough. The higher the principle and the wider the class of phenomena it can predict, the more we can exploit it. Mendeleyev's periodic table does not "explain" why the elements are what they are and follow in a particular order, but it establishes a strict natural regularity that can be utilized to our advantage. The higher the level of generality, the wider the epistemic base, and the more knowledge can be expanded and tightened by deductive methods as opposed to experiments and statistical inference. An epistemic base can be wide in this sense, or simply "broad" in the sense that it contains a large number of (poorly "understood" but carefully cataloged) empirical observations.

The other conflict between the way economists and sociologists of science see the development of useful knowledge relates to the social construction of useful knowledge. The Kuhnian position that useful knowledge is a communal and consensual convention has been extended by more radical thinkers to mean that no useful reality can be assumed to exist, and that the body of useful knowledge is little more than one of many possible constructs set up by a dominant group. The two extreme positions can be juxtaposed by asking whether useful knowledge consists of a game against nature, or whether it is a zero-sum game against other players, in a struggle for influence and resources. The economist's position is that even in a one-person society there are natural regularities to be observed and techniques to be carried out and that the social character of knowledge is incidental to the need for a division of labor. The other position, in its extreme form, maintains that all useful knowledge is a social convention, constructed in a particular context and invalid as a general proposition. Some of the solutions to these seemingly irreconcilable positions will be suggested in chapter 6 of this book, where persuasion and political choices are shown to be paramount and where rational behavior is shown to be potentially inimical to technological progress. While as an economist I cannot overcome my biases altogether, it would be folly to think that nothing can be learned from looking at these highly complex issues from a different point of view.

In addition to economists, historians, and sociologists, psychologists have had a lot to say about useful knowledge, and there is no way I can do justice to their work in this volume. It is worth pointing out, however, that the notion of how techniques in use rely on epistemic bases in Ω-knowledge is consistent with recent theorizing in cognitive sciences. Rachel Laudan (1984) has argued that one way to think of the cognitive activity that generates technological knowledge is to see it as problem-solving. In recent years, it has become more and more accepted to think of the human mind as the result of hundreds of thousands of years of evolutionary growth in small societies much different from our own. John Tooby and Leda Cosmides (1992, 1994) have argued that natural selection determined that the best adapted mind was not the cool and calculating all-purpose rational mind that economists often assume people have, but a network of more or less functionally specialized problem-solving devices that could choose simple optimal strategies or routines that would on average work best in most circumstances. Cosmides and Tooby use as a test case the intersection between reasoning and social exchange in interactions between people, but nothing in their work excludes the application of the same specialized functions to operations between humans and their physical environment. Such a structure of the mind could therefore design a set of techniques supported by a simple and incomplete epistemic base and execute it without necessarily worrying about the details of why and how the technique works. The specialized problem-solving part of the mind would realize that a given technique solved a particular problem and it is natural for us to employ techniques without worrying about their modus operandi and trying to expand their epistemic base. If the problem is "a headache" and the instruction to the solution reads "take an aspirin," neither physician nor patient may be much inclined to worry a great deal about how aspirin does its work. Indeed, the amazing phenomenon is that anybody asked those questions at all.

Modern economic growth demonstrates that in some societies, people overcame the tendency of accepting that techniques work without worrying about why they did so. Therein lies the answer to the origins of the technological miracles that created our prosperity. In what follows, I trace this development and explore some of its ramifications. The next two chapters are devoted to a detailed account of how this happened, reassessing the historical event we call the Industrial Revolution. The two following chapters deal with some of the other consequences of the growth in knowledge: the rise of the factory during the Industrial Revolution and the changes in health and the concomitant changes in the household in the late nineteenth and twentieth centuries. Then I take a closer look at the political economy of useful knowledge. The last chapter speculates on the relative roles of institutions and technological progress in economic growth and on the possible connections between them.

Chapter 2

The Industrial Enlightenment: The Taproot of Economic Progress

> *It is clear from the preceding that every "art" [technique] has its speculative and its practical side. Its speculation is the theoretical knowledge of the principles of the technique; its practice is but the habitual and instinctive application of these principles. It is difficult if not impossible to make much progress in the application without theory; conversely, it is difficult to understand the theory without knowledge of the technique. In all techniques, there are specific circumstances relating to the material, instruments and their manipulation which only experience teaches.*
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> — Denis Diderot, "Arts" in the *Encyclopédie*

Introduction

Can we "explain" the Industrial Revolution? Recent attempts by leading economists focus more on the issue of timing (Why did it happen in the eighteenth century) than on the issue of place (Why western Europe?) (Lucas, 2002; Hansen and Prescott, 1998; Acemoglu and Zilibotti, 1997; Galor and Weil, 2000; Galor and Moav, 2002). Both questions are equally valid, but they demand different types of answers. In what follows, I answer only the first question, although the ideas used here can readily be extended to the second. The answer for the timing question is to link the Industrial Revolution to a prior event or to a simultaneous event that it did not cause. Rather than focus on political or economic change that prepared the ground for the events of the Industrial Revolution, I submit that the Industrial Revolution's timing was determined by intellectual developments, and that the true key to the timing of the Industrial Revolution has to be sought in the scientific revolution of the seventeenth century and the Enlightenment movement of the eighteenth century. The key to the Industrial Revolution was technology, and technology is knowledge.

In what follows I rely on the outline of the theory of knowledge proposed in chapter 1 and apply it to the issues around the sources of the Industrial Revolution in Britain. The central conclusion from the analysis is that economic historians should re-examine the epistemic roots of the Industrial Revolution, in addition to the more standard economic explanations that focus on institutions, markets, geography, and so on. In particular, the interconnections between the Industrial Revolution and those parts of the Enlightenment movement that sought to rationalize and spread knowledge may have played a more important role than recent writings have given them credit for (see e.g., the essays in Mokyr, 1998c). This would explain the timing of the Industrial Revolution following the Enlightenment and—equally important—why it did not fizzle out like similar bursts of macroinventions in earlier times. It might also help explain why the Industrial Revolution took place in western Europe (although not why it took place in Britain and not in France or the Netherlands).

Knowledge, Science, and Technology during the Industrial Revolution

The Industrial Revolution was not the beginning of economic growth. There is considerable evidence that on the eve of the Industrial Revolution Britain and other parts of western Europe had gone through long periods of economic growth, perhaps not as sustained and rapid as modern economic growth, but growth all the same (Mokyr, 1998c, pp. 34–36 and sources cited there). It remains to be seen how much of this growth can be attributed to increases in technological knowledge about production and how much to other factors, such as gains from trade or more efficient allocations. Much of the analysis of growth in history, of course, does not lend itself to such neat decompositions: the geographic discoveries after 1450 and improvements in shipping and navigational technology were in and of themselves a pure growth in Ω, mapping into improved techniques, but they led to increased trade as well. The Industrial Revolution, however, constitutes a stage in which the weight of the knowledge-induced component of economic growth increased markedly. It neither started from zero nor went to unity. All the same, the period 1760–1815 was one in which continuous political disruptions must have reduced the importance of "Smithian (trade-based) growth." Britain's ability to sustain a rapidly rising population without a sharp decline in per capita income may be regarded as a signal for a new "type" of growth.

It has become a consensus view that economic growth as normally defined (a rise in national income per capita) was very slow during the Industrial Revolution, and that living standards barely nudged upward until the mid-1840s (Mokyr, 1998c). Some voices have even called for abandoning the term altogether. Yet it is also recognized that there are considerable time lags between the adoption of major technological breakthroughs (or so-called general-purpose technologies) and their macroeconomic effects. Moreover, traditionally measured growth in Britain was respectable once we take into account the negative political and demographic shocks of the period even during the difficult years between 1760 and 1815. In the longer run, the macroeconomic effects of the technological breakthroughs that constituted the Industrial Revolution have not seriously been questioned. The growth of scientific knowledge was part of this development, but a relatively small (if rapidly growing) component. Most practical useful knowledge in the eighteenth century was unsystematic and informal, often uncodified and passed on vertically from master to apprentice or horizontally between agents. Engineers, mechanics, chemists, physicians, instrument makers, and others could rely increasingly on facts and explanations from written texts, yet the instinctive sense of what works and what does not remained a critical component of what was "known." Formal and informal knowledge were complements in the development of new techniques, and the technology of knowledge transmission itself played a major role.[1]

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[1] Margaret Jacob (1997), whose work has inspired much of what follows, summarizes the developments in eighteenth-century Europe: "Knowledge has consequences. It can empower; if absent, it can impoverish and circumstances can be harder to understand or control" (p. 132). Yet her statement that "people cannot do that which they cannot understand, and mechanization required a particular understanding of nature that came out of the sources of scientific knowledge" (p. 131) goes too far. Depending on what one means by "understand," it is obvious that people *can* do things they do not understand, such as build machines and design techniques on the basis of principles and laws that are poorly understood or misunderstood at the time. Above all, "understanding" is not a binary variable. The epistemic base can be wider, in which case existing techniques are more likely to be improved and adapted, and the "search" for new ones is more efficient and likely to succeed.

The true question of the Industrial Revolution is not why it took place at all but why it was sustained beyond, say, 1820. There had been earlier clusters of macroinventions, most notably in the fifteenth century with the emergence of movable type, the casting of iron, and advances in shipping and navigation technology. Yet those earlier mini–industrial revolutions had always petered out before their effects could launch the economies into sustainable growth. Before the Industrial Revolution, the economy was subject to negative feedback; each episode of growth ran into some obstruction or resistance that put an end to it.[2] Growth occurred in relatively brief spurts punctuating long periods of stagnation or mild decline. After such episodes, the economy asymptoted to a higher steady state, creating something of a "ratchet effect" (Braudel, 1981, p. 430).

The best known of these negative feedback mechanisms are Malthusian traps, in which rising income creates population growth and pressure on fixed natural resources. Pre-1750 economies were "organic" in that they depended to a much greater extent on land as a factor of production, not only to produce food but also as a source of the majority of raw materials and fuel (E. A. Wrigley, 2000). Another was institutional negative feedback. When economic progress took place, it usually generated social and political forces that, in almost dialectical fashion, terminated it. Prosperity and success led to the emergence of predators and parasites in various forms and guises who eventually slaughtered the geese that laid the golden eggs. Tax collectors, foreign invaders, and rent-seeking coalitions such as guilds and monopolies in the end extinguished much of the growth of northern Italy, southern Germany, and the Low Countries. A particularly striking manifestation of this feedback is technological resistance: entrenched interests were able to stop technological progress using non-market mechanisms, a topic I return to in chapter 6.

But perhaps the main root of diminishing returns was the narrow epistemic base of technology. When new techniques came around, often revolutionary ones, they usually crystallized at a new technological plateau and did not lead to a stream of cumulative microinventions. In key areas such as ship design, metallurgy, medicine, printing, and power technology, patterns of "punctuated equilibrium" can be observed between 1400 and

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[2] An early use of the idea of such feedback is found in Needham's description of the social dynamics of Imperial China, which he describes as a "civilization that had held a steady course through every weather, as if equipped with an automatic pilot, a set of feedback mechanisms, restoring the status quo [even] after fundamental inventions and discoveries"(Needham, 1969, pp. 119–20). Needham may have overstated the degree of technological instability in pre-1750 Europe, but his intuition about the difference between the two societies being in the dynamic conditions of stability is sound.

1750. The main reason for this pattern was that too little was known on how and why the techniques in use worked.

In the pre–Industrial Revolution era, narrow epistemic bases were the rule, not the exception, especially in medicine and agriculture, but also in metallurgy, chemicals, and power technology. In both Europe and China, techniques worked despite a lack of understanding of why they worked. Normally, it was enough if someone recognized some exploitable regularity. Whether we look at steelmaking, cattle-breeding, or obstetric surgery, most techniques before 1800 emerged as a result of chance discoveries, trial and error, or good mechanical intuition and often worked quite well despite nobody's having much of a clue as to the principles at work. As I argued in chapter 1, however, narrow-based techniques rarely led to a continuous stream of extensions, refinements, or new applications. For example, if a manufacturer does not know the nature of the fermentation that turns sugar into alcohol, he or she can still brew beer and make wine, but will have only a limited ability to perfect their flavor or to mass produce at low prices. When no one knows why things work, potential inventors do not know what will *not* work and will waste valuable resources in fruitless searches for things that cannot be made, such as perpetual-motion machines or gold from base metals. The range of experimentation possibilities that needs to be searched over is far larger if the searcher knows nothing about the natural principles at work. To paraphrase Pasteur's famous aphorism once more, fortune may sometimes favor unprepared minds, but only for a short while. It is in this respect that the width of the epistemic base makes the big difference. To be sure, there are methods for overcoming the limits of narrow epistemic bases: systematic search and experimentation in chemistry and pharmaceuticals and parameter variation, still employed widely in airplane design when aerodynamics was inadequate, date from the eighteenth century. Engineering knowledge is most crucial precisely when the epistemic base is narrow. It would be a grave error to suppose that the Industrial Revolution in its early stages was driven by a sudden deepening of the scientific foundations of technology. But the gradual and slow widening of the epistemic bases of the techniques that emerged in the last third of the eighteenth century saved the process from an early death by exhaustion.

Beyond that, there is the question of the *tightness* of knowledge. Many parts of Ω may have been suspected to exist by some people, but as long as they could not be "demonstrated" rigorously enough to convince enough others, the knowledge may not have been tight enough to serve as an epistemic base. The great scientific breakthroughs of the late eighteenth and nineteenth centuries, including the refutation of the existence of caloric, phlogiston, miasmas, spontaneous generation, and the ether, had been attempted by many before, but convincing proof had been elusive. If the epistemic base is sufficiently untight, it may be hard to rely on it to support a great deal of research and development.

To oversimplify a bit, the Industrial Revolution could be reinterpreted in light of the changes in the characteristics and structure of Ω-knowledge in the eighteenth century and the techniques that rested on it. As the two forms of knowledge co-evolved, they increasingly enriched one another, eventually tipping the balance of the feedback mechanism from negative to positive. Useful knowledge increased by feeding on itself, spinning out of control as it were, whereas before the Industrial Revolution it had always been limited by its epistemic base and suppressed by economic and social factors.[3] Eventually positive feedback became so powerful that it became self-sustaining. The positive feedback effects between Ω-knowledge and λ-knowledge thus produced a self-reinforcing spiral of knowledge augmentation that was impossible in earlier days of engineering without mechanics, iron-making without metallurgy, farming without organic chemistry, and medical practice without microbiology.[4] The changes in the social environment in which useful knowledge was created and disseminated led not only to an increase in the size of Ω (through discovery) but also to higher density (through diffusion).

All in all, the widening of the epistemic base of technology meant that the techniques that came into use after 1750 were supported by a broader and broader base in Ω. This made a gradual stream of improvements and microinventions possible. Of course, the width of the epistemic base differed from industry to industry and from technique to technique. In some cases, considerable knowledge was required before an epistemic base of sufficient width emerged, while in other industries such as textiles, where the process was mostly mechanical, a great deal of progress could be attained at an early stage. In short, the Industrial Revolution should be understood in the context of changes in useful knowledge and its applications.

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[3] Another explanation of this "phase transition" has been proposed recently by David (1998). He envisages the community of "scientists" to consist of local networks or "invisible colleges" in the business of communicating with each other. Such transmission between connected units can be modeled using percolation models in which information is diffused through a network with a certain level of connectivity. David notes that these models imply that there is a minimum level of persistently communicative behavior that a network must maintain for knowledge to diffuse through and that once this level is achieved the system becomes self-sustaining.

[4] As Cohen and Stewart point out, because Ω and λ have a different "geography" (that is, they contain very different and incommensurate kinds of information), their attractors do not match up nicely and "the feedback between the spaces has a creative effect.... the interactions create a new, combined geography that in no sensible way can be thought of as a mixture of the two separate geographies" (1994, pp. 420--21).

How much of the changes in Ω in Britain before and during the Industrial Revolution could be attributed to what we would call today "science"? The notion that Britain was the first to undergo an Industrial Revolution because somehow British technological success was due to its more "advanced" science is unsupportable. The premise itself is in dispute (Kuhn, 1977, p. 43), and it appears that Britain, despite its industrial leadership, imported at least as much scientific knowledge as it exported to its continental competitors. Moreover, a wide array of economic historians and historians of science and technology have held that the techniques developed during the British Industrial Revolution were generated by "hard heads and clever fingers" and owed little directly to scientific knowledge as we would define it today. Unlike the technologies that developed in Europe and the United States in the second half of the nineteenth century, science, in this view, had little direct guidance to offer to the Industrial Revolution (Hall, 1974, p. 151). Shapin notes that "it appears unlikely that the 'high theory' of the Scientific Revolution had any substantial *direct* effect on economically useful technology either in the seventeenth century or in the eighteenth.... historians have had great difficulty in establishing that any of these spheres of technologically or economically inspired science bore substantial fruits" (1996, pp. 140–41, emphasis added). Gillispie (1957) wonders about the practical effect of all the works of chemists and mathematicians of eighteenth-century France and points out that the majority of scientific endeavors of the time concerned subjects of limited technological use: astronomy, botany, crystallography and early exploration of magnetism, refraction of light, and combustion. Eventually many of those discoveries found economic applications, but these took place, with few exceptions, after 1830. Other scholars, above all Musson and Robinson (1969) and Margaret Jacob (1997, 1998), have felt equally strongly that science was pivotal.[5] How to resolve this debate?

Regardless of how one thinks of science, it seems incontrovertible that the rate of technological progress depends on the way human useful knowledge is generated, processed, and disseminated. This is hardly a new idea.[6] Two historical phenomena changed the parameters of how the societies of western Europe handled useful knowledge in the period before the Industrial Revolution. One was the scientific revolution of the seventeenth century. The other is an event that might best be called the *Industrial Enlightenment.* The Industrial Enlightenment was a set of social changes

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[5] A good survey of the opposing views can be found in McKendrick (1973).

[6] Cognitive scientists such as Merlin Donald (1991) have argued that the emergence of spoken language and, much later, written language is associated with an acceleration in the rate of technological progress.

that transformed the two sets of useful knowledge and the relationship between them. It had a triple purpose. First, it sought to reduce access costs by surveying and cataloging artisanal practices in the dusty confines of workshops, to determine which techniques were superior and to propagate them. Thus it would lead to a wider adoption and diffusion of best-practice techniques. Second, it sought to understand why techniques worked by generalizing them, trying to connect them to the formal propositional knowledge of the time, and thus providing the techniques with wider epistemic bases. The bewildering complexity and diversity of the world of techniques in use was to be reduced to a finite set of general principles governing them. These insights would lead to extensions, refinements, and improvements, as well as speed up and streamline the process of invention. Third, it sought to facilitate the interaction between those who controlled propositional knowledge and those who carried out the techniques contained in prescriptive knowledge.[7] The *philosophes* of the Enlightenment echoed Bacon's call for cooperation and the sharing of knowledge between those who knew things and those who made them. Yet in the 1750s, when the first volumes of the *Encyclopédie* were published, this was still a program, little more than a dream. A century later it had become a reality. What made Bacon's vision into a reality was the Industrial Revolution.

I choose the term "Industrial Enlightenment" with some care. The Enlightenment movement of the eighteenth century was of course a multifaceted and complex phenomenon, aimed at least as much at changing the existing political power structure and the distribution of income it implied as at increasing wealth by making production more rational. Its effect on creating "a public sphere" and a belief in the perfectionability of people and their institutions may well have been a watershed in social and intellectual history. The notion I am proposing is more narrow and more focused. It concerns only that part of rationality that involves observing, understanding, and manipulating natural forces. In this sense, my approach might remind some readers of that of the Frankfurt School, which viewed the Enlightenment as a stage in the battle between people and their environment. The difference is that I do not accept the notion that the "domination" of nature is necessarily tantamount to the domination of other people, let alone a prelude to barbarism. My concern is the purely economic one of how some societies were able to augment the resources at their disposal at a rate that was unprecedented.

Formal and generalized propositional knowledge—what today we would call science—was a factor in the Industrial Revolution primarily

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[7] Somewhat similar views have been expressed recently by other scholars such as John Graham Smith (2001) and Picon (2001).

through the incidental spillovers from the scientific endeavor on the properties of Ω. The changes in social attitudes toward Ω-knowledge affected the way in which new knowledge was generated, but equally important, they affected the technology and culture of *access to* information. Once this took place, it spread beyond the more arcane realms of mathematics and experimental philosophy to the mundane worlds of the artisan, the mechanic, and the farmer. In the century and a half before the Industrial Revolution the language and culture of useful knowledge changed dramatically. The "scientific revolution" is widely identified with it, even if historians of science and cultural historians have debated ad nauseam whether there was a scientific revolution at all, and if so, what it was (Shapin, 1996). Historians have generally not been able to support the notion that the scientific revolution led directly to the Industrial Revolution. The missing link may well be the Industrial Enlightenment, forming the historical bridge between the two.

Be that as it may, the premise of this book is that what people knew affected what they did. There can be no doubt that the Industrial Revolution and the subsequent age of modern growth coincided with a revolution in useful knowledge. In 1789 the chemist James Keir wrote that "the diffusion of a general knowledge, and of a taste for science, over all classes of men, in every nation of Europe or of European origin, seems to be the characteristic feature of the modern age" (cited by Musson and Robinson, 1969, p. 88). But was there a causal link, or is the inference of such a link much like "guilt by association" as some economic historians believe? The link between useful knowledge and the changes in the economy was perhaps more subtle, indirect, and complex than the linear "science leads to technology" models imply, but it did exist.

Part of the confusion is caused by the insistence on separating science from technology or theory from empirical knowledge. As noted, Ω contains much more than formal science, however defined. It includes all natural facts and relationships as well as a master catalog of all techniques that are known to work (since strictly speaking those are natural regularities). A new adaptation of a technique used elsewhere, or a recombination of existing techniques into a novel application, would thus have to depend both on the Ω-base and the ease of access to it. Second, as Shapin notes, "scientifically derived *information*, *skills*, and perhaps attitudes were important resources in all kind of activities" (Shapin, 1996, p. 141, emphasis in original). These spillover effects, as much as the knowledge itself, created the Industrial Enlightenment and set the stage for the changes in technology.

The Industrial Enlightenment's debt to the scientific revolution consisted of three closely interrelated phenomena: scientific *method*, scientific *mentality*, and scientific *culture*. The penetration of scientific *method* into technological activities meant accurate measurement, controlled experiment, and an insistence on reproducibility. Scientific method was influenced by the growing sense that precision was something to be valued for its own sake, as people interested in useful knowledge moved from the world of "more or less" to a universe of measurement and precision in the classic phrasing of Alexandre Koyré (1968, p. 91). High degrees of precision in measurement instruments and equipment were more of a promise than a fact in the age of Galileo, and the superior skills and materials of eighteenth-century craftsmen such as John Harrison and Jesse Ramsden were necessary before the propositional knowledge of the previous century could be made into accurate navigational and surveying technologies. Scientific method also meant that observation and experience were placed in the public domain. Betty Jo Dobbs (1990), William Eamon (1990, 1994), and more recently Paul David (1997) have pointed to the scientific revolution of the seventeenth century as the period in which "open science" emerged, when knowledge about the natural world became increasingly nonproprietary and scientific advances and discoveries were freely shared with the public at large. Thus scientific knowledge became a public good, communicated freely rather than confined to a secretive exclusive few as had been the custom in medieval Europe. This sharing of knowledge within "open science" required systematic reporting of methods and materials using a common vocabulary and consensus standards. This, most decidedly, was *not* the case for λ-knowledge, where property rights were maintained as much as possible, through reliance either on patents or on secrecy.[8] Useful knowledge, it seems, went through something of a bifurcation: Ω-knowledge was increasingly recognized to be a public good and placed in the public realm, with priority determining credit and attribution (which themselves were made into valuable goods) but not ownership; λ-knowledge became subject to attempts to impose intellectual property rights on it. It then bifurcated again: some of the λ-knowledge was patented and thus placed in the public realm where access to the knowledge —if not its application—was open and free, and some was protected by raising access costs artificially—that is, keeping it secret. Enlightenment thinking in the eighteenth century increasingly tended to view intellectual property rights as part of natural law. It was but an application of the Enlightenment

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[8] James Watt's son complained that dyers and printers in Manchester had formed an association, agreeing not to let their employers know anything about their business or processes (Musson and Robinson, 1969, p. 339). The French chemist Claude Berthollet, upon taking up the directorship of the *Gobelins* factory, made a similar complaint (Keyser, 1990, p. 221). Many manufacturers were obsessive about secrecy: Benjamin Huntsman, the steelmaker, ran his works only at night as a security measure.

principle of the primacy of effects over intentions to useful knowledge. Yet it created a tension between those who felt that new knowledge was essential to economic progress and those who had an aversion to monopolies and barriers to the effective diffusion of and cheap access to useful knowledge (Hilaire-Pérez, 2000, pp. 124–42).

Scientific "method" here also should be taken to include the changes in the rhetorical conventions that emerged in the seventeenth century, during which persuasive weight continued to shift away from pure "authority" toward empirics, but which also increasingly set the rules by which empirical knowledge was to be tested so that useful knowledge could be both accessible and trusted.[9] Verification meant that a deliberate effort was made to make useful knowledge tighter and thus more likely to be used. It meant a willingness, rarely observed before, to discard old and venerable interpretations and theories when they could be shown to be in conflict with the evidence. Scientific method meant that a class of experts evolved who often would decide which technique worked best.[10]

The Industrial Enlightenment placed a great of deal of trust in the idea of *experimentation*, a concept inherited directly from seventeenth century science.[11] An experiment, as Bacon and others saw it, was meant to "vex nature," that is, to tease out knowledge by "twisting the lion's tail," making nature cry out her secrets. Experiments created situations that did not occur "naturally" and thus vastly expanded the realm of phenomena that could be cataloged and then harnessed. They could also serve as validations of postulated general relationships. Of course, what an experiment amounted to in practice and how and when a result would be accepted as valid remained contingent and has continued to change over the centuries. Experimental philosophy became the rhetorical tool that connected the scientific revolution of the seventeenth-century to the industrial transformations of the eighteenth. It was realized that the experimental

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[9] Shapin (1994) has outlined the changes in trust and expertise in Britain during the seventeenth century associating expertise, for better or for worse, with social class and locality. While the approach to science was ostensibly based on a "question authority" principle (the Royal Society's motto was *nullius in verba*—on no one's word), in fact no system of useful (or any kind of) knowledge can exist without some mechanism that generates trust. The apparent skepticism with which scientists treated the knowledge created by others increased the trust that others had in the findings, because outsiders could then assume —as is still true today—that these findings had been scrutinized and checked by other "experts."

[10] As Hilaire-Pérez (2000, p. 60) put it, "the value of inventions was too important an economic stake to be left to be dissipated among the many forms of recognition and amateurs: the establishment of truth became the professional responsibility of academic science."

[11] William Eamon (1994, ch. 8) points out the notion of science as *venatio*, a search for the secrets of nature. Because they were hidden beyond the reach of ordinary perception, they had to be revealed by extraordinary means.

method produced a systematic approach to the solution of practical problems, as well as a greater set of facts in Ω, which could then be ordered by rational description (Keyser, 1990, p. 217). But above all the scientific method implied a consensus about the elements in Ω that converged on knowledge that conformed to an objective reality that subsequently could be controlled and manipulated to create new elements in λ. In this way natural philosophers could show the way in which useful knowledge could solve practical problems. That required, however, that this knowledge could be communicated to people on the ground, who actually got their hands dirty. Margaret Jacob has indeed argued that by 1750 British engineers and entrepreneurs had a "shared technical vocabulary" that could "objectify the physical world" and that this communication changed the Western world forever (1997, p. 115). These shared languages and vocabularies are precisely the stuff of which reduced access costs are made.

Even more important, perhaps, was scientific *mentality*, which imbued engineers and inventors with a faith in the orderliness, rationality, and predictability of natural phenomena—even if the actual laws underlying chemistry and physics were not fully understood (Parker, 1984, pp. 27–28). In other words, the view that nature was *intelligible* slowly gained ground. Shapin (1996, p. 90) notes that Bacon, Descartes, Hobbes, and Hooke were all confident that nature's causal structures *could* be identified if only the correct method were applied—even if they differed quite strongly on what the correct method was. Yet "intelligibility" meant something different to the seventeenth-century physicists than it had meant to their Aristotelian predecessors. The deeper question of "why" do heavenly bodies fall was left as unanswerable; intelligibility meant the formal rules that governed these motions and made them predictable. The early seventeenth century witnessed the work of Kepler and Galileo that explicitly tried to integrate mathematics with natural philosophy, a slow and arduous process, but one that eventually changed the way all useful knowledge was gathered and analyzed.

Once the natural world became intelligible, it could be tamed: because technology at base involves the manipulation of nature and the physical environment, the metaphysical assumptions under which people engaged in production operate, are ultimately of crucial importance. The Industrial Enlightenment learned from the natural philosophers—especially from Newton, who stated it explicitly in the famous opening pages of Book Three of the *Principia*—that the phenomena produced by nature and the artificial works of mankind were subject to the same laws. That view squarely contradicted orthodox Aristotelianism. The growing belief in the rationality of nature and the existence of knowable natural laws that govern the universe, the archetypical Enlightenment belief, led to a growing use of mathematics in pure science as well as in engineering and technology. In this new mode, more and more people rebelled against the idea that knowledge of nature was "forbidden" or better kept secret (Eamon, 1990). A scientific mentality also implied an open mind, a willingness to abandon conventional doctrine when confronted with new evidence, and a growing conviction that no natural phenomenon was beyond systematic investigation and that deductive hypotheses could not be held to be true until tested. Yet, as Heilbron (1990) and his colleagues have argued, in the second half of the eighteenth century "understanding" became less of a concern than an "instrumentalist" approach to scientific issues, in which quantifying physicists and chemists surrendered claims to "absolute truth" for the sake of a more pragmatic approach and gained ease of calculation and application of the regularities and phenomena discovered.

Finally, scientific *culture*, the culmination of Baconian ideology, placed applied science at the service of commercial and manufacturing interests (M. Jacob, 1997; Stewart, 1992, esp. ch. 8). Bacon in 1620 had famously defined technology by declaring that the control of humans over things depended on the accumulated knowledge about how nature works, since "she was only to be commanded by obeying her." This idea was of course not entirely new, and traces of it can be found in medieval thought and even in Plato's *Timaeus*, which proposed a rationalist view of the universe and was widely read by twelfth-century intellectuals. In the seventeenth century, however, the practice of science became increasingly permeated by the Baconian motive of material progress and constant improvement, attained by the accumulation of knowledge.[12] The founding members of the Royal Society justified their activities by their putative usefulness to the realm. There was a self-serving element to this, of course, much as with National Science Foundation grant proposals today. But practical objectives were rarely the primary objective of the growth of formal science. Politics and religion remained in the background of much natural philosophy, and simple human curiosity remained a major motive

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[12] Robert K. Merton ([1938] 1970, pp. ix, 87) asked rhetorically how "a cultural emphasis upon social utility as a prime, let alone an exclusive criterion for scientific work affects the rate and direction of advance in science" and noted that "science was to be fostered and nurtured as leading to the improvement of man's lot by facilitating technological invention." He might have added that non-epistemic goals for useful knowledge and science, that is to say, goals that transcend knowledge for its own sake and look for some application, affected not only the rate of growth of the knowledge set but even more the chances that existing knowledge will be translated into techniques that actually increase economic capabilities and welfare.

of the search for knowledge—even if we still need to worry about why people were curious about some things and not others.[13]

Explaining the timing of the Industrial Enlightenment itself is not easy. It can hardly be a coincidence that it occurred in an area of the world that had considerable experience with commercial activity, markets, finance, and the exploitation of overseas resources. Since the Reformation, the notion that different ideas could compete with one another and be chosen by some criterion meant that old truths were increasingly questioned. The demand for material goods and the slowly growing notion that more consumption was not necessarily sinful, must have been in the back of the mind of innovators throughout this period. A world of competitive markets, in which people can enrich themselves without guilt or shame by exploiting innovation is one in which entrepreneurs will look more and more at useful knowledge and ask themselves how they can make money off it. People who had no qualms about exploiting resources of any kind for their own enrichment tend to take a hard-nosed view of newly discovered natural phenomena and new mechanical devices and ask first whether "it works" before asking "what it means" or "is it right?" At the same time, however, measuring these changes is highly subjective and it is hard to find something uniquely European (let alone British) about such attitudes, and the exact nature of what set the process in motion will remain a topic of debate for many generations.

Bacon's view that the primary objective of the expansion of knowledge should be pragmatic was more normative than positive in the early seventeenth century. However, the amazing fact remains that by and large the economic history of the Western world was dominated by materializing his ideals. Their growing acceptance by key players who ran the gamut from practical engineers to natural philosophers to chemists in the eighteenth century prepared the ground for a growing interaction between the two kinds of knowledge.[14] Scientific culture led to the gradual emergence of engineering science and the continuous accumulation of orderly quantitative knowledge about potentially useful natural phenomena in "all matters mineral, animal, and vegetable."[15] Natural philosophers, wrote the

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[13] Adam Smith in his *History of Astronomy* ([1795] 1982, p. 50) notes that curiosity depends on some measure of law and order, leisure, and on subsistence not to be precarious. In other words, there is some positive income elasticity to curiosity-induced increments in Ω.

[14] Baconian principles, of course, were subject to nuanced interpretation. Golinski (1988) points out that they could readily be harnessed to support the primacy of "natural philosophers" over artisans and justify patronage. Self-serving or not, the idea took root that augmented propositional knowledge would lead to more efficient technology.

[15] The paradigmatic figure in the growth of the subset of Ω we now think of as "engineering" knowledge was John Smeaton (1724–92). Smeaton's approach was pragmatic and empirical, although he was well versed in theoretical work. He limited himself to asking questions

influential lecturer John Desaguliers on the eve of the Industrial Revolution, were expected to "contemplate the works of God, to discover Causes from their Effects, and make Art and Nature subservient to the Necessities of Life, by a skill in joining proper Causes to produce the most useful Effects" (cited by Stewart, 1992, p. 257). The paradigmatic document of the Enlightenment, the *Encyclopédie*, embodies the conviction that the mapping from propositional to prescriptive knowledge and their continued interaction held the key to economic progress. In his article "Arts" cited as the epigraph to this chapter, Diderot made the point that the two kinds of knowledge could reinforce one another. At about the time he wrote those words, this dream was slowly being realized. As Peter Dear recently put it, "Knowing *how* was now starting to become as important as knowing *why*. In the course of time those two things would become ever more similar, as Europe learned more about the world in order to command it. The modern world is much like the world envisaged by Bacon" (Dear, 2001, p. 170).

We can think of many examples of individuals whose careers and thought embodied the Industrial Enlightenment. One is Benjamin Franklin, who in Max Weber's view embodied the Calvinist ethic. Franklin energetically studied natural philosophy and was well-read on Newtonian mechanics as well as experimental work. He studiously cataloged natural phenomena he observed, but always with the idea in the back of his mind that "what signifies philosophy that does not apply to some use" (cited by Wright, 1986, p. 59). Franklin's best-known inventions were the lightning rod and bifocal spectacles, but he also invented his famed stove, a new type of candle, a glass harmonica, and a ventilated street lamp. None of those inventions played a major role in the Industrial Revolution, but they are representative of what the Industrial Enlightenment was focused on and

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about "how much" and "under which conditions" without bothering too much about "why." Yet his approach presupposed an orderliness and regularity in nature exemplifying the scientific mentality. Walter Vincenti and Donald Cardwell attribute to him the development of the method of parameter variation through experimentation, which is a systematic way of making gradual improvements in λ in the absence of a wide epistemic base (see Vincenti, 1990, pp. 138–40, and Cardwell, 1994, p. 195 . It establishes regularities in the relationships between relevant variables and then extrapolates outside the known relations to establish optimal performance. At the same time, Smeaton, like Watt, possessed the complementary skills needed for successful invention, including that ultimate umbrella term for tacit knowledge we call "dexterity." In the little workshop he used as a teenager, he taught himself to work in metals, wood, and ivory, and he could handle tools with the expertise of a regular blacksmith or joiner (Smiles, 1891). It may well be, as Cardwell notes, that this type of progress did not lead to new macroinventions, but the essence of progress is the interplay between "door-opening" and "gap-filling" inventions. This systematic component in the mapping from Ω to λ, in addition to his own wide-ranging contributions to engineering, stamps Smeaton without question as one of the "vital few" of the Industrial Revolution.

capable of. His famous *Experiments and Observations on Electricity* was written in accessible language and soon translated into French, German, and Italian. He was in touch with scientists throughout the world, to the detriment of one Professor Georg Wilhelm Richmann in St. Petersburg (who was electrocuted while carrying out the experiments on lightning that Franklin recommended). The decline in access costs, the wholesale adoption of the Baconian pragmatism, his commitment to a scientific mentality and the belief that science could and would unlock the mysteries of the universe, the unfailing reliance on experimental data to prove or disprove a position, and his urge to create institutions that would serve those purposes (such as the American Philosophical Society, founded in 1743), all mark his career as a classic example of the Industrial Enlightenment.

Why and how the Industrial Enlightenment happened is the central question that holds the key to the modern economic history of the West. There is some validity to Elizabeth Eisenstein's claim that the printing of technical literature served as a vehicle for the expression of a "scientific ethos" (1979, p. 558). Returning to the framework laid out earlier, we can point to institutional and technological developments that changed the internal structure of Ω during the eighteenth century and the early nineteenth century. They created a "community" of knowledge, within which much of the knowledge resided. As I argued before, for purposes of technological development what one individual knows matters less than what the community "knows." Yet the significance of communal knowledge matters for economic history only if it can be accessed, believed, and used. Useful knowledge, as Shapin points out, is always communal. No individual can know everything. Western societies experienced both an increase in the size of Ω and an ever-growing ability to map this useful knowledge into new and improved techniques, as access costs declined and new principles of authority, expertise, and verifiability were set up.

Access costs were determined jointly by information technology and institutions. Some developments in the cost of access are well known and documented. The invention of printing has, of course, been widely credited with the reduction of access costs and needs no more elaboration at this point (Eisenstein, 1979). The Royal Society (established in 1662, followed four years later by the Académie des Sciences), of course, was the very embodiment of the ideal of the free dissemination of useful knowledge.[16]

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[16] The activities of the Royal Society were meant to produce a natural philosophy that would benefit "mechanicks and artificers," in the words of Thomas Sprat, an early defender of the society (cited by Stewart, 1992, p. 5). The idea of reducing access costs encountered the kind of problem that is typical in "markets" for technological knowledge, namely how best to secure some form of appropriability for a public good. The Royal Society's project on the history and description of trades (i.e., manufacturing) ran into resistance from craftsmen reluctant to reveal their trade secrets

By the end of the seventeenth century, the members of the society discovered, to their chagrin, that the path from natural philosophy to a widespread improvement in the useful "arts" was far more arduous than they had supposed, and they gradually lost interest in technology. This development reflects, however, merely the attitude of one particular institution, not that of a much broader range of practicing philosophers, mathematicians, engineers, enlightened farmers, and industrialists (Stewart, 1992, p. 14). In eighteenth- and early nineteenth-century Britain, popular lectures on scientific and technical subjects by recognized experts drew eager audiences.[17] Some of these were given at scientific society meeting places, such as the famous Birmingham Lunar Society, whereas others were given in less famous societies in provincial towns such as Hull, Bradford, and Liverpool.[18] The most famous of these lecturers in the first half of the eighteenth century was John Desaguliers, the son of Huguenot émigrés whose lectures were bankrolled by the Royal Society.[19] Others were paid by rich aristocratic patrons. Still others were freelance and ad hoc, speaking in coffeehouses and Masonic lodges. Audiences breathlessly watched experimental demonstrations illustrating the application of scientific principles to pumps, pulleys, and pendulums (Inkster, 1980).

The Society of Arts, a classic example of an access-cost reducing institution, was founded in 1754, "to embolden enterprise, to enlarge science, to refine art, to improve manufacture and to extend our commerce." Its activities included an active program of awards and prizes for successful inventors: over 6,200 prizes were granted between 1754 and 1784 (Hilaire-Pérez, 2000, p.197). The society represented the view that patents were a monopoly, and that no one should be excluded from useful knowledge. It therefore ruled out (until 1845) all persons who had taken out a patent from being considered for a prize and even toyed with the idea of requiring every prize-winner to commit to never take out a patent (Wood, 1913, pp. 243–45). It was thus recognized that prizes and patents were complements

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(Eamon, 1990, p. 355), and while a few volumes were published in the *Philosophical Transactions* (including one by William Petty on the wool trade), the Royal Society in the closing years of the seventeenth century lost interest in the "useful arts" and concentrated on more abstract questions.

[17] Stewart points out that a series of such lectures in London coffeehouses commanded a substantial fee of two or three guineas, demonstrating the immense demand for them from people with means (1992, p. 29).

[18] The Lunar Society clearly was more than a meeting club: it was a place where knowledge was exchanged, bought and sold in exchange for patronage. The buyers were industrialists such as Matthew Boulton and Josiah Wedgwood, the sellers natural philosophers such as Erasmus Darwin and Joseph Priestley.

[19] Of particular interest is the career of Peter Shaw, a chemist and physician, who stressed the need to communicate effectively and methodically, so that potential users could understand the principles at stake and apply them more easily (Golinski, 1983).

rather than substitutes, and that an optimal set of institutions would have room for both. The society also published various periodicals and transactions, served as a model for numerous local provincial societies dedicated to the diffusion of useful knowledge, and helped create networks of interaction and information exchange between engineers, natural philosophers, and businessmen (Hudson and Luckhurst, 1954).[20] At the same time the society illustrates the weaknesses of an incentive system based on the picking of winners by a group of appointed people rather than by decentralized markets: the society was "extremely slow" to take an interest in steam and one of the society's employees mused poetically if not prophetically in 1766 that machines had to be "Work'd by windy power or wat'ry force Or by circumambulating horse" (ibid., p. 112).

Perhaps the culmination of the need to communicate the findings of natural philosophy to those who could find productive uses for it was the founding of the Royal Institute in 1799 by Count Rumford, in which the great Humphry Davy and his illustrious pupil Michael Faraday gave public lectures and did their research. Eight years later the Geological Society of London was founded so that, "above all, a fund of practical information could be obtained applicable to purposes of public improvement and utility" (cited by Porter, 1973, p. 324). The Institution of Royal Engineers (founded in 1818) was a "study association" dedicated to "reading, discussion and the publication of papers" (Lundgreen, 1990, p. 67). Not all of these societies lived up to their promises, and some were little more than gentlemen's dining clubs with little practical value. Yet, as Robert Schofield (1972) has argued, the formal meetings were secondary to the networking and informal exchange of technical information among members. The "invisible colleges"—informal networks of communication among scholars —that predated the Royal Society remain to this day a central part of access technology.

If the formal societies could not supply the needed knowledge, "practical provincial" outsiders such as the great stratigrapher William Smith or the mineral surveyor Robert Bakewell (1769–1843, not to be confused with the more famous animal breeder) did the work. Scientific

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[20] Hilaire-Pérez (2000, pp. 144, 208) has argued that the society's effect was, in addition, to improve the social image of inventors and thus to encourage people to choose invention as a career. The society was also very active in the promotion of agricultural innovation, offering prizes for useful knowledge on soil analysis, farm implements, and the treatment of animals. The premium the society offered to the inventor of a loom to weave fishing nets, reprinted in a British newspaper, made it across the channel and came to attention of Joseph Marie Jacquard, who solved the problem, and thus came to the attention of the French government, which then provided him with the support he needed to invent the Jacquard loom. Such were the unexpected flows of useful knowledge and its encouragement resulting from the Industrial Enlightenment.

culture reinforced the entrepreneurial interests of science's audience by demonstrating how applied mechanics, chemical philosophy, geology, the manipulation of heat and pressure, and many other segments of propositional knowledge could save costs and enhance efficiency and thus profits.

Outside England, formal technical education played a larger role in fulfilling these functions. In France, artillery schools opened in the 1720s; in the late 1740s the École des Ponts et Chaussées and the École du Génie for military officers were opened, to be followed famously by the École Polytechnique in 1794. Other countries on the continent followed suit, with mining schools founded in Saxony and Hungary and elsewhere. England, where the public sector rarely intervened in such matters, lagged behind in formal education, but its system of public lectures, informal scientific societies, and technical apprenticeship sufficed—for the time being.

What was there in natural knowledge that improving landlords, mechanics, and industrialists felt they needed? Despite its apparent shortcomings, eighteenth-century propositional knowledge did provide implicit theoretical underpinnings to what empirically minded technicians did, even if the epistemic base was still narrow. Without certain elements in Ω, many of the new techniques would not have come into existence at all or would not have worked as well. Thus the steam engine depended both on the understanding of atmospheric pressure, discovered by continental scientists such as Evangelista Torricelli and Otto von Guericke, and on the early seventeenth-century notion that steam was evaporated water and its condensation created a vacuum.[21] The discovery led to the idea that this pressure could be used for moving a piston in a cylinder, which could then be made to do work. The proto-idea of an engine filtered down to Thomas Newcomen despite the fact that his world was the local blacksmith's rather than the cosmopolitan academic scientist's. Improvements in mathematics, especially the calculus invented by Leibniz and Newton, became increasingly important to improvements in the design and perfection of certain types of machinery, although in many areas its importance did not become apparent until much later.[22] The advances in water power in the eighteenth

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[21] Usher (1954, p. 342) attributes this finding to Solomon De Caus, a French engineer and architect, in a 1615 book. Uncharacteristically, Usher is inaccurate here: in 1601, Giambattista Della Porta had already described a device based on the same idea, and both were apparently inspired by the appearance in 1575 of a translation of Hero of Alexandria's *Pneumatics*, which, while grasping neither the notion of an atmospheric engine nor that of a condensation-induced vacuum, focused attention on steam as a controllable substance. It is hard to imagine anyone reading Hero without realizing that steam was evaporated water and that upon condensation "the vapor returns to its original condition."

[22] The engineer Henry Beighton was only one to sigh that "it were much to be wished that they who write the Mechanical Part of the Subject [the design of mine-drainage engines] would take some little Pains to make themselves Masters of the Philosophical and Mechanical Laws of

century depended increasingly on a scientific base of hydraulic theory and experimentation despite a number of errors, disputes, and confusions (Reynolds, 1983).[23] The importance of water power in the Industrial Revolution is still not given its due recognition because steam was more spectacular and in some sense more revolutionary.[24] The technique of chlorine bleaching depended on the prior discovery of chlorine by the Swedish chemist Carl Wilhelm Scheele in 1774. Even the invention of the Leblanc soda-making process, often described as a purely "empirical" discovery, has been shown to depend on an epistemic base that contained the nature of salt, first worked out by Henri-Louis Duhamel in 1737, and the discovery of carbonic acid gas by Joseph Black and its recognition as a constituent of chalk and soda (John Graham Smith, 1979, pp. 194–95; 2001). Phlogiston theory, the ruling physical paradigm of the eighteenth century, was eventually rejected in favor of the new chemistry of Lavoisier, but some of its insights (e.g., the Swede Tobern Bergman's contributions to metallurgy) were valuable, even if their scientific basis seems flawed and their terminology quaint to modern readers. Cardwell (1972, pp. 41–43) has shown that the idea of a measurable quantity of "work" or "energy" derived directly from Galileo's work on mechanics and deeply influenced the theories and lectures of engineers such as John Desaguliers. John Harrison's great marine chronometer was conceivable only in the context in which Ω already contained the observation that longitude could be determined by comparing local time with time at some fixed point. Another good example is the knowledge of the properties of materials, one

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[Motion or] Nature" and noted that the engineer who "has skill enough in *Geometry* to reduce the *Physico-mechanical* part to numbers, when the quantity of Weight or Motion is given, and the Force designed to move it, can bring forth all the Proportions...so as to make it almost impossible to err" (cited by Musson and Robinson, 1969, p. 49).

[23] The input of formal mathematics into technical engineering problems was most remarkable in hydraulics and the design of better waterwheels in the eighteenth century. Theoreticians such as the Leonhard Euler and Jean-Charles Borda made major contributions to the understanding of the relative efficiency of various designs. It should be added, however, that experimental work remained central and at times had to set the theorists straight (see especially Reynolds, 1983). Calculus also found its way into mechanical issues in construction such as the theory of beams, such as in Charles Coulomb's celebrated 1773 paper "Statical Problems with Relevance to Architecture."

[24] John Smeaton was well-versed in the theoretical writings of French hydraulic scientists such as Antoine de Parcieux. In the 1750s, Smeaton carried out experiments showing that the efficiency of overshot wheels tended to be around two-thirds, while that of undershot wheels was about one-third. In 1759 he announced his results, firmly establishing the superiority of the gravity wheel. At that point, Smeaton realized the vast potentialities of the breast wheel: it was a gravity wheel, but one that could be constructed in most sites previously suitable only for undershot wheels. Once fitted with the tightly fitting casing, it combined the advantages of the gravity and the impulse wheels. The breast wheel turned out to be one of the most useful and effective improvements to energy generation of the time.

of the cornerstones of all techniques. By the early nineteenth century, this part of material science was being analyzed by scientists who learned to distinguish between elastic strength and rupture strength. But until then, this entire body of knowledge was controlled by old-fashioned engineers and carpenters who "limited themselves to instinctively measuring the influence of the differences in buildings which appear to serve a similar function" (Guillerme,1988, p. 242). An informal, intuitive and instinctive knowledge of natural regularities and of what could and could not be done is what most of Ω consisted of before modern science formalized substantial portions of it. The mechanical inventors who made the breakthroughs in spinning and weaving of cotton could not and did not have to rely on formal mechanics, but had access as never before to mechanical and other engineering feats. Knowing what works and what does not elsewhere directs inventive activity into channels more likely to succeed. In other cases, of course, bogus knowledge usually produced bogus results, as in Jethro Tull's insistence that air was the best fertilizer and the amazingly eccentric theories still rampant in late eighteenth-century medicine.[25]

In the "development" stage of basic inventions—in which engineers and technicians on the shopfloor improved, modified, and debugged the revolutionary insights of inventors such as Arkwright, Cartwright, Trevithick, and Roberts and came up with the microinventions that turned them into successful business propositions—science was of modest importance. The mechanical inventions that constituted much of the Industrial Revolution—especially in the textile industry—involved little that would have puzzled Archimedes, as Cardwell put it (1994, p. 186). Yet they still required a great deal of pragmatic and informal knowledge about how certain materials respond to physical stimuli, moisture, and heat; how motion can be transmitted through pulleys, gears, and shafts; how and where to lubricate moving parts to reduce friction; the use of levers, wedges, flywheels; and other mechanical tricks. More than anything else, they required a systematic method of experimentation and a belief that through experimentation progress was not only possible but highly likely. Similar processes were at work in areas that did not involve machinery: Robert Bakewell and his fellow breeders could make a great deal of

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[25] A Scottish physician by the name of John Brown (1735–88) revolutionized the medicine of his age with Brownianism, a system that postulated that all diseases were the result of over- or under-excitement of the neuromuscular system by the environment. Brown was no enthusiast of bleeding, and treated all his patients instead with mixtures of opium, alcohol, and highly seasoned foods. His popularity was understandably international: Benjamin Rush brought his system to America, and in 1802 his controversial views elicited a riot among medical students in Göttingen, requiring troops to quell it. Brown was alleged to have killed more people than the French Revolution and the Napoleonic Wars combined (McGrew, 1985, p. 36).

progress in the selective breeding of animals without knowing Mendelian genetics. The late eighteenth century witnessed improved cattle, sheep, and pigs. Here, as elsewhere, we see that the Industrial Enlightenment was hardly confined to manufacturing.

An example of how a narrow foundation in propositional knowledge could lead to a new technique was the much hailed Cort puddling and rolling technique.[26] The invention depended a great deal on prior knowledge about natural phenomena, even if science properly speaking had very little to do with it.[27] Cort realized full-well the importance of turning pig iron into wrought or bar iron by removing what contemporaries thought of as "plumbago" (a term taken from phlogiston theory and equivalent to a substance we would today call carbon). The problem was to generate enough heat to keep the molten iron liquid and to prevent it from crystallizing before all the carbon had been removed. Cort knew that reverberating furnaces using coke generated higher temperatures. He also realized that by rolling the hot metal between grooved rollers, its composition would become more homogeneous. How and why he mapped this prior knowledge into his famous invention is not exactly known, but the fact that so many other ironmasters were following similar tracks indicates that they were all drawing from a common pool.[28] All the same, it should be kept in mind that in coal and iron craft-based tacit skills were of unusual importance in the finer details of the jobs, and that codifiable knowledge would be insufficient in these industries unless accompanied by these informal skills (John R. Harris, 1976).

Another example of a technological breakthrough, not normally part of the history of the Industrial Revolution, is that most paradigmatic of all macroinventions, ballooning, which for the first time in history broke the tyranny of gravity. Speculation over how the idea first emerged is widespread, but the verdict that "there is no apparent reason why this technology could not have appeared centuries earlier"(Bagley, 1990, p.

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[26] Hall (1978, p. 101) points to the puddling process as an example of a technique in which familiarity with the underlying "useful knowledge" did not matter for what I have called competence: a man either knows how to do it or he does not.

[27] Cort did consult Joseph Black, one of the leading chemists of the period, but this pertained to operation of the rollers which were in use elsewhere and not to the chemical or physical nature of his process (Clow and Clow, 1952, p. 350). Black wrote to Watt that Cort was "a plain Englishman, without Science" (repr. in Robinson and McKie, eds., 1970).

[28] Reverberatory furnaces had been used in glassmaking and were first applied to iron by the Cranage brothers in Coalbrookdale. Puddling had been experimented with by the Cranage brothers, as well as by Richard Jesson and Peter Onions (who both took out similar patents two years before Cort's success). Grooved rolling had been pioneered by the great Swedish engineer Christopher Polhem. None of those attempts seems to have had much success: recombining obviously must be done in some specific way and not others.

609) is contradicted by the fact that British scientists had only in 1766 discovered the existence of gases lighter than air—specifically "inflammable air" (hydrogen) isolated by Cavendish. The decline in access costs played a demonstrable role in this invention: from 1776 to 1781, the brothers Montgolfier had been reading the French translation of Priestley's *Experiments on Different Kinds of Air*, which introduced them to the discovery of "air-like" fluids (i.e., gases) with different specific weights (Taton, 1957, p. 123). The specific knowledge that hot air expands and thus becomes lighter was communicated to Joseph Montgolfier by his cousin, a medical student at Montpelier. Of course, the scientific basis for ballooning was not yet altogether clear, and contemporaries did not see, for instance, that there was a fundamental difference between hot air and hydrogen balloons (Gillispie, 1983, p. 16). But some minimum knowledge was necessary to establish an epistemic base for ballooning, and those who could use it needed access to it.

Even when the "science" seems to the modern reader to be largely irrelevant to the eventual development of the technology, the relationship between those who possessed useful knowledge and the rest of society in eighteenth-century Britain had changed enormously and indicates a dramatic reduction in access costs. Pre-Lavoisier chemistry, despite its limitations, is an excellent example of how *some* knowledge, no matter how partial or erroneous, could help in mapping into new techniques. The pre-eminent figure in this field was probably William Cullen, a Scottish physician and chemist. Cullen lectured (in English) to his medical students, but many outsiders connected with the chemical industry audited his lectures. Cullen believed that as a philosophical chemist he had the knowledge needed to rationalize the processes of production (Donovan, 1975, p. 78). He argued that pharmacy, agriculture, and metallurgy were all "illuminated by the principles of philosophical chemistry" and added that "wherever any art [that is, technology] requires a matter endued with any peculiar physical properties, it is chemical philosophy which informs us of the natural bodies possessed of these bodies" (cited by Brock, 1992, pp. 272–73).[29] He and his colleagues worked, among others, on the problem of purifying salt (needed for the Scottish fish-preservation industry) and that of bleaching with lime, a common if problematic technique in the days before chlorine. This kind of work "exemplifies all the

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[29] Very similar sentiments were expressed by the author of the article on chemistry, Gabriel-François Venel, in the *Encyclopédie*. He regarded advances in arts and chemical science as reciprocal, bound together on a common trunk (Keyser, 1990, p. 228).

virtues that eighteenth-century chemists believed would flow from the marriage of philosophy and practice" (Donovan, 1975, p. 84).

This marriage remained largely barren. In chemistry the expansion of the epistemic base and the flurry of new techniques it generated did not occur fully until the mid-nineteenth century (Fox, 1998). Cullen's prediction that chemical theory would yield the principles that would direct innovations in the practical arts remained, in the words of the leading expert on eighteenth-century chemistry, "more in the nature of a promissory note than a cashed-in achievement" (Golinski, 1992, p. 29). Manufacturers needed to know why colors faded, why certain fabrics took dyes more readily than others, and so on, but as late as 1790 best-practice chemistry was incapable of helping them much (Keyser, 1990, p. 222). Before the Lavoisier revolution in chemistry, it just could not be done, no matter how suitable the social climate. All the same, Cullen stands for a social movement that increasingly sought to increase its Ω-knowledge for economic purposes, a personification of scientific culture. Whether or not he could deliver, his patrons and audience in the culture of the Scottish Enlightenment believed that there was a chance he could (Golinski, 1988).

In the longer run, this ideology worked. Cullen and his students laid the ground rules of experimental chemistry and refused to found their views on unobservable, hypothesized substances that could not be verified. The Scottish Enlightenment, perhaps more than anywhere else, was industrial. It influenced the career of John Roebuck, a graduate of Edinburgh's famous medical school, whose career personified much of what made the British Industrial Revolution work: a physician and ironmonger, he was an early supporter of James Watt's improvements to the steam engine and inventor of the lead-process in the manufacture of sulphuric acid.[30] Or consider the career of Joseph Black. Like Cullen and Roebuck, Black combined the study of medicine with chemistry and physics, and repeatedly dealt with applied problems of interest to industry. Although his scientific advances, too, were ultimately limited by his adherence to the scientific orthodoxies of his day and his quest for a single, all-encompassing "Newtonian" theory of chemical phenomena, his career exemplifies the spillovers of his method, and of the scientific mentality and culture into the sphere of techniques. He consulted to manufacturers of tar, lead miners, potters, and distillers among others (Clow and Clow, 1952, p. 591). The precise influence of his science on the thinking of the young

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[30] Sulphuric acid was a crucial ingredient in a host of industries, from paper- to button-making. In 1843, Justus von Liebig, the founder of organic chemistry, remarked —with some exaggeration —that the "commercial prosperity of a country may be judged from the amount of sulphuric acid it consumes" (Clow and Clow, 1952, p. 130).

James Watt, whom he knew well in Glasgow, is still in dispute.[31] Any way one looks at the relation between the two, however, makes clear that it was the kind of channel by which propositional knowledge is mapped into a useful technique (Donovan, 1975). Watt himself had no doubt: "The knowledge upon various subjects which [Dr. Black] was pleased to communicate to me, and the correct modes of reasoning and of making experiments of which he set me the example, certainly conduced very much to facilitate the progress of my inventions" (cited by Fleming, 1952, p. 5). Other progressive manufacturers, such as Leeds woollen manufacturer Benjamin Gott, iron tycoon Richard Crawshay, and pottery maker Josiah Wedgwood, recognized the potential importance of such knowledge.

The linear model of a flow of scientific knowledge that was applied to technology is of course a poor description of these flows. McKendrick's (1973) study of Josiah Wedgwood led him to conclude that the economic influence of science was far less persuasive when examined in detail. When limited to the modern concept of "science," the idea of propositional knowledge affecting technology is indeed rather poorly supported (although a few hard-core cases cannot be entirely dismissed). But the wider concept of propositional knowledge as proposed here suffers from no such defects. Indeed, Wedgwood's career can be thought of as the embodiment of the Industrial Enlightenment. He was, by all accounts, a compulsive quantifier, an obsessive experimenter, and an avid reader of scientific literature. He corresponded with many scientists, including Lavoisier, Priestley, Armand Seguin (Lavoisier's star student), and James Keir. He equally consulted artisans who had specialized in areas of interest to him, such as a Liverpool glassmaker, Mr. Knight (ibid., p. 296). Useful knowledge was to be accessed and applied wherever it could be found.

It might be objected that Wedgwood was not typical, but the argument of this book is that such unrepresentativeness is the heart of the process of technological change: we could think of Wedgwood, Smeaton, and Watt as members of Hooke's "Cortesian army" cited in the epigraph to this book. Once they had solved the problems and written the new chapters in the book of prescriptive knowledge, others followed through even if they did not possess the epistemic base. For the historical development of

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[31] Donovan notes that Watt's early attempt to make the Newcomen engine more efficient —concentrating on the heat acting in the engine rather than on its mechanical aspects— was inspired by Black's approach to chemistry (1975, p. 256). Watt himself credited the work of Cullen, as well as his contacts with Black and another Scottish natural philosopher, John Robison, for the insight that to make a perfect steam engine the cylinder should be as hot as the steam entering it, and that the steam should be cooled down to exert its full powers. Fleming (1952) is the *opus classicus* for the opposing viewpoint; see also Cardwell (1971, pp. 41–55).

knowledge, *averages* are therefore not very important: a few critical individuals drive the process. It is in this sense that the evolutionary nature of knowledge growth matters: selectionist models stress that what matters to history is that under the right circumstances *very rare* events get amplified and ultimately determine the outcome (Ziman, 2000).

Some of the changes in λ during the Industrial Revolution were made by the very same people who also were contributing to science (even if the exact connection between their science and their ingenuity is not always clear). The importance of such "hybrid" or dual careers, as Eda Kranakis (1992) has termed them, is that access to the propositional knowledge that could underlie an invention is immediate, as is the feedback to propositional knowledge. In all examples, the technology shapes the propositional research as much as the other way around. The idea that those contributing to propositional knowledge should specialize in research and leave its "mapping" into technology to others had not yet ripened. Among the inventions made by people whose main fame rests on their scientific accomplishments were the chlorine bleaching process invented by the chemist Claude Berthollet, and the mining safety lamp invented by the leading scientist of his age, Humphry Davy (who also, incidentally, wrote a textbook on agricultural chemistry and discovered that a tropical plant named *catechu* was a useful additive to tanning).[32] In 1817 the mathematician and optician Peter Barlow (1776–1862) published a book entitled *Essay on the strength of Timber and other Materials* which went through six editions before 1867. He became an authority on the construction of railroads and locomotives, contributed to the development of the telegraph, and helped correct the deviation of ship compasses. Typical of the "dual career" phenomenon was Benjamin Thompson (later Count Rumford), an American-born mechanical genius who was on the loyalist side during the War of Independence and later lived in exile in Bavaria, London, and Paris; he is most famous for the proof that heat is not a liquid that flows in and out of substances. Yet Rumford was deeply interested in technology, helped establish the first steam engines in Bavaria, and invented (among other things) the drip percolator coffeemaker, a smokeless-chimney Rumford stove, and an improved oil lamp. He developed a photometer designed to measure light intensity and wrote about science's ability to improve cooking and nutrition (G. I. Brown, 1999, pp. 95–110). Indifferent to national identity and culture, Rumford was a "Westerner" whose world

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[32] It is unclear how much of the best-practice science was required for the safety lamp, and how much was already implied by the empirical propositional knowledge accumulated in the decades before 1815. It is significant that George Stephenson, of railway fame, designed a similar device at about the same time.

spanned the entire northern Atlantic area (despite being an exile from the United States, he left much of his estate to establish a professorship at Harvard). In that respect he resembled his older compatriot inventor Benjamin Franklin, who was as celebrated in Britain and France as he was in his native Philadelphia. Rumford could, within the same mind, map from his knowledge of natural phenomena and regularities to create things he deemed useful for mankind (Sparrow, 1964, p. 162). Like Franklin and Davy, he refused to take out a patent on any of his inventions—natural philosophers were already committed to the concept of open knowledge, although others eventually learned to distinguish between their contributions to propositional knowledge, which were to become a public good, and their inventions, which were entitled to intellectual property right protection.[33]

All the same, the nature and rate of progress in Ω in the eighteenth century had not changed all that much from a century earlier. Research was still often carried out by amateurs, driven by a mixture of curiosity and a desire to please and impress peers and friends of similar proclivities, or wealthy patrons for whom the presence of eminent scientists in their circles might have been as much conspicuous consumption as a desire to support the growth of knowledge. As a result, the agenda of eighteenth-century natural philosophy was perhaps not as focused on the kind of propositional knowledge that could serve as an epistemic base for technical advances as it would have been if the communication between the *savants* and the *fabricants* had been more commercial and less personal. Yet in the second part of the eighteenth century, these bridges were becoming wider and easier to cross. On both sides of the channel, Enlightenment scientists felt the need to communicate with practical people, and vice versa. More and more people concluded that there was no contradiction between the culture of action and matter, and that of learning (Hilaire-Pérez, 2000, pp. 159–60). Moreover, the artisanal and pragmatic knowledge possessed by mechanics and apothecaries, botanists and cattle-breeders, gardeners and ironmasters kept improving and became more accessible.

To summarize, then, the changes in technological knowledge in the century after 1750 involved three different types of processes. First, there may have been some "pure" additions to Ω that occurred as part of an autonomous system of discovery about nature, driven by curiosity or other "internal factors" only weakly motivated by the economic needs they

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[33] The most extreme case of a scientist insisting on open and free access to the propositional knowledge he discovered was Claude Berthollet, who readily shared his knowledge with James Watt, and declined an offer by Watt to secure a patent in Britain for the exploitation of the bleaching process (J. G. Smith, 1979, p. 119).

eventually helped satisfy. Such expansions in useful knowledge led to new mappings and eventually became one of the driving forces behind technological advances. Second, there were changes in some of the properties of Ω and λ, which became denser (because more people shared the knowledge) and more accessible (better organized and easier to communicate). These changes yielded new mappings into λ—that is inventions—drawing on both the new and a preexisting pool of knowledge. At first glance it may be hard to see, for instance, what there was in the original spinning jennies that could not have been conceived a century earlier.[34] Yet once such techniques are discovered, they are added to the catalog of possible techniques that is part of Ω, and subsequent inventors could then draw upon this catalog to extend it and find new applications. Samuel Crompton's famous mule was a standard example of recombining two existing techniques into a novel one. The Etruria pottery factory adopted a "rose-turning" lathe that enabled the operator to cut repetitive curved patterns, which Wedgwood had first observed at the Boulton and Watt works in Soho in 1767 (Reilly, 1992, p. 74).

Explaining the exact timing of such mappings is impossible, but the changing structure of Ω in terms of density and access costs was of central importance. In other words, changes in the overall size of Ω (what was known) may have been less important in the Industrial Revolution than the access to that knowledge. Moreover, the process was highly sensitive to outside stimuli and incentives. The social and institutional environment has always been credited with a central role in economic history. All I would argue is that the setup proposed here sheds some light on how this mechanism worked.[35] Britain was a society that provided both the incentives and the opportunities to apply existing useful knowledge to technology. In that respect the evolution of technology again resembles biological evolution: changes in the environment (including changes in the availability of complements and substitutes) may trigger the activation of "dormant" knowledge or select those techniques that happen to "express" information adapted to a new environment.

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[34] Acemoglu and Zilibotti (1997, p. 716) attribute with apparent approval to E. J. Hobsbawm the absurd statement that there was "nothing new in the technology of the British Industrial Revolution and the new productive methods could have been developed 150 years before." In fact Hobsbawm's assertion is that the scientific revolution cannot explain the Industrial Revolution because at the end of seventeenth century European "scientific technology" (sic) was potentially quite adequate for the sort of industrialization that eventually developed (1968, p. 37). It is still wrong, yet pointing this out does not deny that venture capital scarcity of the type emphasized by Acemoglu and Zilibotti and a change in its supply was important as well in determining the timing of the Industrial Revolution.

[35] For some attempts in this direction, see Mokyr (1998c, pp. 39–58).

Third, there was feedback from techniques to propositional knowledge. A great number of major and minor scientific revolutions were driven not just by conceptual innovation but by new tools and techniques.[36] Famous examples are the steam engine, which led to the formulation of the laws of thermodynamics, and the improvements in the microscope, which made bacteriology possible.[37] Such feedback from technology to propositional knowledge is what made the continued evolution of technology the sustainable norm rather than an ephemeral exception.

A Knowledge Revolution

More or less contemporaneous with the Industrial Revolution was a revolution in what we would call today information technology (Headrick, 2000). The knowledge revolution affected the nature of Ω and through it the techniques mapped from it. Some of these changes were directly related to scientific breakthroughs, but what matters here are the advances in the organization, storability, accessibility, and communicability of information in Ω, as well as the methods of expanding it. The blossoming of open science and the emergence of invisible colleges—that is, informal scholarly communities spanning different countries, within which seventeenth-century scholars and scientists kept close and detailed correspondences with each other—compounded these advances. A great deal of knowledge that previously was tacit and oral was codified and described in scientific and technical writings and drawing. The Industrial Enlightenment meant that useful knowledge would henceforth be judged by its intrinsic value, not by the nationality of its origin. The nations of the West keenly studied and copied one another.[38]

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[36] This is emphasized in Dyson (1997, pp. 49–50) and Price (1984a). The telescope, which drove the Galilean revolution in astronomy, was made possible by a rather mundane technical advance, namely the glass lathe that made the grinding of thick, concave lenses, developed in the late sixteenth century. In a different age, Paul Ehrlich's methods of staining cells and bacteria using coal tar dyes helped Robert Koch identify the tubercle bacteria, and X-ray diffraction helped determine the structure of big molecules drove the DNA revolution (Travis, 1989).

[37] The impact of technology on propositional knowledge is stressed by Nathan Rosenberg (1982), though Rosenberg confines his essay to "science." Yet many advances in Ω were made possible through better techniques that we would not think of as "science," including for example the European discoveries of the fifteenth century, made possible by better ship-building and navigational techniques. As Price (1984b, p. 52) puts it, "thermoscopes and thermometers created a world in which one thought more clearly about heat, knowing that neither pepper nor passion were really hot."

[38] J.R. Harris points out that there is more to be learned about coal mining—even British coal mining—from French sources than from English ones (1976, p. 171). Keyser (1990) contrasts the high quality of the work of French chemists such as Berthollet with that of the applied work of British writers on the topic. William Hamilton, the translator of Berthollet's *Art of Dyeing,*

As a consequence, the size of Ω-knowledge on which techniques in actual use could draw increased. In other words, the manipulation of natural processes and regularities in farming, engineering, chemistry, medicine, and other fields came to depend on increasingly deep propositional knowledge. Although there is a difference between the knowledge necessary to write the instructions in λ (to make an invention) and that needed to carry them out, in many industries the knowledge needed to operate best-practice techniques became so large that no single individual could possess it all. Thus the division of labor, much as Adam Smith thought, was an important element in technological change, but it was not so much "limited by the extent of the market" as it was necessitated by the extent of the knowledge involved and the limitations of the human mind. The growth of useful knowledge led to the rise of specialization and the emergence of experts, consulting engineers, accountants, and other professionals. Coordination among the activities of these specialists became increasingly necessary, and hence we have one more explanation of the rise of the factory system, the hallmark of the Industrial Revolution. I shall return to this matter in chapter 4.

Often overlooked is the speed and efficiency with which knowledge traveled. As J. R. Harris has argued (1976, p. 173; 1998), much of the tacit, crafts-based knowledge spread through the continuous movement of skilled workers from one area to another and "industrial espionage" remained an important part of access technology. Printed text may have remained secondary to personal contact and artifacts for most of the nineteenth century, and the growing effectiveness of the transportation system must be considered of fundamental importance to the reduction of access costs. Printed and written texts were probably complements to rather than substitutes for personal contact and artifacts in the transfer of useful knowledge. In France, the government actively used diplomatic channels to acquire technological information from other countries. Lower access costs implied a greater mobility of useful knowledge, and this mobility took many forms.

It is natural to think that the great discontinuity in this area occurred after the Industrial Revolution: the railroads in the early 1830s, the telegraph about a decade later. Yet as Rick Szostak (1991) has shown, the cost of moving about in Britain started to decline in the eighteenth century with the advent of an improved road system and faster, cheaper, and more

noted that "every country must be much benefited, which by means of early translations, possesses itself of the fruits of the labours of foreign nations." It was natural for him to translate the work, since "in the application of scientific chemistry to the arts, we have been surpassed by our neighbours on the continent" (Berthollet, 1791, p. iv).

reliable stagecoach service.[39] Moreover, the transmission of certain types of information was already becoming cheaper and faster before the telegraph. The Chappe semaphore telegraph, operating throughout France as well as in other parts of western Europe, was a first step in this direction.[40] The Chappe system was a government monopoly and did not serve as a means of transmitting private information, yet it testifies to the age's increasingly rational and innovative approach to the transmission and dissemination of knowledge. The same is true for postal services: cross-posts (bypassing London) came into being after 1720, and by 1764 most of England and Wales received mail daily. Although the rates were high and their structure complex until Rowland Hill's postal revolution, which established the inland penny postage in 1840, postal services in England long before that were providing easy and reliable access to knowledge generated elsewhere. In the United States the postal service was a truly revolutionary agent (John, 1995). In 1790 each post office served 43,000 people; by 1840 each post office served only about 1,100 persons, and for many years the postal service was by far the largest branch of the federal government. Much of the post delivered consisted of newspapers.

Equally important to the decline in access costs was the standardization of information. For communication between individuals to occur, a common terminology is essential. Language is the ultimate general purpose technology, to use Bresnahan and Trajtenberg's (1993) well-known term. It provides the technology that creates others. Language is one aspect of culture that can affect the pathway from knowledge to technology and thus economic performance in the long run. It is a standard of efficient communication, necessary if people are to draw knowledge from storage devices and from each other. How important is the language of useful knowledge as a component of the kind of culture that eventually brings about economic development?

In the seventeenth and eighteenth centuries technical and scientific writings in Europe switched from Latin to the various vernacular languages. Even those without a classical education—as presumably many

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[39] Merton ([1938] 1970, pp. 216ff.) points out that by the end of the seventeenth century a system of stagecoaches and postal service was already in operation, and argues that social interaction and the exchange of information were crucial to the development of science in this period.

[40] Under optimal conditions the semaphore system could transmit a bit of information from Paris to Toulon in 12 minutes in contrast with the two full days it would take a messenger on horseback. A 100-signal telegram from Paris to Bordeaux in 1820 took 95 minutes; in 1840 it took half as long. Given that a "signal" was picked from a code book with tens of thousands of options, this was a huge amount of information. The optical telegraph at its peak covered 5,000 miles and included 530 relay stations. For details, see Field (1994).

fabricants were—were given access. For those who really mattered, the ignorance of another European language was an obstacle to be conquered: Smeaton taught himself French to be able to read the papers of French hydraulic theorists and traveled to the Netherlands to study their use of wind power firsthand. Watt learned German to be able to read the works of Jacob Leupold. Of course, this openness to foreign knowledge reflects demand as much as cultural change. Either way, it marks the growing trend toward lower access costs in western European culture in the century before the Industrial Revolution.[41] To be sure, language and its use can adapt to changing circumstances, and Chinese writing today is quite different from the traditional *wen yen* or "written words."[42]

The most widely cited consequence of the scientific revolution was the increasing use of mathematics in natural philosophy and eventually in technical communications. It was associated primarily with Galileo; he famously wrote that the book of the universe was written in the language of mathematics, without which it is impossible to understand a single word of it. Yet what counted was not just better and more useful mathematics, but also its accessibility to the people who might use it: engineers, instrument makers, designers, chemists, artillery officers, and others.[43]

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[41] The importance of language as a communication tool and the need for a language designed along rational precepts modeled after mathematics, with exact correspondences between words and things, was particularly stressed by Etienne Bonnot de Condillac (1715–80), a central figure of the French Enlightenment (see for instance Rider, 1990).

[42] All the same, an eminent Sinologist, Derk Bodde, has made the startling argument that language can be an impediment to the emergence and diffusion of scientific and technological knowledge. Bodde (1991) points out the inherent weaknesses of the Chinese language as a mode of transmitting precise information and its built-in conservative mechanisms. To summarize his views, Chinese language placed three obstacles in the way of the growth of useful knowledge in China. One was the large gap between literary Chinese and spoken Chinese. This made written documents far less accessible for people without considerable training and thus made it less easy for artisans and technicians to draw on the useful knowledge accumulated by scholars and scientists. Second, the absence of inflection and punctuation created considerable ambiguity over what texts meant. Bodde's critics are right to point out that much of this ambiguity could be resolved if one knew the context, but the point is that efficient communication must be able to provide as much technical information as possible with little context. Bodde also points out that written Chinese was a formidably conservative force: it created a cultural uniformity over time and space that was the reverse of the dynamic diversity in Europe. The way a nineteenth-century official would describe Western barbarians was very similar in metaphor and illustration to the way this would have been done by a Han statesman two millennia earlier (Bodde, 1991, p. 31).

[43] Arithmetic, of course, was an international language that could be understood by all. But more complex mathematics was changing the world as well. For instance, Mahoney (1990) points out that in the seventeenth century the mechanical view of the world and the formal science of motion changed dramatically because of the ability of mathematicians to represent it as differential equations of one form or another. This advance involved a dramatic change in the way mathematics was understood, yet once it was accepted it clearly represented a vastly superior way of representing relations between physical objects.

Peter Dear (2001) has argued that Galileo and his colleagues fought hard to raise the social prestige of mathematics from a practical tool to a status on a par with natural philosophy. Once this was accomplished, this bridge between propositional knowledge and industry was reinforced on both sides. The role of mathematics in the emergence of new technology and its application has been disputed. Edward Stevens argues that mathematics was descriptive, not explanatory, and cites Einstein's dictum that "as far as the laws of mathematics refer to reality they are uncertain, and as far as they are certain, they do not refer to reality (1995, pp. 58–62)." What is missed here is the role of mathematics as a language, a tool of communication that produced a compact and less ambiguous means of conveying complex relationships. Eisenstein notes that uniform mathematical symbols "brought professors closer to reckonmasters (1979, p. 532)." In chemistry too, as we have seen, the scientific revolution created a movement of better notation, which led to better comprehensibility and smoother communication, thus also reducing access costs (Golinski, 1990). The increasing quantification of the methods and streamlining of the language of chemistry in the eighteenth century made it increasingly accessible to potential users (Lundgren, 1990).

Another important component of such a system of communication is an accepted set of standards for weights and measures. During the eighteenth century, technology gradually became more systematic about its reliance on quantitative measures (Lindqvist, 1990), and standardization became essential. Useful knowledge, much more than other kinds of knowledge, requires a strict and precise "I-see-what-you-see" condition to be communicated and transmitted efficiently.[44] Mathematics was one such language, quantitative measures and standards another. The introduction of the metric system on the continent during the French Revolution and the Napoleonic period established a common code that despite some serious resistance eventually became universally accepted.[45] The United States and Britain chose to stick to their own system: in the eighteenth century most people used accepted measures of the pound, and the standard yard was made in 1758–1760 and deposited in the House of Commons (Headrick, 2000, ch. 2). In 1824, Britain enacted the Imperial System of Weights and

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[44] It might be objected that unitary standards were no more necessary for scientific innovation than standardized spelling was for great literature (Pyenson and Sheets-Pyenson, 1999, p. 191), but this misses the point that such standardization reduces access cost and thus makes its diffusion and application more likely.

[45] After some backtracking from the pure metric system as passed in 1799, the French government brought it back in full force in 1837; after 1840 it became the only legal system in France (see Alder, 1995).

Measures codifying much of the existing system.[46] Standardizations had been attempted many times before, but they required the coercive powers and coordination capabilities of the modern state.

Metrology was thus of considerable importance. The uniform organization of measurement and standards is a critical property of Ω if marginal access costs are to be kept low.[47] Many systems of codifying technical knowledge and providing standards were devised or improved during the Enlightenment. Headrick mentions two of the most important ones: the Linnaean system of classifying and taxonomizing living species, and the new chemical nomenclature designed by John Dalton and simplified and improved into its current form by Jöns Berzelius in 1813–14.[48] But other useful concepts were also standardized. In 1784 James Watt set the horsepower as the amount of energy necessary to raise 33,000 pounds one foot in one minute. Less well known but equally important is the work of Thomas Young (1773–1829), whose modulus of elasticity (1807) measured the resistance of materials under stress in terms of the pull in pounds that it would take to stretch a bar to double its original length.[49] There were even some attempts to quantify precisely the amount of physical work one man could be expected to do in a day (Ferguson, 1971; Lindqvist, 1990).

Of great importance in streamlining access to knowledge were what Ferguson (1992) has called "tools of visualization." As Ferguson (1992), Stevens (1995), and others have repeatedly stressed, mechanical knowledge and design rest primarily on spatial cognition and representation. Perhaps it should be added that this is true primarily for machines, much less so for the chemical and biological processes that also played a central role in the Industrial Revolution. The art of mechanical illustration was an early

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[46] Witold Kula has drawn a link between the Enlightenment and the eighteenth-century attempts to standardize measures, arguing that "disorder" of the kind caused by their proliferation could not be tolerated (1986, pp. 117–19). Although the reforms clearly had political and fiscal reasons, they led, perhaps as a largely unintended by-product, to a rationalization in knowledge-transmission.

[47] Latour (1990, p. 57) states with some exaggeration that "the universality of science and technology is a cliché of epistemology but metrology is the practical achievement of this mystical universality."

[48] Although the periodic table of elements was not finalized by Mendeleev until 1869, earlier attempts to represent the elements in an orderly and organized manner go back to Lavoisier himself. In 1817 a German chemist, Johann Döbereiner, showed how the elements known at that time could be arranged by triads, encouraging others to search for further patterns (see Scerri, 1998).

[49] Young's work was complex and poorly written and might have been forgotten in an earlier age. The Industrial Revolution era, however, had ways of disseminating important knowledge, and his work found its way to the engineering community through the textbooks of Thomas Tredgold (widely read by engineers at the time) and articles in the Encyclopaedia Britannica.

phenomenon and well established in the second half of the sixteenth century. Yet the great books of technical illustrations published at that time by Besson (1578) and Ramelli (1588) do not describe real machines as much as idealized concepts, and were lacking in visual perspective. Only the illustrations accompanying the *Encyclopédie* and the eighty volumes of the *Descriptions des arts et métiers* (1761–88) approached technical mastery. Ferguson thinks that the impact of these volumes on stimulating technological change was "probably slight" and is more inclined to attribute radical changes to the systematic works describing possible rather than actual mechanical movements, such as Jacob Leupold's *Theatrum Machinarum* (1724–39) (1992, p. 135). Ferguson thus underestimates the importance of access to knowledge of existing techniques as a key to their improvement and their recombination into novel "hybrids." In any case, the eighteenth century witnessed a great deal of progress in "technical representation," and by the middle of the eighteenth century technical draftsmanship was being taught systematically (Daumas and Garanger, 1969, p. 249).[50] In addition, between 1768 and 1780 the French mathematician Gaspard Monge developed descriptive geometry (Alder, 1997, pp. 136–46), which made graphical presentations of buildings and machine design mathematically rigorous.[51] In Alder's words, "It marks a first step toward understanding how the way things are made has been transformed by the way they are represented" (p. 140). The impact of Monge's sophisticated diagrams on the practice of engineering was probably modest at first, and technical drawings and orthographic projections were used by other engineers independently and long before Monge's work.[52] My argument is simply that "the way things are represented" is a way of organizing Ω and that the visual organization of technical knowledge made

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[50] Alder (1998, p. 513) distinguishes between three levels of mechanical drawing in prerevolutionary France: the thousands of workshops where experienced artisans taught free-hand drawing to their apprentices; state-sponsored schools in which drawing teachers taught basic geometry; and the advanced engineering schools in which mechanical drawing was taught by mathematicians.

[51] Monge's technique essentially solved the problem of reducing three-dimensional entities to two dimensions while at the same time depicting the relationships between the parts constituting the shape and configuration of the entity.

[52] Monge's work was kept unpublished (as a military secret) for many years and published only in 1795. Its impact on technological progress outside the military was limited until 1851, when Monge was translated and published in Britain. Booker (1963, p. 130) notes that Monge's work was conducted on too theoretical a level to be of much direct use "for the practical Englishman" (see also Belofsky, 1991).

enormous progress in the age of Enlightenment.[53] No doubt Alder is right in pointing out that all such ways are "social constructions" and "cultural conventions," yet it is hard to deny that some social constructions lend themselves to access and diffusion of knowledge better than others. To be sure, no device can be reproduced from a drawing alone, and when French engineers tried to assemble a Watt steam engine from a drawing prepared by him, the pieces did not always fit (Alder, 1997, p. 146). Yet such drawings clearly told people what could be done and what had been done, and the mechanical principles on which it was based. No amount of dexterity and instinctive technical sense could make much progress without access to such knowledge. Moreover, Alder points out that these precise representations made standardization and interchangeability possible and thus led eventually to the modularization characteristic of the second Industrial Revolution.

If the access costs are to be affordable so that production can draw on accumulated useful knowledge, there has to be social contact between "knowers" and "doers." There is too much tacit and uncodifiable knowledge in technology for the written word and the graphical representation to do it all. Any society in which a social and linguistic chasm exists between workers, artisans, and engineers on one side, and natural philosophers and "scientists" (the word did not exist until the 1830s) on the other, will have difficulty mapping continuously from useful knowledge onto the set of recipes and techniques that increase economic welfare. Interestingly, the bridging of the social gap between the sphere of the learned scientist and that of the artisan was used to explain the origins of modern science, but with few exceptions it has not figured large in explanations of the Industrial Revolution (see, for instance, Eamon, 1990, pp. 345–46; Cohen, 1994, pp. 336ff.). If the *savants* do not deign to address practical problems where their knowledge could help resolve difficulties and do not make an effort to communicate with engineers and entrepreneurs, the *fabricants* will have difficulty accessing Ω.

Within Europe, the depth of this chasm varied substantially (though nowhere was it totally absent). Gillispie attributes France's moderate technological achievement to the fact that "France was playing Greece to

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[53] In an interesting and iconoclastic paper, Latour (1990) attributes the emergence of modern science and technology to the representation of information in two-dimensional space where it can be manipulated and processed. He calls these representations "inscriptions" and points out that the role of the mind has been exaggerated, and that the mind's ability to process knowledge depends entirely on whether it has to deal with the real world or with these representations. On a less lofty but more sensible level, Alder (1998) argues that graphical representation was a mechanism to make "thick" (complex) reality into something "thin" (that is, comprehensible).

the modern world, and men of learning clearly and instinctively distinguished between the domains of science and practice.... in this attitude French scientists were more severe, perhaps, than their colleagues in other countries and especially in Great Britain" (1957, p. 403). Yet compared to China or classical antiquity, the gap anywhere in Europe appears to have been shallow.[54] Even in France, scientists such as Berthollet, Chaptal, Gay-Lussac, Chevreul, and many others were keenly interested in practical problems even if they were, as Lavoisier pointed out, motivated primarily by the love of science and the enhancement of their own reputations (cited by Gillispie, 1957, p. 402). Even if scientists were "pure"—that is, motivated exclusively by epistemic motives, and industrialists were *homines economici* motivated exclusively by material gain (an absurd oversimplification, of course), this should not necessarily have been a barrier to technological progress, provided the greedy moneygrubbers had access to the propositional knowledge generated by their loftier neighbors. Nor did the national differences matter all that much: as long as knowledge could move readily across boundaries, both scientific and technological "leads" would be temporary. Even if all the theorists had lived in France and all practical entrepreneurs had lived in Britain, abstract knowledge should have moved from France to Britain, been turned into technology there, and eventually returned to the continent in the form of machines and the men who knew how to operate them. This is roughly what happened between 1760 and 1850.

Of course, this tale presupposes that the research agenda of the *savants* is not entirely dominated by knowledge with no conceivable immediate application (as was the case, for instance, for Jewish rabbis). From the sixteenth century on, natural philosophers were increasingly attracted to the issues raised by the practical difficulties of industry and agriculture. Edgar Zilsel (1942), who was the first to stress this phenomenon, places the turning point at around 1550. This spirit permeates the writings of Paracelsus, who died in 1541, and whose writings appeared mostly posthumously (in German). Whether it was social change such as the "rise of commercial capitalism" that drove the phenomenon, religious change, or the reduction in access costs brought about by printing (as Eisenstein, 1979, has maintained), the changes were real. These deep transformations moved at the rate of continental drift. One should not expect that their

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[54] Even the champions of Chinese science and technology have to concede that Chinese artisans were remarkably good at carrying out empirical procedures of which they had no scientific understanding. The real work in engineering was "always done by illiterate or semi-literate artisans and master craftsmen who could never rise across that sharp gap which separated them from the 'white collar literati'" (Needham, 1969, p. 27).

expression in the influential writing of Bacon would be followed within a few decades by a technological upheaval like the Industrial Revolution. Yet, as we have seen, by 1800 or so, the mutual interaction between propositional and prescriptive knowledge reached the critical area, and Bacon's dreams became increasingly realistic. This was precisely the nature of the Industrial Enlightenment.

The connection is undeniable. Above all, Britain was the country in which the gap between those who engaged in propositional knowledge and those who applied it to production may already have been the narrowest by 1700, and it was becoming narrower over the eighteenth century. The historical question is not whether engineers and artisans "inspired" the scientific revolution or, conversely, whether the Industrial Revolution was "caused" by science. It is whether practical men could have access to propositional knowledge that could serve as the epistemic base for new techniques. It is the strong complementarity, the continuous feedback between the two types of knowledge, that set the new course. As noted, many people whom we would regard today as "scientists" used their Ω-knowledge directly to make inventions. Many inventors, however, were relatively unschooled, and when they needed some knowledge as the basis for a new technique, they could get access to it with ever-greater ease.[55] Self-educated engineers and chemists could be successful because they had easy access to the texts and the magazines in which the information they needed could be found.[56] If formal and codified knowledge was needed, access could be had through personal contacts. When William Cooke, an anatomist and talented entrepreneur, was inspired by a German lecturer to begin working on an electrical telegraph, he first consulted Michael

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[55] Consider the career of Richard Roberts, who has been called the most versatile mechanic of the Industrial Revolution. Roberts was far from a scientist and never had a scientific education. His fame rests primarily on the invention of the self-acting mule in 1825, which automated the spinning machines invented in the 1770s and 1780s and became the backbone of the British cotton industry in the following decades, all the way to 1914. Roberts, however, was a universal mechanical genius with an uncanny ability to access and grasp pieces of Ω and map them into new techniques that worked. In 1845 he built an electromagnet that won a prize for the most powerful of its kind and was placed in the Peel Park museum in Manchester. When first approached about the project, he responded, characteristically, that he knew nothing of the theory or practice of electromagnetism, but that he would try to find out (Smiles, [1863] 1967, p. 272). By this time, if an engineer wanted to "find out" something, he could do so by talking to an expert, consulting a host of scientific treatises and periodicals, encyclopedias, and engineering textbooks, as Roberts no doubt did.

[56] John Mercer (1791–1866), one of Lancashire's most successful colorists and dye specialists, was entirely self-taught yet was elected in 1852 as a fellow of the Royal Society. Another self-taught engineer was Eaton Hodgkinson (1789–1861), a specialist in the strength of materials, whose classic paper showing how to determine the strength of iron beams (1836) was widely used by civil engineers.

Faraday, and eventually he called on Professor Charles Wheatstone, an experienced investigator of electricity. Together the duo of Wheatstone and Cooke patented the first telegraph in 1837. Although this partnership ended in acrimony, it is interesting to note that the arbitrators who attempted to settle the dispute gave Wheatstone the credit for the research that had shown the invention to be feasible, and Cooke the credit for applying that knowledge (Morus, 1998, p. 214).

A century ago, historians of technology felt that individual inventors were the main actors that brought about the Industrial Revolution. Such heroic interpretations were discarded in favor of views that emphasized deeper economic and social factors such as institutions, incentives, demand, and factor prices. It seems, however, that the crucial elements were neither brilliant individuals nor the impersonal forces governing the masses, but a small group of at most a few thousand people who formed a creative community based on the exchange of knowledge. Engineers, mechanics, chemists, physicians, and natural philosophers formed circles in which access to knowledge was the primary objective. Paired with the appreciation that such knowledge could be the base of ever-expanding prosperity, these elite networks were indispensable, even if individual members were not. Theories that link education and human capital to technological progress need to stress the importance of these small creative communities jointly with wider phenomena such as literacy rates and universal schooling.

The personal and informal contacts so central to the operation of these creative communities took place in the scientific societies, academies, Masonic lodges, coffeehouse lectures, and other meetings. Some of those contacts had the purpose of smoothing the path of knowledge between scientists and engineers on the one side and those who carried out the instructions and used the techniques on the other side. The circulation and diffusion of knowledge within Ω was equally important, and hence the significance of such bodies as the Royal Society and the Society of Civil Engineers founded by Smeaton in 1771. By the middle of the nineteenth century, there were 1,020 associations for technical and scientific knowledge in Britain with a membership of roughly 200,000 (Inkster, 1991, pp. 73, 78–79).[57]

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[57] The Royal Institute in London was explicitly intended to spread useful knowledge among the public. Jacob and Reid (2001) point to similar institutions such as the Manchester Mechanics' Institute (founded in 1825) as an important means for popularizing science and encouraging specialized knowledge among factory employees. The institute provided lectures on such topics as the operation of gears in couplings and governors and plaster and wax casting.

Access to useful information also was determined by literacy and the availability of reading material. It is now widely agreed at least for Britain that increases in literacy were relatively modest during the Industrial Revolution (Mitch, 1998). Yet literacy is not particularly useful unless people actually read, and for the purposes of technological change it also matters how much and what people read. At least two well-known inventions of the Industrial Revolution made the availability of reading material more widespread: the Robert method of producing continuous paper (applied in Britain by Brian Donkin around 1807) and the improvements in printing due to the introduction of cylindrical printing and inking using steam power invented by the German immigrant Friedrich Koenig in 1812. With the development of lending libraries and the decline in the price of books, reading materials became more widely available.[58] Newspapers increased steadily in number and circulation, although the period of the Industrial Revolution was one of steady progress rather than quantum leaps forward (Black, 1994). This is not to suggest, of course, that people actually found technical descriptions in newspapers. The self-referential structure of Ω implies that before one can try to access knowledge, one must know that it actually exists. Once it is known that a technique is used somewhere, a search can be initiated. Here newspapers, magazines, and even "popular encyclopedias" had an important function. Part of the improvement in access-technology resulted from an ability to ask better questions that were based on shards of knowledge. Without these shards, producers might not know what to look for. Asking the correct question and knowing whom to ask is more than halfway to getting the answer.

Moreover, access to relevant and useful knowledge became easier even for nonspecialists. A major contributor to this decline in access costs was the growth of general-purpose encyclopedias that arranged material alphabetically or thematically. Encyclopedias had been an old idea, and in 1254 Vincent of Beauvais completed his vast *Speculum*. By the time of the scientific revolution, the idea had caught on that existing knowledge could be tapped only if this knowledge was sorted and arranged systematically. Not surprisingly, the most eloquent call for such a project came from Francis Bacon himself.[59] The alphabetical organization of the material was first

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[58] Ferrant notes the rise of circulating libraries (or *cabinets littéraires* in France) and points out that even some coffeehouses made books available to their customers (2001, p. 188). The printing industry began catering to a wider and wider market. An example is the gradual replacement of leather with cloth binding, which made books "less aristocratic, less forbidding, less grand" (Manguel, 1996, p. 140).

[59] In his famous *Novum Organum,* Bacon called for an organization of knowledge according to Platonic notions, much as his contemporary Mathias Martini had done (1606). His inspiration was acknowledged by the *encyclopédistes*: d'Alembert ([1751], 1995), acknowledged "the

attempted in Louis Moréri's *Grand Dictionnaire Historique* (1674). Fifteen years later Antoine Furetière published his issue of *Dictionnaire Universel des Arts et Sciences* (1690), which placed the kind of emphasis on arts and sciences that Bacon had called for. The first encyclopedia of useful knowledge in English, John Harris's *Lexicon Technicum* appeared in 1704 and dealt with a host of technical issues. Its most prominent successor in English was Ephraim Chambers's *Cyclopedia*, first published in 1728, which went through many editions. Harris's book was perhaps the prototype of a device meant to organize useful knowledge efficiently: it was weak on history and biography, strong on brewing, candle-making, and dyeing. It, too, contained hundreds of engravings, cross references, and an index. It was, in Headrick's words, "a handy and efficient reference tool." The epitome of Enlightenment literature is Diderot's justly famous *Encyclopédie*, with its thousands of detailed technical essays and plates.[60] As Headrick points out, the editors of the *Encyclopédie* covered the useful arts in painstaking detail, after visiting workshops and interviewing the most skilled craftsmen they could find. The approximately 72,000 entries included long ones on mundane topics such as masonry (thirty-three pages), glass making (forty-four pages), and mills (twenty-five pages). These essays were accompanied by many clear engravings. The *Encyclopédie*, moreover, was a best-seller. The original version sold 4,000 copies, but the total may have reached 25,000 copies if the many pirated and translated versions are counted, at an average of thirty volumes per set.[61] Diderot and d'Alembert's masterwork was widely imitated. The Encyclopaedia Britannica, the most famous of these products in the English language, first appeared in 1771 as a fairly small project (three volumes in three years) written by one person, William Smellie. It too focused on the sciences, useful arts, medicine, business, and mathematics. Much larger editions soon expanded the range. German equivalents followed as well, starting with

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immortal chancellor of England" as "the great man we acknowledge as our master" even if he and Diderot eventually chose a somewhat different way of organizing the knowledge (pp. 74–76).

[60] In the *Encyclopédie* article on "Arts," Diderot himself made a strong case for the "openness" of technological knowledge: condemning secrecy and confusing terminology and pleading for easier access to useful knowledge as a key to sustained progress. He called for a "language of [mechanical] arts" to facilitate communication and to fix the meaning of such vague terms as "light," "large," and "middling" to enhance the accuracy of information in technological descriptions. The *Encyclopédie,* inevitably perhaps, fulfilled these lofty goals only very partially, and the articles on technology differed immensely in detail and emphasis. For a recent summary of the work as a set of technological representations, see Pannabecker (1998).

[61] Interestingly, the *encyclopédistes* no more than Adam Smith had any inkling of the imminent Industrial Revolution. The author of the article on *Industrie*, Louis Chevalier de Jaucourt, noted that Industry appears to have entered a stage in which changes are much more mild and the shocks far less violent than before (Lough, 1971, p. 360).

Johann Theodor Jablonski's *Algemeines Lexicon* (1721; 1748–67) and culminating in the formidable Brockhaus, an encyclopedia that began appearing in 1809, and the *Oeconomische-Technologische Encyclopädie*, started in 1796, which had 221 volumes by the time it was completed (Pinault Sørensen, 2001, p. 444).[62] The redoubtable Andrew Ure published his *Dictionary of Arts, Manufactures and Mines* in 1839 (an earlier edition, dedicated mostly to chemistry, had appeared in 1821), a dense book full of technical details of crafts and engineering in over 1,300 pages of fine prints and illustrations, which by the fourth edition (1853) had expanded to 2,000 pages.

It remains to be seen if the encyclopedias and compilations were more than an expensive device by which a nouveau riche bourgeoisie, for whom, in Headrick's words, the technical essays constituted "intellectual voyeurism" demonstrated its intellectual prowess. At times, the knowledge contained in these compilations was already obsolete at the time of publication or became so soon after. In other cases, books about the useful arts were written by scholars to whom the esteem of the scholarly world was of first concern, and who were more inclined to cite past authorities than to examine with care what was happening on the shop floor (J. R. Harris, 1976, p. 169). Articles in the same work at times contradicted one another, leaving the reader in confusion. Yet the entire project hammered home Diderot's belief, paradigmatic of the Industrial Enlightenment, that the *savants* should respect the *fabricant* and that the *fabricant* should seek guidance and counsel from the natural philosophers. This notion raised the prestige of studying the practical arts in a systematic way, narrowing the social and intellectual chasm between those who studied nature and those who tried to manipulate it. Best-practice propositional knowledge was made available to all, even if best-practice looks somewhat rudimentary to the twenty-first century reader.

Of course I do not argue that one could learn a craft just from reading an encyclopedia article (though some of the articles in the *Encyclopédie* read much like cookbook recipes). But they informed the reader of the dimensions and limits of Ω underlying λ, and once the reader knew what was known, he or she could look for details elsewhere.[63] The order of

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[62] Johann Beckmann, whose *Anleitung zur Technologie* (1777) was one of the first works to actually use the term, became a professor of technology in Göttingen in the 1770s.

[63] The chamber of commerce in Rouen complained in 1783 that the description of certain tools used in the combing of flax (known as *rots*) in the *Grande Encyclopédie* was incorrect and inspired a manufacturer of the tool to set the record straight (Hilaire-Pérez, 2000, p. 158). Thomas Blanchard, in his 1820 application for a patent on his lathe, attributed the cam motion that created irregular shapes to Diderot's *Encyclopédie* as well as to a depiction in the *Edinburgh Encyclopedia* (M. R. Smith, 1977, p. 125; but see Cooper, 1991, pp. 83–84 for doubt whether these articles really

articles was organized in a form designed to minimize access costs: although alphabetization was not new, the idea of organizing useful information in that way was quite radical.[64] This system, with its logical extension, the alphabetical index, must be regarded as the first search engine, though by the time of the Industrial Revolution it was far from perfect, as readers consulting original editions of *The Wealth of Nations* can verify. It might be added that Chinese characters do not lend themselves to to alphabetization and that the organization of useful knowledge in Chinese encyclopedias and compilations was awkward. Encyclopedias and technical manuals also began cross referencing, the eighteenth-century equivalent of hypertext.

Other ways of cataloging useful knowledge also emerged, especially in France. Encyclopedias and "dictionaries" were supplemented by a variety of textbooks, manuals, and compilations of techniques and devices that were somewhere in use. An early example was Joseph Moxon's 1683 *Doctrine of Handyworks*; the biggest one was probably the massive *Descriptions des arts et métiers* produced by the French Académie Royale des Sciences.[65] Specialist compilations of technical and engineering data appeared, such as the detailed descriptions of windmills (*Groot Volkomen Moolenboek*) published in the Netherlands as early as 1734. A copy was purchased by Thomas Jefferson (Davids, 2001). Jacques-François Demachy's *l'Art du distillateur d'eaux fortes* (1773) (published as a volume in the *Descriptions*) is a "recipe book full of detailed descriptions of the construction of furnaces and the conduct of distillation" (John Graham Smith, 2001, p. 6). In agriculture, meticulously compiled data collections looking at such topics as yields, crops, and cultivation methods were

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inspired him). The eminent scientist Thomas Young was inspired as a boy by a *Dictionary of Arts and Sciences* he discovered in the library of a neighbor (Musson and Robinson, 1969, p. 166). The young Michael Faraday was enthralled by the article on electricity he read in the *Encyclopaedia Britannica* (Thompson, 1898, pp. 5–6), a fascination that was to have far-reaching consequences. John Mercer's interest in formal chemistry was awakened by a *The Chemical Pocket Book* by James Parkinson, a natural philosopher and physician otherwise famous for the discovery of Parkinson's disease (Nieto-Galan, 1997, p. 5).

[64] Although not all encyclopedias or compendia followed this format, when they did not they became series of unrel ated textbooks, less efficient for some purposes but still crammed full of relatively accessible knowledge. An example is Charles-Joseph Panckoucke's *Encyclopédie Méthodique*, a huge work conceived in the 1780s, which over half a century published 157 volumes of text alone and contained no fewer than 5,943 engravings.

[65] The set included 13,500 pages of text and over 1,800 plates describing virtually every handicraft practiced in France at the time, and every effort was made to render the descriptions "realistic and practical" (Cole and Watts, 1952, p. 3).

common.[66] Following the theoretical work of Monge and Lazare Carnot, the *polytechniciens* developed kinematics, a method of classifying mechanical movements by function, resulting in Jean Hachette's *Traité élémentaire des machines* (1808) and similar compendia. By the middle of the nineteenth century, reference books such as Henry T. Brown's *Five Hundred and Seven Mechanical Movements* (1868) had become exhaustive.

In the decades after 1815, a veritable explosion of technical literature took place. Comprehensive technical compendia appeared in every industrial field. This expansion was due to supply as well as demand factors: there was more and more useful knowledge to communicate; at the same time more and more *fabricants* felt, correctly or not, that they could benefit from access to this useful knowledge if it were sufficiently accessible. Thomas Tredgold (1788–1829) produced a stream of discourses on the strength of cast iron and the principles of carpentry, hydraulics, and steam engines. John Farey's *Treatise on the Steam Engine* appeared in 1827, and was meant to be a practical manual accessible even to relatively poorly educated mechanics (Woolrich, 2000). In mechanics John Nicholson's *The Operative Mechanic and British Machinist* (1825) cataloged virtually every machine known with descriptions and instructions for building them. Nobody will confuse such works with "science," yet their proliferation after 1815 illustrates the new regime of interaction between propositional and prescriptive knowledge, which prevented the eighteenth-century "wave of gadgets" from fading.

Despite the relatively low rate of success of its application to industry, this systematization of knowledge was also extended to chemistry. It was believed that a compilation of the properties of all substances would eventually lead to their successful industrial utilization. This belief led to a plethora of chemical compilations such as P. J. Macquer's famous *Dictionnaire de chimie* (1766), which was soon translated into English, German, Italian, and Danish. Many such encyclopedias and compilations followed, culminating in Antoine Fourcroy's magisterial *Système des Connaissances chimiques* (1800), which codified the new Lavoisier chemistry around the concepts of elements, bases, acids, and salts. Claude Berthollet's *Art de la teinture* (1791) summarized the state of the art in dyeing technology for a generation, and his *Statique chimique* (1803) "was not only the summation of the chemical thought of the entire eighteenth century...but also laid out the problems that the nineteenth century was to solve" (Keyser, 1990, p.

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[66] One of the great private data collection projects of the time was Arthur Young's, who collected hundreds of observations on farm practice in Britain and the continent, although at times his conclusions were contrary to what his own data indicated(see Allen and Ó Gráda, 1988).

237). William Partridge's *Practical Treatise on the Dyeing of Woolen, Cotton and Silk* (1973) was published in New York in 1823 and for thirty years remained the standard text "in which all the most popular dyes were disclosed...like cookery recipes" (Garfield, 2001, p. 41).

An example of the eighteenth-century thirst for cataloged and ordered information (what we would call today "data") was the rise of botanical gardens such as the Jardin Royal des Plantes and the famed Kew Gardens in London, which were run for almost fifty years by Joseph Banks, who collected plant specimens from the four corners of the world. Linnaeus's system of classification and identification created order in this rapidly growing catalog of natural phenomena, and their importance for gardening—a much underrated economic activity—was inestimable.

Of particular interest is the rise of statistics as a way of interpreting information about the physical world. The Newtonian view of the world was strictly deterministic rather than stochastic, and natural scientists were uneasy about the uncertainty it implied. It was readily realized, however, that a probabilistic approach was necessary for the formalization of empirical regularities in natural phenomena, the mechanisms of which were not fully understood and for which not all the information necessary was available.[67] As Gigerenzer et al. point out (1989, p. 44), the areas that adopted statistical approaches were, not surprisingly the ones that dealt with entities too numerous or remote to be understood individually. Eventually this field carried over to purely physical phenomena as well, culminating in the work of Maxwell and Boltzmann. Knowledge could become tighter if empirical regularities about partially understood natural (and social) phenomena could be shown to be the rule even if exceptions were allowed. The notion that inferences could be made this way and that knowledge from large samples trumped personal experience no matter how detailed is another product of the Enlightenment. Demography, medicine, crime, and public health were obvious applications of statistics, but eventually they were applied to other areas in which they would prove useful, such as agriculture. These increments in Ω eventually mapped into some clearly defined techniques, as we shall see below.

Did all this organization of useful knowledge matter? It is beyond question that the technological leaders of the Industrial Revolution, men like Smeaton, Watt, Trevithick, Roebuck, Wilkinson, Maudslay, and Roberts, were well-read in technical matters. So, by all accounts, were

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[67] The insight that only an omniscient Supreme Being could dispense with probability because it had infinite knowledge but that human ignorance required some knowledge of the error term was first fully formulated by Laplace in the three-volume *Théorie analytique des probabilités* (1812–20) (see T. Porter, 1986, pp. 71–73).

scores of lesser lights whose contribution, cumulatively, made all the difference. Moreover, in Britain many literate people, including entrepreneurs and peers in the House of Lords, possessed, in Margaret Jacob's words, "significant technical competence." By the second quarter of the nineteenth century, the commitment to useful knowledge trickled down from the elite to the middle classes. In 1828 one observer noted, "In every town, nay almost in every village, there are learned persons running to and fro with electrical machines, galvanic troughs, retorts, crucibles, and geologist hammers" (cited by Inkster, 1976, p. 287).

Exactly how this familiarity with "science" and more widely with technical and useful knowledge affected Britain's inventiveness remains a matter of some controversy. All codified knowledge surely needed to be complemented by tacit and implicit skills such as dexterity, hand-eye coordination, and a sense of "what worked." Tacit knowledge and formal visual or verbal knowledge should not be thought of as substitutes but as complements. Mechanics and designers thought in non-verbal language and were often frustrated by the incommensurability of verbal expression and spatial-mechanical skills based on visualization and experience.[68] But often such skills are directed and focused by knowledge acquired from others or from reading. For certain technical devices the knowledge that it worked at all or a very rough outline of how it did so sufficed for skilled engineers, physicians, chemists, and farmers. They could fill in the details.[69] What Britain had in relative abundance is what Edward W. Stevens (1995) has called "technical literacy," which required, in addition to literacy, the understanding of notation and spatial-graphic representation. In Britain, these skills were transmitted through an apprenticeship system, in which instruction and emulation were intertwined and codifiable knowledge packaged together with tacit knowledge. As long as the application of the technology did not require a great deal of formal knowledge, this system worked well for Britain. The exact mapping from

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[68] The importance of tacit knowledge has been re-emphasized by Ferguson (1992), relying on the work of John R. Harris. The French had figured out that, as one mid-eighteenth-century French author put it, "eye and practice alone can train men in these activities."

[69] Two cases of difficult access to *existing* stored knowledge are often cited. One is the existence of a copy of Vittorio Zonca's *Nuovo Teatro di Machine et Edificii* (pub. in 1620) in the open shelves of the Bodleian, unbeknownst to John Lombe, who spent two years traveling in Italy to secure knowledge on the silk-throwing machine described therein that he could have found closer to home. The other is the existence of a copy of Euclid's elements—translated into Chinese—in the Imperial Library in the thirteenth century (Needham, 1959, p. 105), yet which apparently was never noticed by the Chinese astronomers. The Zonca anecdote is usually cited as support for the importance of hands-on experience and personal observation, yet it is still unresolved whether detailed prior knowledge of what the machine looked like and how it worked would have greatly facilitated Lombe's adoption.

propositional knowledge to technique took complex forms, and it is striking that France and Germany seem to have led Britain in formal technical education, engineering textbooks, encyclopedias, and other access-cost-reducing developments.[70] Yet this observation does not refute the argument I have made here. Britain's success in the Industrial Revolution was to a remarkable extent based on French inventions. From chlorine bleaching to gaslighting to Jacquard looms, Britain greedily looked to France for inspiration. To oversimplify to the point of absurdity, one could say that France's strength was in Ω, Britain's in λ, and that the mapping function bridged the Channel.[71]

Perhaps the crucial difference between the two nations was in the way the political structures affected the mapping from propositional to prescriptive knowledge. In France, engineering knowledge was mostly regarded as inspired by and in the service of national interests and political objectives, on the part of both those in control of the state and those wishing to undermine it. In Britain, overall, the subsets of λ of interest to the engineers and scientists of the time were far more industrial and commercial. At the same time, the French government soon became aware of its backwardness and took various measures to reverse what Jean-Antoine Chaptal called this "inversion of natural order" (cited by M. Jacob, 1998, p. 78). Chaptal, who was minister of the interior under Napoleon, was convinced that British industrial success was due to its superior "mechanical knowledge" and the close ties between the *savants* and the *fabricants* (Jacob, 1997, pp. 182–83). France's innovation in this regard, in addition to engineering schools, was the organization of industrial expositions, in which technical knowledge was diffused in an efficient and concentrated manner. These are merely differences of degree and timing, minor if we compare the West to eastern Europe or the Middle East, but perhaps enough to explain many of the differences within western Europe.

To sum up: the knowledge revolution in the eighteenth century was not just the emergence of new knowledge; it was also better access to

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[70] Although the value of a periodical is of course proportional to its subject matter, the quality of the research, and the scope of its circulation, it is striking that the vast majority of scientific journals published in the eighteenth century appeared not in England or France but in Germany. Over 61 percent of all "substantive serials" appeared in Germany, with France and England accounting for 10.7 percent and 6.9 percent, respectively. The actual gap was smaller, because German scientific journals were comparatively short-lived, but correcting for this does not alter the picture (Kronick, 1962, pp. 88–89). There were similar gaps between countries, although not as large, for the proceedings of scientific societies. The only category in which England led, perhaps significantly, was "translations and abridgements" (pp. 114–15).

[71] For more details on the different scientific and technological trajectories of France and Britain, see Mokyr (1998c).

knowledge that made the difference. In some instances scholars have tended to overstate how much novelty had occurred in the centuries before the Industrial Revolution, minimizing its technological achievements.[72] To be sure, engineering knowledge during the age of the baroque had achieved some remarkable successes, and besides Leonardo a number of brilliant engineers and inventors are known to have proposed precocious devices: one thinks of Cornelis Drebbel, Simon Stevin, Giambattista Della Porta, Robert Hooke, Blaise Pascal, and Gottfried Wilhelm Leibniz, among many others. Yet obtaining access to their knowledge remained very difficult for subsequent rank-and-file engineers and mechanics, because it was often presented to a selected audience or never published. The Enlightenment began a process that dramatically lowered these access costs.[73] The knowledge revolution of the eighteenth century—that is, the changes in the structure of Ω—made the process of evolution more efficient in the sense that superior techniques spread faster because the ways they became known and could be tested improved. In its publication of the *Descriptions* of handicrafts, the French Académie Royale made an effort to choose the best-practice methods, and although it emphasized description and not improvement, the description of the useful arts by those carrying the "torch of physical science" dramatically lowered access costs to the λ-knowledge and is likely to have stimulated technological advances as well, if only because more minds trained in science brought their skills to bear on practical problems.

After all, a substantial portion of invention consists of recombination, the application of a sometimes remote and disjoint sections of Ω together to form something novel. It is one of the chief reasons why lower access costs are so important in triggering the new mapping of techniques from Ω to λ. If taken to an extreme, recombination can lead to dazzling rates of invention, because the rate of invention will be combinatorial, which is faster than exponential (Weitzman, 1996). Both Cort's puddling and rolling process and Crompton's mule were recombinations, but less famous examples

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[72] Thus Ferguson (1992, pp. 63–64) states that a modern automobile engine contains mostly components that were known when Leonardo was alive, leaving electrical components and microprocessors aside. Yet the concept of the engine itself, transforming heat into work by burning fossil fuels, was clearly absent in Leonardo's day.

[73] The notion that the Enlightenment experience involved patterns of communication and interaction that were crucial to the extension of useful knowledge through society at large has been noted by historians of science. See for instance Golinski (1992, p. 6) and Stewart (1992, esp. ch. 8).

are not hard to come by.[74] It may be an exaggeration to say with François Jacob that "to create is to recombine" (Jacob, 1977, p. 1163), because some elements were truly novel, but it surely is true that much of technological innovation consists of precisely such activities. Hence the importance of efficient and accessible sources of useful knowledge in which one could check what was known about a particular natural phenomenon or process, or about techniques in use, and transfer them to novel applications.

Because invention is a cognitive process, lower access cost can have a further impact through knowing what is technically feasible. Laudan (1984) argues that we can look at invention as basically a process of problem-solving. The solutions, I have argued, depended on the epistemic bases available and their access costs. But beyond that, Laudan asks, which of all the problems that might be solved will an ingenious and creative individual apply his or her efforts to? The answer must be based in part on the signals that the market or another device sends to the potential inventor about the private and social benefits. In addition, however, the inventor must believe that the problem is *soluble*, and this prior belief must depend on which problems have been solved in the past. Thus, easy access to existing practices elsewhere, as advocated by the torchbearers of the Industrial Enlightenment, served as a source of new techniques as much as a diffusion mechanism of best practices.

Conclusion

Any historical account of economic progress, and above all accounts of the Industrial Revolution and its aftermath, need to incorporate the concept of useful knowledge explicitly. The Industrial Revolution followed from the Industrial Enlightenment, which was not a British but a *Western* phenomenon. The order in which things happened in Europe, the leadership of Britain and the much-discussed backwardness of France and the Netherlands were second-order phenomena. The intellectual and social developments that drove the expansion of Ω and the changes in its diffusion and access costs were spread over an area larger than Britain if much smaller than the world. Technology was not spread equally thickly: some areas in "the West" were late in jumping on the bandwagon of innovation. There were a variety of reasons for such lateness, and Spain, Ireland, and the Netherlands—all "Western" societies—proved in one way or another

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[74] Thus Richard Roberts's multiple spindle machine used a Jacquard-type control mechanism for the drilling of rivet holes in the wrought iron plates used in the Britannia tubular bridge (Rosenberg and Vincenti, 1978, p. 39).

resistant to innovation.[75] The changes in useful knowledge, both propositional and prescriptive, came from a variety of sources in Britain, France, Germany, and Scandinavia and spread quickly beyond these sources to other societies in the Northern Atlantic region. In that sense the Industrial Revolution, much like the Enlightenment that preceded and triggered it, was a Western event.

What the Industrial Revolution did was to create opportunities that simply did not exist before. There was, however, no mechanism that *compelled* any society to take advantage of them. Britain was simply the first to do so: in that sense the Industrial Revolution was British. All the same, Britain's leadership was neither a necessary condition for it to happen nor an equilibrium state that could survive in the long run in the world of competition and national jealousies that emerged in Europe after 1815.

Thanks to the "information and communications technology revolution" of our own age, marginal access costs have been lowered enormously, and in many areas have been reduced practically to zero. The idea of a "knowledge economy" is of course something of an exaggeration if taken literally: people still need food and hardware, and nobody can live on knowledge alone, not even graduate students. But the accelerating decline in access costs has opened the floodgates to further technological progress in our age, not just thanks to a single advance such as the Internet but through a host of changes that reduced access to knowledge as it increased the size of Ω. The differences between the two episodes are at least as instructive as the similarities, and not too much should be made of such historical analogies. One more striking conclusion to be drawn is that it is enormously difficult for contemporaries to realize how dramatically their world is changing, what the important elements are, and how technological change will shape their future. The great economic minds of the age, from Adam Smith to David Ricardo, had only the faintest notion of the pending changes.[76] This, of course, is not true for our own age, although whether the knowledge economy is truly a "new economy" is still a matter of serious dispute. As Stuart Kauffman has noted, in a world of positive feedback, self-sustaining and self-reinforcing changes, and nonlinear dynamics, "all bets are off."

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[75] For an analysis of the Netherlands, much the most mysterious case, see Mokyr (2000a).

[76] This is much less true for other writers of the time. For more details about to what extent contemporary writers were unaware of the Industrial Revolution, see Mokyr (1994c and 1998c).

Chapter 3

The Industrial Revolution and Beyond

> *The discoveries of Watt and Arkwright, which yielded at once such immense national as well as individual prosperity, must ever be regarded as forming a new era in the arts of life and the domestic policy of nations. The riches, extraordinary as unprecedented, inexhaustible as unexpected, thus acquired by a skilful system of mechanical arrangement for the reduction of labor, gave the impetus which has led to numerous discoveries, inventions, and improvements in every department of our manufactures, and raised them to their present state of perfection.*
>
> —John Nicholson (1826)

Introduction

The people alive during the first Industrial Revolution in the late eighteenth century were largely unaware of living in the middle of a period of dramatic and irreversible change. Most of the benefits and promises of the technological changes were still unsuspected. Adam Smith could not have much sense of the impact of the innovations taking place around him in 1776 and still believed that when the process of growth was completed, the economy could "advance no further" and both wages and profits would be very low. Napoleon, following Smith, famously referred to Britain as a nation of shopkeepers, not of cotton-spinners or steam-engine operators. By the time of the Battle of Waterloo, however, perceptions had already changed (Mokyr, 1998c, pp. 3–5). Horace Greeley, the editor of the *New York Tribune*, pronounced in 1853, "We have universalized all the beautiful and glorious results of industry and skill....we have democratized the means and appliances of a higher life." These were to some extent prophetic words, since only the second Industrial Revolution brought technological progress to the advantage of the consumer. By the end of the nineteenth century, James P. Boyd, the author of *Triumphs and Wonders of the 19th Century, The True Mirror of a Phenomenal Era,* concluded that by the inventions and progress that have most affected the life and civilizations of the world, "the nineteenth century has achieved triumphs...equal, if not superior to all centuries combined" (M. R. Smith, 1994, pp. 5–7).

Terms like "revolution" tend to be overused and abused by historians. They draw attention. They sell books. But do they have historical content? In economic history especially, melodramatic terms have a bad name, because the field tends to be relatively *un*dramatic. Most of the elements that drive modern economic growth work gradually, slowly, and almost imperceptibly: the dissemination of technological ideas, the accumulation of capital, even the changes in economic institutions were rarely very spectacular. Whenever a genuinely dramatic general-purpose invention occurred, its impact on the productivity of the economy as a whole took many years to be felt. The first Industrial Revolution used to be regarded as the watershed event in the economic history of mankind since the invention of agriculture and has often been mentioned in one breath with the drama-laden contemporaneous French Revolution. It has now been shown to have had only modest effects on economic growth before 1815 and practically none on real wages and living standards before 1840, more than a century after the appearance of the first steam engine. The second Industrial Revolution, similarly, was slow in manifesting its full impact on the economies in question and took much of the twentieth century to work out its effects fully. The paragon of the putative third Industrial Revolution, the computer, has still apparently not wholly lived up to the hopes and expectations regarding productivity and output.

Few scholars nowadays think of the Industrial Revolution as a series of events that abruptly and significantly raised the rate of sustained economic growth (Mokyr, 1998c). Most of the effects on income per capita or economic welfare were slow in coming and spread out over long periods. All the same, even though the dynamic relation between technological progress and per capita growth is hard to pin down and measure, it is the central feature of modern economic history. We are uncertain how to identify the technology-driven component of growth, but we can be reasonably sure that the unprecedented (and to a large extent undermeasured) growth in income in the twentieth century would not have taken place without technological changes. It seems therefore more useful to measure "industrial revolutions" against the technological capabilities of a society based on the knowledge it possesses and the institutional rules by which its economy operates. These technological capabilities must include the potential to produce more goods and services, but they could equally affect aspects that are poorly measured by our standard measures of economic performance, such as the ability to prevent disease, to educate the young, to move and process information, and to coordinate production in large units. By those standards, it is hard to deny that the 1990s witnessed an industrial revolution, but we need to assess it in terms of those capabilities, with the macroeconomic consequences following eventually but often much later.

The First Industrial Revolution

The economic significance of the Industrial Revolution is not so much in the great gadgets that were invented in the "years of miracles" between 1760 and 1790 as it is in that the process of innovation, which did not run into diminishing returns and fizzle out after 1800 or 1820. This is what had happened repeatedly in earlier episodes when Europe (and non-European societies) experienced clusters of macroinventions. In the pre-1750 environment technological progress failed to generate *sustained* economic growth. The challenge is to explain why.

The negative feedback mechanisms that prevented earlier economies from growing weakened in the eighteenth century. Consider the constraints on resources, the basis of the Malthusian negative feedback. E. A. Wrigley (2000) has argued that the Industrial Revolution constituted a transition to an inorganic and mineral economy, in which stored-up resources such as fossil fuels and iron replaced currently produced ones such as wood and animal power. In an organic economy, energy and materials are derived from the earth and the sunlight it absorbs and constitute fixed factors that eventually lead to diminishing returns. A mineral-based economy is much less vulnerable to population pressure. Yet the transition from organic to mineral economy still needs to be explained itself.

The weakening of the "institutional negative feedback" is more complex. In each society, entrepreneurs face the choice between making their money through the exploitation of political opportunities that increase their share of income without increasing (or even while reducing) the overall level, or through getting rich by the socially beneficial exploitation of technological or commercial opportunities. In a variety of ways, the Enlightenment produced political change that made "productive" activity more attractive relative to rent-seeking and opportunistic behavior. North and Weingast (1989) have pointed to the British Glorious Revolution as the critical institutional juncture. The American and French Revolutions, and the rise of the free-trade movement inspired by the Scottish Enlightenment, were part of this change. This historical phenomenon is of enormous economic importance, and it cannot possibly be done justice here. But in and of itself, without changing the knowledge base of society, it would not have been able to account for sustained growth. It is worth keeping in mind that growth based primarily on institutional changes can be easily reversed by political catastrophes. The prosperity of the Roman Empire dissolved as the empire declined, and the gains from the globalized economy that had emerged in the gold standard international economy melted away in the fateful summer of 1914. Such disastrous reversals cannot be quite excluded in a growth process based on the expansion of useful knowledge, but clearly it is less vulnerable to such shocks.

Before 1750, most techniques in use or known to be feasible rested on very narrow epistemic bases, although we tend to discount unjustly the bodies of early Ω such as phlogiston theory and the humoral theory of disease, which formed the base of many operational techniques. The famed inventions that formed the basis of the Industrial Revolution were accompanied by a deepening as well as a widening of the epistemic base of the techniques in use. Perhaps by our standards the direct technological achievements of the scientific revolution appear to be modest, and there is clearly much to recommend A. Rupert Hall's view that the early inventions of the Industrial Revolution lacked support in science proper (Hall, 1974). Yet, as I argued above, this is an overly restricted definition of the knowledge base of technology. Propositional knowledge included a great deal more knowledge that we would call "useful" but which was artisanal knowledge rather than "science": examples are the lubricating qualities of oils, the hardness and durability of different kinds of woods, the location of minerals, the direction of the trade winds, and the strength and dietary needs of domestic animals. On the eve of the Industrial Revolution, with "science" in the modern sense in its infancy, this was what propositional knowledge mostly consisted of. It worked, but its ability to support sustained progress was limited.

In the decades around 1800, advances in chemistry, mechanics, energy, material science, and medicine continuously expanded the informal and formal parts of Ω-knowledge, including—but not limited to—the well-known scientific advances of Lavoisier, Priestley, Davy, Dalton, Faraday, and their colleagues. By the time of the restoration in France, notes John Graham Smith (2001, p. 1), the tone of the literature about the Baconian utility of science to industry shifts from exhortation to celebration. Some of this expansion of useful knowledge was self-propelled. A lot, however, can be attributed to the feedback of technological advances into science and engineering.

All the same, before 1850, the contribution of *formal* science to technology remained modest. Much of the technological progress in the first half of the nineteenth century came from the semi-formal and pragmatic knowledge generated by the great engineers of the Industrial Revolution: Henry Maudslay, Brian Donkin, the Brunels, the Stephensons, Richard Roberts, Neilson, and their colleagues. In France the "Big Three *polytechnicien*" engineers of the early nineteenth century, Gustave-Gaspard Coriolis, Jean-Victor Poncelet, and Louis Navier, placed mechanical and civil engineering on a formal base, and supported practical ideas with more formal theory than their more pragmatic British colleagues (Buchheim and Sonnemann, 1990, pp. 190–92). In Germany, the work of Ferdinand Redtenbacher published in the 1840s applied the theoretical insights of the French theorists to machine construction and water power. Some scholars, such as Wengenroth (2002), have expressed doubt whether all this formalization really fed into increased productivity, and—with some notable exceptions—the record suggests that most of the economic payoff to formal theory lagged decades behind its development.

This qualification does not invalidate the argument that the interaction between propositional knowledge and techniques was the driving force behind technological expansion, only that we are missing most of the action if we concentrate our efforts on formal science. Two stereotypic cartoons—the one of an ignorant amateur "tinkerer" who stumbled into great inventions through a combination of inspired intuition and sheer luck, the other of the methodical, well-informed scientist whose rigorous papers inform applied scientists and engineers of the exploitable natural regularities—are ahistorical. In between, there was a semidirected, groping, bumbling process of trial and error by clever, dexterous professionals with a vague but gradually clearer notion of the processes at work.[1] They enjoyed occasional but increasingly frequent successes, squeezing a messy, poorly defined blob of useful knowledge, some of it formal and codified, some of it propositional knowledge passed on orally in the form of "this works and this does not" (in Ω), that mapped into "here is how you do this" (in λ).[2] Instructions, not ideas, make things work. The early

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[1] The discovery of jasper by Josiah Wedgwood was based by experimenting on 10,000 trial pieces. McKendrick assesses that "every conceivable mixture was tried, every possible combination tested" (1973, p. 286). Yet Wedgwood instinctively felt that science would streamline this costly process, and if it were not materialized in his lifetime it would be the wave of the future.

[2] The way this came about was best described by the French chemist Claude Berthollet: "we are frequently able to explain the circumstances of an operation [that is, technique], which we owe entirely to blind practice, improved by the trials of many ages; we separate from it everything superfluous; we simplify what is complicated; and we employ analogy in transferring to one process what was useful in another. But there are still a great number of facts which we cannot explain, and which elude all theory. We must then content ourselves with detailing the processes of the art; not attempting idle explanations, but waiting till experience throws greater light upon the subject" (Berthollet, 1791).

application of techniques were often based on the vaguest of ideas. Operating a technique led to a better and better notion of *why* something worked and from there to how to make it work more efficiently or how to make it do something else. Watching a machine work or a telegraph signal pass without knowing why it does so serves as an irritant to a mind trained in science. In this sense, technology works as a "focusing device," to use Rosenberg's (1976) term, for the growth of Ω-knowledge.

How revolutionary was the Industrial Revolution? Modern economic historians have stressed the continuities as much as the transformations. The transition from an organic to a mineral economy had been going on for centuries before 1750.[3] Steam engines looked spectacular, but water power continued to supply much of the inanimate power everywhere. Cotton spinning and mechanical weaving were equally revolutionary, but the techniques in use in other textiles (wool, linen, and silk) were much slower to change, although eventually they all did. Apparel-making and millinery remained manual domestic industries well into the nineteenth century. The Cort process revolutionized wrought iron, but the making of cheap steel for industrial purposes remained out of reach until the 1850s, and ironmongery remained a small-scale artisanal sector until well into the nineteenth century. The great changes in industrial engineering—interchangeable parts, continuous flow processes, mass production of cookie-cutter standardized products—were all in the air by 1815, but were not realized at an economically significant scale until the second half of the nineteenth century.[4] Much of the British economy was affected very little until the middle of the nineteenth century; productivity growth was minimal, income per capita edged upward very slowly before 1830, and real wages barely rose until the mid-1840s (Mokyr, 1998c).

All the same, the technological changes that occurred in western Europe between 1760 and 1800 heralded a new age in the generation of

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[3] John R. Harris (1988) has pointed out that the switch from charcoal to coal-based fuels in the iron industry in the second half of the eighteenth century is believed by some to be the first such transition whereas in fact it was "virtually the last." Industries such as soapboiling, brewing, and glassmaking had switched to coal centuries earlier, and home-heating (the largest use for fuel) had become dependent on coal in medieval times.

[4] The famous Portsmouth block-making machines, devised by Henry Maudslay together with Marc Brunel around 1801 to produce wooden gears and pulleys for the British Navy, were automatic, and in their close coordination and fine division of labor resembled a modern mass-production process, in which a labor force of ten workers produced a larger and far more homogeneous output than the traditional technique that had employed more than ten times as many (Cooper, 1984). For an early application of the idea of interchangeability in France's musket-making industry, see Alder (1997). The *opus classicus* on the role of machine tools in the emergence of precision engineering is Rosenberg (1976). The continuous-flow process of the early mechanical spinning mills is emphasized by Chapman (1974).

new prescriptive knowledge. It was slowly becoming less random and serendipitous. As a result, the 1820s witnessed another "wave" of inventions and conceptual breakthroughs, which, while perhaps not as spectacular and pathbreaking as the classic inventions of the *"annus mirabilis,"* created a second wind that prevented the process from slowing down and petering out. These microinventions, which extended and consolidated earlier advances were possible because they could rely on an ever-widening epistemic base and much of its widening was the result of deliberate searches. The advances in epistemic bases seem modest when compared with what was to follow and hence have not been much noticed. Yet besides the great advances associated with Lavoisier and his followers, there were myriad advances in the physics of heat, the understanding of the location of mineral deposits, mechanics, electric current, hydraulics, and soil management.

Among the best-known breakthroughs in λ-knowledge of the 1820s are James Neilson's hot blast (1828), which sharply reduced fuel costs in blast furnaces, and the self-actor perfected by Richard Roberts in the late 1820s.[5] In energy production, the continuous improvement in high-pressure engine design and transmission in the 1820s, by a large team of engineers, led to George Stephenson's locomotive in 1828. Equally paradigmatic of this second wave was the work of Michel Eugène Chevreul, who discovered the nature of fatty acids and turned the manufacture of soap and candles from an art into a science. As director of dyeing at the *Manufacture des Gobelins,* he had a direct interest in the chemistry of dyes and colors. The original work on the chemistry of dyeing had been carried out by his predecessor at the *Gobelins*, Claude Berthollet, but his work had been cut short by his political activities (Keyser, 1990, p. 225), and it fell to Chevreul to realize his program.

We could say, then, that the process of innovation was gradually becoming "less Darwinian" in the sense that the mutations in useful knowledge were becoming less random and more directed. Many areas in Ω-knowledge that had previously been informal, artisanal, and thus limited as epistemic bases, were increasingly infused with the methods of science. To a large extent, this change was endogenous and a function of industrial needs. Yet oddly, much of the systematic expansion of Ω-knowledge was carried out in France and Germany, especially after the continent recovered from the social and political upheavals of the revolutionary

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[5] Neilson's breakthrough, which reduced the fuel consumption of blast furnaces by two-thirds, was inspired and informed by the courses in chemistry he took in Glasgow, where he learned of the work of the French chemist Gay-Lussac on the expansion of gases (Clow and Clow, 1952, p. 354).

period. After 1820, some of the important inventions were less the result of serendipity than of concentrated efforts by informed engineers, chemists, and machinists. Some of the ideas generated in this period, however, were not realized until after 1860, marking the beginning of the second Industrial Revolution.

The Second Industrial Revolution

It is part of accepted wisdom that the techniques that came into being after 1860 were the result of applied science, which had made enormous advances in the first two-thirds of the nineteenth century.[6] In some industries this is surely true: one can hardly imagine the advances in the chemical industry after 1860 without the advances in organic chemistry that followed von Liebig and Wöhler's work in the 1820s and 1830s. The industrial R&D lab, the greatest innovation of the time in the technology of generating technology, made its entrance in the 1860s in the German chemical industry.[7] Indeed, some techniques that emerged as a result of the new Ω-knowledge were instrumental in expanding useful knowledge even further. The two types of knowledge, propositional and prescriptive, kept reinforcing each other. The invention that may have heralded the second Industrial Revolution, William Perkin's aniline purple (or mauve) process in 1856, was largely a matter of good fortune, although it happened to a prepared mind. But it set in motion a process that brought industrial and academic chemists ever closer together, culminating in the discovery in 1869 of alizarin dyes (by the Germans Carl Graebe and Carl Liebermann). The pivotal breakthrough in the propositional knowledge set was the identification of the structure of the benzene molecule by the German chemist August von Kekulé in 1865, after which the search for synthetic dyes became simpler and faster. Benzene had been known for a few decades, so the discovery of the chemical structure is a paradigmatic example of a broadening of the epistemic base of an existing technique. The result was a continuous stream of innovations which, instead of slowing down as it might have a century earlier, gathered force to become a veritable torrent as chemists focused on the problem and gradually worked out the chemistry of synthetic dyes (Fox and Guagnini, 1999, p. 34). Yet as always there was more continuity than is often allowed for. Invention by trial and error,

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[6] Mowery and Rosenberg (1989, p. 22) maintain that if one had to choose any fifteen-year period on the basis of the density of scientific breakthroughs, it would be hard to beat the decade and a half after 1859.

[7] The first "research lab" is traditionally dated to 1868, when Heinrich Caro founded such a facility at BASF in Ludwigshafen.

luck, and instinct was not replaced entirely by a more complete understanding of the natural processes at work. Moreover, while the importance of the specialized sector of R&D in some industries was large, Fox and Guagnini rightly insist that the laboratory remained the tip of an iceberg, most of which was still rooted in practice, experience, and serendipity.

A full survey of the technological advances during the second Industrial Revolution is not possible here, but a few illustrative examples may help explain the subtle interplay between epistemic base and technique in this period.[8] Many of the arguments advanced here are illustrated by the history of the iron and steel industry in the nineteenth century. Gillispie's notion that "the metal industries were at first little changed by the development of a science of metallurgy—they simply began to be understood" (1957, p. 405) reflects the discovery, made in 1786, by three French academicians (Berthollet, Vandermonde, and Monge) that the difference between cast iron, wrought iron and steel was in the carbon content (J. R. Harris, 1998, pp. 214–20), yet did not immediately affect the practice of steelmaking. A "linear"model running from Ω to λ would be an in accurate description of these developments.

Perhaps the paradigmatic invention of the second Industrial Revolution, the Bessemer steelmaking process of 1856, was made by a man who by his own admission had "very limited knowledge of iron metallurgy."[9] Henry Bessemer's knowledge was so limited that the typical Bessemer blast, in his own words, was "a revelation to me, as I had in no way anticipated such results" (Carr and Taplin, 1962, p. 19). All the same, the growth of the epistemic base in the preceding half-century was pivotal to the development of the process. Bessemer knew enough chemistry to realize that his process had succeeded and similar experiments by others had failed because the pig iron he had used was, by accident, singularly free of phosphorus. By adding carbon at the right time, he would get the correct mixture of carbon and iron—that is, steel. He did not know enough, however, to come up with a technique that would rid the iron of phosphorus; the so-called basic process that solved this problem was discovered twenty years later.[10] Moreover, the epistemic base at the time was much larger than Bessemer's knowledge. This was demonstrated when an experienced metallurgist named Robert Mushet, showed that Bessemer

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[8] A more detailed survey can be found in Mokyr (1999), available in English on the website http://www.faculty.econ.northwestern.edu/faculty/mokyr/.

[9] This example is also used by Arora and Gambardella (1994).

[10] Bessemer's later life demonstrates the hazards of inventing with a narrow epistemic base. He lost a large amount of money in building the *Bessemer* steamship, which would have built-in stabilizers around its saloon to prevent seasickness, from which he suffered severely, and with which he became obsessed.

steel contained excess oxygen, a problem that could be remedied by adding a decarburizer consisting of a mixture of manganese, carbon, and iron. The Bessemer and related microinventions led, in the words of Donald Cardwell (1994, p. 292), to "the establishment of metallurgy as a study on the border of science and technology." In the years following Bessemer and Mushet's work, the Siemens Martin steelmaking process was perfected, and Henry Clifton Sorby discovered the changes in crystals in iron upon hardening and related the trace quantities of carbon and other constituents to the qualities and hardness of steel (Higham, 1963, p. 129).[11]

Energy utilization followed a comparable pattern. Engines in the sense we would recognize today—that is, devices that convert heat to work in a controlled way—had existed since the first Newcomen engines, but the physics underlying their operation and governing their efficiency was not properly understood. Good mechanical intuition coupled to a sound experimental method was, up to a point, a good substitute for formal science and helped James Watt to transform a crude and clumsy contraption into a universal source of industrial power. In the first decades of the nineteenth century Richard Trevithick, Arthur Woolf, and their followers created the more compact high-pressure engine, which a few decades later revolutionized transportation. But the epistemic base that could help analyze and explain the efficiency of such engines did not exist.[12] John Farey, the best expositor of the mechanical details of the steam engine, still regarded the steam engine in 1827 as a vapor-pressure engine rather than a heat engine. The same is true for one of the most influential treatises on steam, François Marie Pambour's 1837 *Théorie de la machine à vapeur,* which became a standard work and was translated into German and English. It was written for an audience of engineers and foremen, but it

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[11] Sorby's work is a classic example of the expansion of the epistemic base of existing technology: he discovered how the known properties of iron and steel were caused by the crystal structures of the metal which changed under high temperatures (C. S. Smith, 1960, pp. 181–84). Yet the economically most important advance in applied metallurgy after the breakthroughs of Bessemer and Siemens Martin around 1860 was the development of the Gilchrist-Thomas process in 1878 to remove phosphorus from the materials used to make Bessemer steel. Its inventor, Sidney Thomas, was an amateur chemist who was inspired by a course in chemistry at Birkbeck College, where he had heard a lecturer say that whoever eliminated phosphorus from the Bessemer process would make a fortune (Carr and Taplin, 1962, p. 98).

[12] An interesting example of an invention supported by a narrow epistemic base was the Stirling air engine, patented in 1816 by a Scottish clergyman, Robert Stirling. In principle the machine could be optimized thermodynamically, since it uses a closed regenerative cycle– though that principle was not fully grasped till the middle of the nineteenth century. The Stirling engine is still believed to be a piece of dormant useful knowledge that might be resuscitated under the right circumstances. See for instance http://www.sesusa.org/.

required considerable mathematical sophistication (Kroes, 1992).[13] Perhaps typical of the division of labor between Britain and France, the first enunciation of the principles at work here—efficiency was a function of the differences in temperature—was laid out by a French engineer, Sadi Carnot, in 1824, after he observed the differences in efficiency between a high-pressure Woolf engine and an older model.[14] The next big step was made by an Englishman, James P. Joule, who showed the conversion rates from work to heat and back.[15] Joule's work and that of Carnot were then reconciled by a German, R. J. E. Clausius (the discoverer of entropy), and by 1850 a new branch of science dubbed "thermodynamics" by William Thomson (later Lord Kelvin) had emerged (Cardwell, 1971, 1994).[16]

Yet this expansion of the epistemic base on which the practice of steam engines rested would have mattered little had it not led to applications in engineering. Old engines were made better and new ones were created. William Rankine, the author of *Manual of the Steam Engine* (1859), made thermodynamics accessible to engineers, and Scottish steam engines made good use of the Carnot principle that the efficiency of a steam engine depends on the temperature range over which the engine

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[13] As late as 1878, Robert Thurston could write of Pambour's book "The work is far too abstruse for the general reader, and is even difficult reading for many accomplished engineers. It is excellent beyond praise, however, as a treatise on the thermodynamics of heat engines" (1878, ch. VII).

[14] Sadi Carnot, *Reflexions sur la puissance motrice du feu* ([1824], 1986). In his introduction, Robert Fox points out that French technology was widely regarded to be behind British in all matters of power engineering, yet French engineering was distinctly more theoretical than British; and a flurry of interest in the theory of heat engines. It is interesting to note that Carnot's now famous book was wholly ignored in France and found its way second-hand and through translation into England, where there was considerably more interest in his work by the builders of gigantic steam engines such as William Fairbairn in Manchester and Robert Napier in Glasgow (Crosbie Smith, 1990, p. 329). Carnot's work was incomplete and initially contained little of help to engineers, but it was rediscovered by William Thomson (Lord Kelvin) in the 1840s.

[15] The ways in which the growth of practical knowledge can influence the emergence of propositional knowledge are well illustrated by Joule's career: he was a child of industrial Lancashire (his father owned a brewery) and in the words of one historian, "with his hard-headed upbringing in industrial Manchester, was unambiguously concerned with the *economic* efficiency of electromagnetic engines...he quite explicitly adopted the language and concerns of the economist and the engineer" (Morus, 1998, p. 187, emphasis in original). As Ziman remarks (1976, p. 26), the first law of thermodynamics could easily have been derived from Newton's dynamics by mathematicians such as Laplace or Lagrange, but it took the cost accountancy of engineers to bring it to light.

[16] Research combining experiment and theory in thermodynamics continued for many decades after that, especially in Scotland and in Mulhouse, France, where Gustave Adolphe Hirn, a textile manufacturer, led a group of scientists in tests on the steam engines in his factory and was able to demonstrate the law of conservation of energy.

operates.[17] Rankine developed a new relationship between science and technology (Channell, 1982, p. 42). He distinguished between three kinds of knowledge: purely scientific, purely practical, and the application of sound theory to good practice (Smith and Wise, 1989, p. 660).

Unlike the Baconian ideals promulgated two and a half centuries earlier, Rankine was describing, at least in some sectors, a growing reality in his days. His study of the effects of expansion led him to recommend applying steam-jacketing to heat the cylinder (a technique previously tried but abandoned). One of Rankine's students, John Elder, developed the two-cylinder compound marine engine in the 1850s, which sealed the eventual victory of steam over sailing ships. An odd curiosum in this context is the somewhat obscure pamphlet published in 1862 by Alphonse Beau de Rochas, which proved theoretically that the Carnot principles applied to all heat engines and that the most efficient system would be a four-stroke cycle. Not long thereafter, N. A. Otto started to work on an internal combustion gas engine and in 1876 filed a patent based on the same four-stroke principle. Yet apparently the two were independent events.[18]

A third example of the widening of the epistemic base of technology leading to the emergence and then continuous improvement of techniques is the telegraph. Many eighteenth-century scientists, such as the great French physicist Charles-Augustin de Coulomb, believed that magnetism and electricity were unrelated. But in 1819 a Danish physicist, Hans Oersted, brought a compass needle near a wire through which a current was passing. It forced the needle to point at a right angle to the current. Electricity and magnetism turned out to be related after all. Electromagnetism, once discovered, was turned into a legitimate field of inquiry by the work of William Sturgeon, Michael Faraday, and above all Joseph Henry. Their work in turn created the epistemic base for the work of Wheatstone, Cooke's partner, as well as that of Samuel Morse. The first successful submarine cable was laid by Thomas Crampton's Company between Dover and Calais in 1851, a technological triumph that lasted thirty-seven years. The idea of using electrical current on a magnetized needle to transmit information at a speed much faster than anything previously possible was a classic macroinvention. Contemporaries praised

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[17] Rankine did more than anyone in his time to bridge the gap between science and engineering by writing four textbooks that made the findings of the new science available to engineers. His *Manual of Applied Mechanics* went through twenty-one editions between 1858 and 1921, and the *Manual of the Steam Engine* through seventeen editions between 1859 and 1908 (Cardwell, 1994, pp. 335, 529).

[18] Otto vehemently denied having any knowledge of Beau de Rochas's work, and given its limited diffusion, most scholars find that claim plausible (L. Bryant, 1967, p. 656).

the new invention as "this subjugation of nature and conversion of her powers to the use and will of man actually do, as Lord Bacon predicted it would, a thousand times more than what all the preternatural powers which men have dreamt of" (cited by Morus, 1998, p. 194).

The long-distance telegraph, however, required many subsequent microinventions. Submarine cables were a difficult technology to master. Signals were often weak and slow, and the messages distorted. Worse, cables were subject at first to intolerable wear and tear.[19] The techniques of insulating and armoring the cables properly had to be perfected, and the problem of capacitance (increasing distortion on long-distance cables) had to be overcome. Before the telegraph could become truly functional, the physics of transmission of electric impulses had to be understood. Again, the technique started off with a fairly narrow epistemic base, but the obvious economic and political importance of the invention placed the underlying Ω-knowledge on the agenda. Developments in the techniques and the knowledge underlying it proceeded cheek by jowl. Physicists, and above all Kelvin, made fundamental contributions to the technology. Kelvin's was a classic example of a hybrid career, in which technology shaped science as much as it was supported by it (Kranakis, 1992; Smith and Wise, 1989). He worked out the principles governing the relation between the signal and the resistance, inductive capacity, and length, and computed the resistivity of copper and the inductive capacity of gutta-percha, the insulating material. He also invented a special galvanometer, a siphon recorder (which automatically registered signals), and a technique of sending short reverse pulses immediately following the main pulse, to sharpen the signal (Wise, 1988; Headrick, 1989, pp. 215–18). These inventions were directly based on best-practice mathematical physics, and although the epistemic base was far from complete (Kelvin resisted Maxwell's electromagnetics and held on to the notion of ether believed to be the weightless medium for the transmission of electromagnetic waves), his contributions to submarine telegraphy and magnetic instruments were crucial (Smith and Wise, 1989, esp. chs. 19 and 22). In this close collaboration between science and technology, telegraphy was clearly a second-generation technology, in that wider epistemic bases made the process of

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[19] Of the 17,700 kilometers of cable laid before 1861, only 4,800 kilometers were operational in that year—the rest were lost. The transatlantic cable, through which Queen Victoria and President James Buchanan famously exchanged messages in August 1858, ceased to work three months later. It was this failure that stimulated Kelvin to take up the problem of telegraphy, a good example of feedback from technology into the growth of Ω-knowledge.

invention faster and more efficient than trial-and-error methods.[20] Another example of a hybrid career was that of the physicist Hermann von Helmholtz, the inventor of the ophthalmoscope in 1851. Helmholtz possessed the necessary knowledge of both physics and physiology to complete this invention.

It would be a mistake to suppose that all new technology during the second Industrial Revolution required or could rest on broad epistemic bases. The complex relationship between propositional and prescriptive knowledge is illustrated by the profound difference between two pathbreaking inventions of the period: aspirin (discovered in 1897) and electric generators (perfected between 1865 and 1880). Aspirin had a very narrow epistemic base. In 1763 a British clergyman, the Rev. Edmund Stone, drew attention to willow bark, which, he thought, would serve as a remedy against ague (malaria) because willows grew in damp places and God planted cures where diseases originated (Porter, 1997, p. 270). Not much was done with this "insight" until the 1820s, when chemists became once again interested in it. It was recognized that the active ingredient was salicin, and in 1835 Karl Löwig isolated salicylic acid. Although the chemical structure of these substances was known, they had little medical value because of severe side effects. These were eliminated when Felix Hoffman stumbled on the acetyl compound of salicylic acid, later known as aspirin, which was a true wonder drug: effective, without serious negative side effects, and cheap to produce. His employer, Bayer, hit the jackpot. Yet no one knew how and why aspirin did what it did. It was not until the 1970s that aspirin's physiological *modus operandi* became more evident. With this extension of the epistemic base of an existing technique, further adaptations were possible.[21] The epistemic base became wider, thus reducing the number of experiments and making the search a little bit more efficient. There was still a very long way to go. Paul Ehrlich's Salvarsan drug, which provided an effective treatment for syphilis (1910), was known as "Ehrlich's 606" in view of the fact that 605 earlier compounds had been tried and discarded. The same empirical and pragmatic methodology was followed even for the most epochal invention of the early twentieth century, Fritz Haber's ammonia-fixing process: despite a rapid widening

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[20] After the success of the transatlantic cable in 1866, Kelvin pointed out that "abstract science has tended very much to accelerate the results, and to give the world the benefits of those results earlier than it could have had them if left...to try for them by repeated efforts and repeated failures" (cited by Smith and Wise, 1989, p. 683).

[21] The pathbreaking work was carried out by John Vane, Bengt Samuelsson, and Sune Bergström, who showed how aspirin inhibited the formation of prostaglandins. Following this insight, other analgesics and anti-inflammatory drugs such as acetaminophen and ibuprofen were developed (see Landau, Achilladelis, and Scriabine, 1999, pp. 246–51).

of the epistemic base, too little was known about the underlying atomic structures of catalysts to design the optimal ones from first principles. Alwin Mittasch's laboratory at BASF had by 1922 tried no fewer than 4,000 different substances as catalysts (Smil, 2001, p. 96).

The refinement of electricity generation, on the other hand, could not make much commercial progress before some of the principles had been worked out. Faraday's narrow-based discovery of the dynamo demonstrated the possibility of generating electricity by mechanical means in 1831.[22] The technical problem with which engineers struggled for decades was the generation of electricity in quantities and at prices that would make it economically viable. Until then, despite the hopes of contemporaries and the claims of some historians (Morus, 1998, p. 192) regarding the commodification of electricity, the uses of electricity were limited to electroplating and the telegraph. The various experimental designs showed what electricity *could* do, but neither the electromagnetic engines built by, among others, Joseph Henry, nor the electric arc lights used in 1849 to illuminate performances and Trafalgar Square were long-term successes. The epistemic base for the techniques that would materialize the hopes of electricity as a source of light or a replacement for steam simply was not there.[23] The epistemic base on which advances in electricity rested came in part from the industry itself and from practical engineering, rather than from theoretical natural science (König, 1996).

The pioneers of the telegraph, Cooke and Wheatstone, patented the magneto in 1845. Joule had shown a few years earlier that the magneto converts mechanical energy into electricity (and not, as was believed until then, magnetism into electricity). The crucial implication of this insight was that the huge amount of mechanical power that the steam engines could create by that time was convertible into electrical energy.[24] Although not all the underlying physics had been worked out by 1865, Joule's work suggested how it could be done. A full generation after Faraday, the discovery of the principle of self-excitation in 1866–67 led to the construction of large generators in the early 1870s and eventually to the

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[22] The first working dynamo was constructed a year later by Hippolyte Pixii in Paris. Faraday himself oddly lost interest in the mechanical production of electricity soon thereafter.

[23] The physicist James Joule, who made seminal contributions to the underlying theory of energy, eventually lost his faith in the ability of electricity to fulfill its promise (Morus, 1998, p. 190).

[24] Oddly, few physicists understood what Joule argued or took the trouble to try, given that he was a professional brewer and an amateur scientist. Fortunately, young William Thomson was one of the few who realized its importance; he collaborated with Joule for many years.

electrical revolution.[25] Electrical technology, much like organic chemistry, represents a new kind of λ-knowledge that emerged in the nineteenth century, and in which the minimum epistemic base is much larger than ever before. Edison, no scientist himself, employed Francis Upton, a mathematical physicist, and Hermann Claudius, who had a Ph.D. in electrical engineering. Yet the *exact* physical processes that underlie the generation of electrical power were not really understood until much later.[26]

For human nutrition, the most important discoveries were in the area of soil nutrients. Since the early days of agriculture, fertilizing fields and recycling plants had been known to improve yields. Fertilization was practiced in ancient Greece and Rome and was widely diffused throughout China. Nitrogen-fixing plants have been grown in all farming cultures since antiquity. The problem was that these practices rested on a very narrow epistemic base, and as a consequence many agricultural techniques were inefficient in restoring the minerals needed for plant growth. Thus the practice of burning straw and stalks, widely employed among traditional farmers, instead of returning the nitrogen into the earth, releases most of it back in the atmosphere where it is lost to the farmers (Smil, 2001, p. 24).

The period of the second Industrial Revolution, roughly speaking, is when the riddles of soil chemistry were resolved: nitrogen was identified in the 1830s as one of the crucial ingredients, and von Liebig formulated his famous law of minimum: plant growth is constrained by the scarcest mineral relative to the needs. It was understood at about the same time that legumes, not the atmosphere, were the source of soil nitrogen. Only in the 1880s, however, was the importance of nitrogen-fixing bacteria in the process understood and the need to find a process to acquire nitrogen fertilizer fully realized. Obviously, the traditional techniques had worked reasonably well for millennia despite their very narrow epistemic base, but they did not lend themselves to expansion and improvement until more was known about how and why they worked.[27] This epistemic base is still

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[25] The self-excited electric generator was a case of simultaneous, independent invention by Werner von Siemens, Charles Wheatstone, C. F. Varley, and others. The first working generators were constructed in the early 1870s by Z. W. Gramme.

[26] The epistemic base of the Voltaic cell remained untight, as scientists were divided between chemical and anti-chemical ("contact") theories of what made the battery work (Kragh, 2000). Nelson and Rosenberg point out that Edison observed the flow of current across a gap between the hot filament and the wire in his lamp, without of course realizing that he was observing the motion of electrons—the existence of which was to be postulated twenty years later (1993, pp. 7–8).

[27] There were also serious costs associated with traditional methods of nitrogen fixing and preservation: the use of manure and nightsoil as fertilizer led to serious incidence of parasitic diseases, and some of the pulses grown to replace nitrogen were low-yielding and required extensive preparation and cooking before they could be eaten (Smil, 2001, pp. 36–37).

growing, and genetic engineers may soon develop modified bacteria that have been "trained" by manipulation of their DNA to fix nitrogen in plants other than pulses.

A similarly ambiguous process applies to the technology of surgery, which underwent two quantum leaps in the mid-nineteenth century: the application of anesthesia in the late 1840s, and the sterilization of surgical tools after 1865. The sterilization of surgical instruments, one of the simplest and cheapest life-saving ideas in history, failed at least twice to convince the medical world. It is usually attributed to Oliver Wendell Holmes (father of the Justice) and Ignaz Semmelweis in the 1840s, and the idea was suppressed until revived two decades later by Joseph Lister. Yet the idea went back to the eighteenth century.[28] The discovery that physicians caused puerperal fever in women by conducting autopsies and then, without washing their hands, performed obstetric examinations, was made in 1843 by Holmes and a few years later by Semmelweis and yet ran into so much determined opposition that Holmes dropped the idea and Semmelweis was chased out of Vienna in disgrace. It is usually argued that the resistance to this idea came from physicians unwilling to admit that they themselves transmitted disease. Part of the problem, however, was that Holmes and Semmelweis had no idea *why* these sanitary techniques worked. It seems clear that the difference between Holmes's and Semmelweis's failures and Lister's eventual success was that by the 1860s the epistemic base of the technique was wider: people understood how and why surgeons and obstetricians infected their patients.[29] Although Lister's findings were not immediately accepted either (especially in the United States), by the late 1870s his recommendations had become standard techniques. The tale of asepsis is a perfect illustration of the importance of the tightness of an epistemic base for a new technique to overcome the initial skepticism and resistance. The experimental and statistical techniques in the 1870s and 1880s had changed, and the rhetorical power of scientists to convince one another and eventually others was becoming more effective.

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[28] Alexander Gordon, a Scottish physician, had noted as early 1795 that puerperal fever might be connected to contaminated matter transmitted by physicians or midwives, and recommended the cleansing of hands. Holmes's 1843 paper cited Gordon's work.

[29] The story of Lister's discovery is well known: he heard of Pasteur's discovery by chance and was, in fact, not the first English doctor to note its significance. Pasteur's papers were read by a professor of chemistry, Thomas Anderson, a colleague of Lister's in Glasgow who brought them to his attention. He immediately realized that Pasteur's work provided a theoretical justification for his belief that treatment with carbolic acid reduced the chances of infection (Nuland, 1988, pp. 363–64). Lister's own techniques became quickly obsolete when antiseptic methods were replaced by asepsis, boiling and autoclaving instruments before their use. Yet these further improvements were made possible precisely because the epistemic base, by then, was wide enough.

The implications of this particular addition to knowledge were huge: doctors no longer needed to follow Apollinaire Bouchardat's (1806-86) advice and wait several days between assisting one maternity patient and another—it was enough to wash one's hands in carbolic lotion (Latour, 1988, p. 48). The understanding of germs and contagion brought about a change in the architecture of hospitals: instead of having one big ward, patients with contagious diseases were placed in smaller areas linked to the public wards but completely isolated from them (Goubert, 1989, p. 133). Maternity patients were given their own area surrounded by an antiseptic cordon. The risk of mothers dying at childbirth or during confinement did not decline appreciably in England during the second half of the nineteenth century. On the other hand, there was a marked decline in maternal mortality in hospitals over the same period (Loudon, 1986). The increasing gap between maternal mortality in hospitals versus rural homes (where help during labor was given by "ignorant midwives") illustrates how important it is to distinguish between health practices in different populations and households. The discovery of germs may have enhanced the survival rates of women who went to hospitals, but it took another thirty years for all English women to reap the benefits.

Where did the new knowledge that drove economic growth after 1850 come from? In a their pioneering study, Fox and Guagnini (1999) emphasize that in the second half of the nineteenth century engineers in many areas began to engage in "research and development" (the term is slightly anachronistic for the nineteenth century) that was less experimental and more directed. Many advances were made simply because the limitations of the narrow epistemic bases of old technologies were shed and inventors increasingly had access to the propositional knowledge they needed. To be sure, many techniques still rested on very narrow epistemic bases. But in industry after industry, the knowledge base expanded, streamlining and accelerating the rate of technological progress. To return to the question posed in the previous chapters: why did this growth accelerate and accumulate rather than slow down and then fade out to settle in a new and somewhat higher state?

The answer is that the co-evolution of Ω- and λ-knowledge by this time had settled on a different dynamic, one that eventually led to a fundamental instability of the set of useful knowledge. These changes cannot be timed precisely, and they differed from industry to industry, but they spread slowly throughout the West, and by the beginning of the twentieth century they had covered most of the areas of the economy: agriculture, transport, mineral extraction, medicine, and manufacturing.

As in the earlier period, the interaction between propositional and prescriptive knowledge took place in both directions. New (and sometimes old) propositional knowledge increasingly mapped into new techniques. This mapping should not be confused with the linear models of science and technology, popular in the mid-twentieth century, which depicted a neat flow from theory to applied science to engineering and from there to technology. Much of the propositional knowledge that led to invention was pragmatic, informal, and empirical, but eventually it became increasingly formal and consensual, what we think today of as "science." The other direction in which useful knowledge moved, back from λ to Ω, provided the positive feedback between the two types of knowledge and led to continuous mutual reinforcement. This positive feedback mechanism took a variety of forms. One is the trivial observation that once a technique is known to work this knowledge itself is added to the catalog of known natural regularities in Ω and then can be further expanded, adapted, and combined into additional elements in λ. In and by itself, such a process is not likely to lead to sustained technological change.

Another feedback mechanism is the idea of technology as a "focusing device," in which technology simply posed well-defined problems to engineers and scientists and focused their attention on some areas that turned out to be fruitful for further mapping.[30] The classic examples of this type of feedback from prescriptive to propositional knowledge are the already-noted emergence of thermodynamics as an endogenous response to theoretical problems posed by the operation of the steam engine and the work on electricity stimulated by the problems of long-distance telegraphy.[31]

A less well known example of this feedback mechanism, but equally important to economic welfare, is the interaction between the techniques of food-canning and the evolution of bacteriology. The canning of food was invented in 1795, right in the middle of the Industrial Revolution, by a French confectioner named Nicolas Appert. He discovered that when he placed food in champagne bottles, corked them loosely, immersed them in boiling water, and then hammered the corks tight, the food was preserved for extended periods. Neither Appert nor his English emulators who perfected the preservation of food in tin-plated canisters in 1810 knew why and how this technique worked, because the definitive demonstration of the notion that microorganisms were responsible for putrefaction of food was still in the future. It is therefore a typical example of a technique with

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[30] See especially Rosenberg (1982). At times, of course, engineering knowledge develops within the practice itself, and the practitioners who have gained knowledge from experience enrich those who try to enlarge the epistemic base by recounting what works "on the ground." For an interesting example of such a reverse flow of knowledge, see König (1996).

[31] Norton Wise (1988) rephrases Rosenberg's idea by formulating the concept of "mediating machines." The steam engine and the telegraph in different ways helped Kelvin to formulate his research program in investigating thermodynamics and electromagnetic theory.

a narrow epistemic base. The canning of food led to a prolonged scientific debate about what caused food to spoil. In 1864, Frederick Crace Calvert, in a set of lectures given before the Society of Arts in London, maintained that the true sources of putrefaction were "sporules or germs of cryptogamic plants or animals," using for his experiments cans of preserved food lent to him by Fortnum & Mason (Thorne, 1986, p. 142). The debate was not put to rest until Pasteur's work in the early 1860s. Pasteur knew of Appert's work, and eventually admitted that his work on the preservation of wine was only a new application of Appert's method. Be that as it may, his work on the impossibility of spontaneous generation clearly settled the question of why the technique worked. Only in the 1890s was it demonstrated that air was not the critical factor, because some bacteria did not need it. The epistemic base of food canning became wider, and with it, techniques improved: the optimal temperatures for the preservation of various foods with minimal damage to flavor and texture were worked out by two MIT scientists, Samuel Prescott and William Underwood.[32] The entire story demonstrates neatly how propositional and prescriptive knowledge can enrich each other.

The other channel through which the feedback from λ-knowledge to Ω-knowledge worked, was experimentation: instruments and laboratory equipment and techniques (Dyson, 1997, pp. 49–50; Price, 1984a,b). Our senses limit us to a fairly narrow slice of the universe that has been called a "mesocosm": we cannot see things that are too far away, too small, or not in the visible light spectrum (Wuketits, 1990, pp. 92, 105). The same is true for our other senses, for the ability to make very accurate measurements, for overcoming optical and other sensory illusions, and the computational ability of our brains. Technology consists in part in helping us overcome these limitations that evolution has placed on us and learn of natural phenomena we were not meant to see or hear—what Price (1984a) has called "artificial revelation."[33]

Much of the progress in Ω occurs through the agency of new research techniques, themselves often relatively minor advances in λ, such as the improvements in lens grinding in the late sixteenth century that led to the telescope, or the development of in vitro culture of micro-organisms (the Petri dish was invented in 1887 by R. J. Petri, an assistant of Koch's). Price

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[32] A University of Wisconsin scientist, H. L. Russell, proposed to increase the temperature of processing peas from 232° to 242°, thus reducing the percentage spoiled can from 5 percent to 0.07 percent (Thorne, 1986, p. 145).

[33] Derek Price notes that Galileo's discovery of the moons of Jupiter was the first time in history that somebody made a discovery that had been totally unavailable to others by a process that did not involve a deep and clever thought (1984b, p. 54).

feels that such advances in knowledge are "adventitious"(1984a, p. 112). Indeed, the widespread use of glass in lenses and instruments in the West was itself something coincidental, a "giant accident," possibly a by-product of demand for wine and different construction technology (Macfarlane and Martin, 2002). It seems plausible that without access to this rather unique material, the development of propositional knowledge in the West would have taken a different course.

Something similar holds for precision clocks, which have often been held to be central to the measurement of natural phenomena. Improved observation and measurement reveals new natural phenomena. Once these phenomena are known, we can manipulate them further, and so on. The notion of atmospheric pressure would have been difficult to verify without the invention of the barometer by Torricelli in 1643 and that of the air pump by Guericke in 1650. In this way the positive feedback loops from tools to knowledge and back led to the development of steam power. Travis (1989) has documented in detail the connection between the tools developed in the organic chemical industry and advances in cell biology. These connections between prescriptive and propositional knowledge are just a few examples of advances in scientific techniques that can be seen as adaptations of ideas originally meant to serve an entirely different purpose, and they reinforce the contingent and accidental nature of much technological progress (Rosenberg, 1994, pp. 251–52). This dynamic is reminiscent of the biological notion of "exaptation," the development of uses for a trait that are quite different from the original function that favored selection for this trait (Gould and Vrba, 1982).

During the Industrial Revolution itself, many examples of artificial revelation can be cited. One is the work of instrument makers, the best one of whom was Jesse Ramsden (1735–1800), who devised new precision instruments including a variety of theodolites, pyrometers (to measure the expansion of gases), improved telescopes, and a dividing machine for mathematical scales of unprecedented accuracy. Interestingly enough, the largest impact of this work was on geography, culminating in the Great Theodolite constructed by Ramsden that was instrumental in the Ordnance Survey of Great Britain. Geodesical instruments thus improved rapidly (the French scientist Jean-Charles Borda designed a competing instrument in about 1784) and the accuracy in mapping (essential to safe and efficient shipping, surveying, and military applications) improved dramatically in the 1780s. Another example of how λ-knowledge fed back into Ω-knowledge was in chemistry. Lavoisier and his circle designed and used better laboratory equipment that allowed them to carry out more sophisticated experiments.[34] Alessandro Volta invented a pile of alternating silver and zinc disks that could generate an electric current in 1800. Volta's battery was soon produced in industrial quantities by William Cruickshank. Through the new tool of electrolysis, pioneered by Humphry Davy, chemists were able to isolate element after element and fill in much of the detail in the maps whose rough contours had been sketched by Lavoisier and Dalton. Volta's pile, as Davy put it, acted as an "alarm bell to experimenters in every part of Europe" (cited by Brock, 1992, p. 147).

Or consider the interaction between geology and coal mining. In the mid-eighteenth century coal prospecting and exploring had still been an unsystematic activity, resting on an epistemic base that could best be described as folkloristic (Flinn, 1984, p. 70). Yet the need to develop a better method to prospect for coal inspired William Smith toward a growing understanding of geology and the ability to identify and describe strata on the basis of the fossils found in them. The idea (already widely diffused on the continent but unknown to Smith) that there were strong natural regularies in the way geological strata were layered led to the first geological maps, including Smith's celebrated Geologic Map of England and Wales with Part of Scotland (1815), the "map that changed the world" (Winchester, 2001), which increased the epistemic base on which mining and prospecting for coal rested.[35] We can track with precision where and through which institutions this interaction between propositional and prescriptive knowledge took place and the institutional environment that made them possible.[36] Although the marriage between geology and mining took a long time to yield results, the widening epistemic base in mining technology surely was the reason that the many warnings that Britain was exhausting its coal supplies turned out to be false alarms.

The invention of the modern compound microscope by Joseph J. Lister (father of the famous surgeon) in 1830 serves as another good example. Lister was an amateur optician, whose revolutionary method of grinding lenses greatly improved image resolution by eliminating spherical aber-

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[34] The famous mathematician Pierre-Simon de Laplace was also a skilled designer of equipment and helped to build the calorimeter that resulted in the celebrated "Memoir on Heat" jointly written by Laplace and Lavoisier (in 1783), in which respiration was identified as analogous to burning. Much of the late eighteenth-century chemical revolution was made possible by new instruments such as Volta's eudiometer, a glass container with two electrodes intended to measure the content of air, used by Cavendish to show the nature of water as a compound.

[35] Davis notes that the "laws of stratigraphy as established by Smith had a universal application and his methods in this science are practiced today by coal and oil field geologists" (1942–43, p. 93).

[36] More often than not, these institutions were provincial specialized societies such as the Newcastle Literary and Philosophical Society (founded in 1793), dedicated to mining technology and geology (its name notwithstanding) (see Porter, 1973).

rations.[37] His invention changed microscopy from an amusing diversion to a serious scientific endeavor and eventually allowed Pasteur, Koch, and their disciples to refute spontaneous generation and to establish the germ theory, a topic I return to below. The germ theory was one of the most revolutionary changes in useful knowledge in human history and mapped into a large number of new techniques in medicine, both preventive and clinical. The speed and intensity of this interaction took place was still slow, but it was accelerating, and by the close of the eighteenth century it had become self-sustaining. In our time, new instrumentation has been an underestimated and unsung hero of advances in useful knowledge (Rosenberg, 1994).

A third way in which technology "fed back" into propositional knowledge was through the rhetoric of technology: techniques are not "true" or "false." Either they work or they do not, and thus they confirm or refute the propositional knowledge that serves as their epistemic base. Ω-knowledge has varying degrees of tightness, depending on the degree to which the available evidence squares with the rhetorical conventions for acceptance. Laboratory technology transforms conjecture and hypothesis into an accepted fact, ready to go into textbooks and to be utilized by engineers, physicians, or farmers. But a piece of propositional knowledge can be also be tested simply by verifying that the techniques based on it actually work. Wedgwood felt that his experiments in the pottery actually tested the theories of his friend Joseph Priestley, and professional chemists, including Lavoisier, asked him for advice. During the nineteenth century, the general confidence in the Ω-knowledge generated was reinforced by the undeniable fact that the techniques based on it worked. Thus, once biologists discovered that insects could be the vectors of pathogenic microparasites, insect-fighting techniques gained wide acceptance. The success of these techniques in eradicating yellow fever and malaria was the best confirmation of the hypotheses about the transmission mechanisms of the disease and helped earn them wide support.

Had it not been for the cascading interaction between Ω-knowledge and λ-knowledge, the finiteness of the epistemic base would at some point have imposed a binding constraint on the expansion of the book of blueprints, as it had done in the past. Without a widening epistemic base, the continuous development of techniques will eventually run into diminishing returns simply because the natural phenomena can be understood

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[37] The invention was based on a mathematical optimization for combining lenses to minimize spherical aberration and reduced average image distortion by a huge proportion, from 19 to 3 percent. Lister is reputed to have been the first human being ever to see a red blood cell.

only partially, and arguably only superficially. It is, of course, not easy to say precisely where the point of diminishing returns occurs. Complicating matters is that even when techniques rest on a fixed epistemic base, they can be recombined into compound techniques, and thus technological creativity can continue expanding even when the epistemic base was fixed—provided potential inventors have sufficiently inexpensive access to the catalog of techniques in use. All the same, if the epistemic base does not expand, technological progress will eventually slow down. Once the Ω and λ sets are subject to sufficient positive feedback, however, there is no way to predict the economic system's dynamics, and it may well diverge from its original state forever.[38]

That growing access to a common knowledge base was a catalyst in technological progress in the second Industrial Revolution cannot be proven rigorously, but a fair amount of historical evidence can be amassed to support it. An example is the simultaneity of many major inventions. The more a new technique depends on an epistemic base that is in the common domain and accessible to many inventors at low cost, the more likely it is that more than one inventor will hit upon it at about the same time. As useful knowledge became increasingly accessible and universal, it is hardly surprising that many of the inventions of the period were made independently by multiple inventors who beat one another to the patent office door sometimes by a matter of days.[39] Some scholars have suggested that the second Industrial Revolution rested as much on industry-based science as on the more common concept of science-based industry, implying feedback from λ to Ω (König, 1996).

As already noted, the *kind* of knowledge that was admissible as the basis for techniques and the mechanisms by which propositional knowledge could be verified and tightened also changed after 1830. An important element of the second Industrial Revolution was the growing recognition and admissibility of statistical evidence to establish natural regularities. Although the use of statistics has eighteenth-century origins, the growing legitimacy of statistical data as a source of useful knowledge

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[38] As evolutionary theorists such as Geerat Vermeij (1994) and system analysts such as Stuart Kauffman (1995) have pointed out, dual systems that interact in such a way can reach a critical point, at which they become dynamically unstable and start to diverge from an equilibrium.

[39] The phenomenon of independent simultaneous invention has often been interpreted as supporting the effect of demand conditions on the search for innovation, but obviously the ability of inventors to draw on similar bases in propositional knowledge provides a complementary explanation. Thus Frank Whittle developed the original jet engine based on knowledge of aerodynamics principles and new material science (which mapped into the making of alloys capable of withstanding very high temperatures). In parallel to the British team, Germans such as Hans von Ohain and Max Hahn came up with more or less the same mapping from the same body of knowledge. See Merton (1961) for a survey of the duplication-of-invention literature.

can be traced back to the work of Adolphe Quetelet, Edwin Chadwick, William Farr, Villermé, and their colleagues in the 1820s and 1830s.[40] After 1815 statistics flourished, statistical societies were founded everywhere, and governments all over the West started to collect more or less orderly statistical censuses and other types of data. This kind of empirical methodology led to important breakthroughs in clinical medicine, such as the doubts regarding the efficacy of bloodletting therapy spearheaded by the statistical research of C. A. Louis and the discoveries that cholera and typhus are transmitted through water (Lilienfeld, 1978; La Berge, 1992). Statistical evidence ("data") was a new investigative tool that made persuasion possible even if the underlying mechanisms were poorly understood. Natural regularities could be "tightened" by showing that they occurred in the majority of cases, even if there were unexplained outliers and the knowledge was "shallow" in the sense that the mechanisms accounting for the regularities were unknown. This approach led to an expansion of the epistemic base of public health. Villermé, Chadwick, and others showed that poverty was associated with higher morbidity and mortality (Hodgkinson, 1968; Mokyr, 1996). From there it was a natural step to techniques that prevented diseases from breaking out and reduced mortality long before effective cures had been found. Statistics was also used in the study of agriculture and the determinants of productivity, most famously at John Bennet Lawes's experimental farm at Rothamsted.

Beyond that, again, was the further level of interaction and feedback between human knowledge and the institutional environment in which it operates. Had institutional feedback been negative, as it had been before 1750, technological progress would have been short-lived. The economies that were most successful in the second Industrial Revolution were those in which the connections were the most efficient. The institutions that created these bridges are well understood: universities, polytechnic schools, publicly funded research institutes, museums, agricultural research stations, research departments in large financial institutions. Improved access to useful knowledge took many forms: cheap and widely diffused publications disseminated it. Technical subjects penetrated school curricula in every country in the West (although Britain, the leader in the first Industrial Revolution, lost its momentum in the last decades of the Victorian era). All over the Western world, textbooks, professional journals, technical encyclopedias, and engineering manuals appeared in every field and made it easier to "look things up." The professionalization of experts meant that anyone who needed some piece of useful knowledge could find someone

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[40] For some insights in the emergence of the statistical method in post-1830 Europe, see especially Porter (1986) and Cullen (1975).

who knew, or who knew who knew. The learned journal first appeared in the 1660s and by the late eighteenth century had become one of the main vehicles by which Ω-knowledge became accessible, if perhaps through the intermediation of experts who could decode the jargon. Review articles that summarized and abstracted the learned papers began appearing, an obvious example of an access-cost reduction.

The driving force behind progress was not just that more was known, but also that institutions and culture collaborated to create better and cheaper access to the knowledge base. Technology in the nineteenth century co-evolved with the new institutions of industrial capitalism. Institutional evolution in many ways followed its own dynamic. For instance, the repeal of the Bubble Act in 1825 was in large part the result of a power struggle between parties that believed they stood to gain from it (Harris, 2000). The creation of modern management ran into endless difficulties as documented in the late Sidney Pollard's still unsurpassed classic (Pollard, 1965). Yet on balance the feedback from technology to institutions was positive. Rent-seeking and unproductive behavior never disappeared in any human society, but in the years after 1815 in the West they were more and more subjugated by a free-market liberal ideology that provided incentives for entrepreneurial behavior which enhanced efficiency and productivity on a wide front. It is characteristic of competitive industrial capitalism as it emerged in those decades to spend effort and resources on microinventions and to make the new useful knowledge work (Baumol, 2002).

The co-evolution of technological knowledge and institutions during the second Industrial Revolution has been noticed before. Nelson (1994) has pointed to a classic example, namely the growth of the large American business corporation in the closing decades of the nineteenth century, which evolved jointly with the high-throughput technology of mass production and continuous flow. In their pathbreaking book, Fox and Guagnini (1999) have pointed to the growth of practically-minded research laboratories in academic communities, which increasingly cooperated and interacted successfully with industrial establishments to create an ever-growing stream of technological adaptations and microinventions. Many other examples can be cited, such as the miraculous expansion of the British capital market which emerged jointly with the capital-hungry early railroads and the changes in municipal management resulting from the growing realization of the impact of sanitation on public health (Cain and Rotella, 2001). But co-evolution did not always quickly produce the desired results. British engineering found it difficult to train engineers using best-practice Ω- knowledge, and the connections between science and engineering remained looser and weaker than elsewhere. In 1870 a panel appointed by the Institute of Civil Engineers concluded that "the education of an Engineer is effected by...a simple course of apprenticeship to a practicing engineer...it is not the custom in England to consider *theoretical* knowledge as absolutely essential" (cited by Buchanan, 1985, p. 225). A few individuals, above all William Rankine at Glasgow, argued forcefully for more bridges between theory and practice, but significantly he dropped his membership in the Institute of Civil Engineers. Only in the late nineteenth century did engineering become a respected discipline in British universities.

Elsewhere in Europe, the emergence of universities and technical colleges that combined research and teaching, thus simultaneously increasing the size of Ω and reducing access costs, advanced rapidly. An especially good and persuasive example is provided by Murmann (1998), who describes the co-evolution of technology and institutions in the chemical industry in imperial Germany, where the new technology of dyes, explosives, and fertilizers emerged in constant interaction with the growth of research and development facilities, institutes of higher education, and large industrial corporations with a knack for industrial research.[41] Institutions, then, remained a major determinant of access costs. To understand the mapping from Ω to λ, we need to ask who talked to whom and who read what. Yet the German example illustrates that progress in this area was halting and complex; it needs to be treated with caution as a causal factor in explaining systematic differences between nations. The famed *technische Hochschulen,* the German equivalent of the French *polytechniques,* had lower social prestige than the universities and were not allowed to award engineering diplomas and doctorates till 1899. The same is true for the practical, technically oriented *Realschulen* which had lower standing than the more classically inclined *Gymnasien.* Universities conducted a great deal of research, but it goes too far to state that what they did was a *deliberate* application of science to business problems. James (1990, p. 111) argues that Germany's "staggering supremacy" was not due to scientists looking for applicable results but came about "because her scientists experimented widely without any end in mind and then discovered that they could apply their new information." This seems a little overstated, but all the same we should be cautious in attributing too much intent and directionality in the growth of Ω-knowledge. Much of it was in part random, and it was the selection process that gave it its technological significance. In that respect, the evolutionary nature of the growth in useful knowledge is reaffirmed.

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[41] Most famous, perhaps, was the aforementioned invention of alizarin in 1869, a result of the collaboration between the research director at BASF, Caro, with the two academics Graebe and Liebermann.

A Third Industrial Revolution?

The half-century or so that followed the beginning of World War I is odd in at least three respects. First, it was a period of major political and economic upheavals that affected growth and productivity in many of the leading industrial countries, although in different ways. Second, as DeLong (2000) has recently reminded us, notwithstanding these disruptions, the twentieth century was a period of unprecedented growth. Third, much of this growth was technological in origin, yet true macroinventions were scarce in the period between 1914 and 1950 in comparison with the preceding decades. While science and useful knowledge in general kept expanding at an exponential pace, this era actually produced few radical new departures. Instead, a continuous flow of microinventions was the driving force behind much of the economic growth in the period 1914–73. The striking phenomenon here is that it took a very long time for these microinventions to start running into diminishing returns, and their effects on the productivity and thus on the standard of living were pervasive and ubiquitous. The main cause for the persistence and sustainability of technological progress was the widening of the epistemic base of techniques *already in existence* (some of them, admittedly, barely) in 1914, which created continuous opportunities for economic expansion and productivity growth.[42] When that base was narrow, as it was in pharmaceutics and synthetic materials, progress was halting and depended on serendipity. When that base was wider, as it was in mechanical engineering, electricity, and metallurgy, progress was relentless and continuous.

For many years, then, technological progress in the twentieth century followed the trajectories established in the years before 1914. In automobiles, chemicals, energy supply, industrial engineering, food processing, telephony and wireless communications, and synthetic materials, the developments after 1914 should be regarded as primarily *micro*-inventions. Microinventions tend to be the result of directed and well-organized searches for new knowledge, what the twentieth century has increasingly termed R&D.

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[42] Consider the following quote from a recent newspaper essay on the "new economy": "The computer, of course, is at its heart—but not as a miracle machine spinning a golden future comparable to the industrial leap forward that came in the late 19th and early 20th centuries. Then, the electric motor, the light bulb, the internal combustion engine, petroleum, natural gas and numerous new chemicals all came on the scene —rearranging the economy and making it vastly more productive. The electric motor alone made possible the factory assembly line and mass production." Note that no such "industrial leap" is identified for the post-1914 period (see Louis Uchitelle, "In a Productivity Surge, No Proof of a 'New Economy,'" *New York Times*, October 8, 2000).

Perhaps the most important development of the twentieth century is the change in the nature of the process of invention with the emergence of corporate, university, and government-sponsored R&D, what Mowery and Rosenberg (1998) have called the "institutionalization of innovation."[43] Whether individual independent inventors would eventually be made redundant by this development has been the subject of a long and inconclusive debate (Jewkes, Sawers, and Stillerman, 1969). A fair description of what happened in the twentieth century is that technology and the institutions on which it depended continued to co-evolve in the way I described above. In some industries, technological change may well have favored in-house research, particularly in the chemical and automotive industries, where large-scale facilities were all but indispensable. Yet the relation changed as the nature of technology and the environmental parameters changed. The twentieth century was the one century in which both the nature and the speed of technological progress were actively determined by politics. Governments invested in and encouraged research for strategic reasons.[44] Defense accounted for the lion's share of federal R&D in the United States, and the federal government financed a substantial proportion of R&D. In other countries, governments and other coordinating agencies were equally important. Much of the history of technology in the twentieth century can be described as a continuous search for the right "mix" of private and public efforts in R&D. The fundamental dilemma is well known to any economist: the private sector systematically underinvests in R&D because of the appropriability problems in the market for propositional knowledge. Government agencies, in both market and command economies, have done a poor job of picking winners, however, and have only haphazardly contributed to civilian techniques.

Despite the widely held belief that the twentieth century was qualitatively different from anything that came before (DeLong, 2000), much of the technology that deluged consumers with new and improved products and that accounted for unprecedented growth in total factor productivity was around—if in somewhat preliminary form—in 1914. As noted, the number of epochal macroinventions in the 1914–50 period was comparatively small. Nuclear power, of course, would rank at the top of those. It demonstrates that the minimum epistemic base for some

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[43] Here, too, there were clear-cut nineteenth century roots. The great German dye manufacturers and large U.S. corporations such as General Electric and Alcoa established the corporate research laboratory and the university as the prime loci where the technological frontier was pushed out, but the spread of this idea to the rest of the economy was slow and gradual.

[44] Mowery and Rosenberg (1998, p. 28) note the irony in the post-1945 view that the great research projects of World War II (the Manhattan Project, antibiotics, and synthetic rubber) demonstrated the capabilities of "Big R&D" to enhance social welfare.

technologies had become very extensive. Although quantum mechanics and nuclear physics were without doubt major expansions of the set of propositional knowledge, and the use of nuclear power a true discontinuity, nuclear power did not lead to the usual pattern of diffusion and microinventions. Improvements in the technique continued, but the costs of nuclear fission reactors in its fast breeder or thermal versions never quite became sufficiently low to drive out fossil fuels, and the safety and disposal problems have remained hard to solve.[45] More than any technology since the Industrial Revolution, nuclear power generation has become a target of political opposition (a topic I return to below). Nuclear fusion, which has the potential to produce limitless energy at low prices, has so far failed to become a reality except in hydrogen bombs. One might say that the minimum epistemic base required for handling materials at exceedingly high temperatures was not attained.

Quantum physics was less objectionable, perhaps because it was difficult to understand and its applications were less intrusive, at least at first. Much of the modern information and communication technology is in some way dependent on epistemic bases that belong to quantum physics. Tegmark and Wheeler reckon, perhaps somewhat heroically, that today an "estimated 30 percent of U.S. GNP is based on inventions made possible by quantum mechanics" including all microprocessors, lasers, and magnetic resonance imaging (2001, p. 69).

The other major macroinvention in the first half of the twentieth century was antibiotics (Kingston, 2000). It too followed a rather unusual path, but for quite different reasons. The minimum epistemic base for antibiotics to work was the knowledge that specific bacteria existed and that they caused diseases. Without the germ theory, Alexander Fleming's discovery of penicillin would not have taken place, since he would never have realized that his molds killed bacteria. Yet Fleming's discovery that certain molds were bactericidal and could be deployed in combating infectious disease was famously accidental. Fortune favored the prepared minds of Howard Florey and Ernst Chain, who purified and made possible the mass production of penicillin. Once the knowledge that antibiotics are feasible had been added to propositional knowledge, the development of other antibiotics followed. The epistemic base was still rather narrow: it is fair to say that no one had a very good idea precisely how antibiotics

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[45] The other great breakthrough of the last quarter of the twentieth century, biotechnology, has encountered similar problems, but for different reasons. Although the breakthroughs in this area may be as momentous as any technological advance since 1750, the genetic modification of crops, to say nothing of cloning, so far has not been able to gain the trust of large segments of the population.

affected the germs they kill. Even the structure of the penicillin molecule was not fully understood until 1949. The way in which substances such as penicillin kill bacteria has been elucidated only in recent years leading to the possibility of replacing side chains of the molecule and thus overcoming bacterial resistance (Nicolaou and Boddy, 2001). Much work in pharmaceutics, even in the twenty-first century, still follows some systematic and computerized "try every bottle on the shelf" algorithm. The difference from other technologies was that antibiotics, much like insecticides, are subject to a negative feedback mechanism (the mutation of living species makes them immune to harmful substances), which after a while weakens their effectiveness. As a result, it is conceivable that the gains in the war against infectious diseases were temporary and that in the end humankind won a battle but not the war.

There were, of course, other major breakthroughs in the post-1914 decades. One thinks, for example, of the jet engine, catalytic cracking, and the emergence of man-made fibers and substances such as nylon. Many of these were, however, improvements upon *existing* techniques rather than totally new techniques.[46] These improvements and extensions (many of them, of course, major) became possible thanks to the continuous widening of the propositional knowledge on which they rested, but also because "modern science" made this knowledge tighter. Experimental and statistical methods to establish natural regularities and "causes" became more sophisticated, and new propositional knowledge, after being subjected to rigorous tests and critiques, when it became consensual, became the basis of searches for new prescriptive knowledge.

Perhaps the most discontinuous breakthroughs in the 1920s came in physiology. One of those was the discovery of insulin in 1922 and its extraction from animal pancreases, which made the treatment of diabetes possible. Another was the growing realization that trace elements (called vitamins in 1920) played a major role in preventing diseases that were recognized as caused by nutritional deficiency. The propositional knowledge about nutrition mapped directly into techniques employed by households in preparing food for their families, as well as by the food industry, which fortified products such as margarine with trace elements to ensure adequate intake.

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[46] The definition of a macroinvention does not exclude the possibility that the ultimate form the technique takes results from a number of discontinuous complementary breakthroughs. The best example is the steam engine, which arguably was not complete until the reciprocal (double-acting) cylinder and the separate condenser were added by Watt. It seems a matter of preference whether one thinks of the jet engine and plastics in the same way.

Much of the progress in the first half of the twentieth century consisted of "hybrid" inventions, which combined components that had been worked out before 1914. The principles of the use of electrical power to run engines, activate vacuum tubes, and heat objects could be combined into radios, dishwashers, vacuum cleaners, fans, and virtually every other household appliance. Other pre-1914 inventions formed the basis of much industrial development until 1950 and beyond. The internal combustion engine and its cousin, the diesel engine—both up and running by 1914—eventually replaced steam as the main source of power.

The story of the chemical industry is a bit more complex (see Arora, Landau, and Rosenberg, 1998). Much of the chemical science underlying the synthetic materials industry was simply not around in 1914. A few synthetics such as celluloid and Bakelite were developed on a very narrow epistemic base.[47] Even so, some true macroinventions predate 1914.[48] Yet the advance of this industry into large-scale manufacturing of mass produced commodities such as nylon and polyester had to await the establishment of its epistemic base by Hermann Staudinger, who discovered the chemical structure of large polymers in the 1920s. The subsequent development of new materials depended crucially on this advance. The boundaries of chemicals expanded enormously in the interwar years, into synthetic alcohol and fuels, paints, petrochemical organic feed stocks, new pharmaceuticals, and photographic materials (Murmann and Landau, 1998, p. 47). Yet the "golden age" of petrochemicals started only in 1945. The same dynamic holds for aerodynamics, where the epistemic base kept expanding as a response to technical successes, but which served as a further input into their design. The Wright brothers flew in 1903, a year before Ludwig Prandtl, the great theorist of aerodynamics,

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[47] Bakelite was patented in 1909 and manufactured on a commercial scale from 1910 on, but its chemical formula was not even established until 20 years later. Rosenberg also points out that pilot plants were necessary simply because no body of scientific knowledge could answer the necessary questions (1998b, p. 212).

[48] Of those, the technique to fix ammonia from the atmosphere perfected by Fritz Haber and his associates in 1909 must count as one of most momentous in modern history. Vaclav Smil (2001, p. xv) estimates that without the Haber-Bosch process, two fifths of the world's population might not have been around. Such counterfactuals are always somewhat hazardous without specifying the exact historical "rewrite," but there can be no doubt that nitrates were the critical ingredient in both the fertilizer and the explosives industries and its fixation from the atmosphere had far-reaching consequences not only for agriculture but also for the prolongation of World War I. Thermal cracking, which separates the long-chain hydrocarbons of petroleum into smaller but more important ones such as gasoline, was first employed commercially in 1913 by Standard Oil researcher William Burton. Catalytic cracking was developed by Eugène Houdry in the 1920s and speeded up the process considerably.

became a professor in Göttingen.[49] Only in 1918 did Prandtl publish his magisterial work on how wings could be scientifically rather than empirically designed and the lift and drag precisely calculated (Constant, 1980, p. 105; Vincenti, 1990, pp. 120–25). Even after Prandtl, not all advances in airplane design were neatly based on their epistemic base and derived from first principles, and the ancient method of trial and error was still widely used in the search for the best use of flush riveting in holding together the body of the plane or the best way to design landing gear (Vincenti, 1990, pp. 170–99; Vincenti, 2000).[50]

Much of the productivity increase in the twentieth century was the result of the perfection of production techniques and process innovation. Again, the roots of many of these ideas had been around in 1914, but the scale of organization and accuracy of detail continued to grow. These led to a continuous transformation in organizational methods, most obviously in mass production in manufacturing techniques but eventually in services and agriculture as well. For better or for worse, these changes have become known as "the American system of manufacturing" (actually their historical roots were complex), and their dissemination to the rest of the industrialized world was inevitable. It is perhaps a matter of semantics whether we think of these changes as "technological" or "organizational." What matters is that they co-evolved with the ability of the capital goods industry to produce the tools and machinery that made their deployment practical, relying on an ever-growing epistemic base of materials and mechanical engineering.

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[49] Much of the knowledge in aeronautics in the early days was experimental rather than theoretical, such as attempts to tabulate coefficients of lift and drag for each wing shape at each angle. The fundamentals were laid out by George Cayley in the early nineteenth century. The Wright brothers relied on the published work (especially of Otto Lilienthal) at the time to work out their own formulas, but they also ended up working closely with the leading aeronautical engineer of the time, Octave Chanute, who supplied them with advice right up to their pioneering flight at Kitty Hawk in 1903 (Crouch, 1989). It is clear, however, that the Wright brothers were avid consumers of engineering science and that their greatness lay in the mapping function. It might be added that the Ω set they worked from was quite untight: in 1901 the astronomer and mathematician Simon Newcomb (the first American since Benjamin Franklin to be elected to the Institute of France) opined that flight carrying anything more than "an insect" would be impossible. He was joined in that verdict by the Navy's chief engineer, Admiral George Melville (Kelly, 1943, pp. 116–17; Crouch, 1989, p. 137). Nor were the inventors themselves all that certain: in a widely quoted remark, Wilbur Wright in a despondent mood remarked to his brother that "not within a thousand years would men ever fly" (Kelly, 1943, p. 72).

[50] The hardening process of aluminum, in which the metal hardens slowly over the week following heating and quenching, was discovered accidentally by Alfred Wilm in 1909 and eventually led to the use of aluminum in all aircraft construction. Metallurgists had a difficult time explaining the phenomenon of age hardening, and it took years until even a partial epistemic base had been uncovered (Alexander, 1978, p. 439).

The modernization of techniques can be broken down into several elements. The first is *routinization,* which made production processes interchangeable. Assembly, welding, painting, and packing all became increasingly similar for different products, a development with obvious implications for the specificity of human capital and skills. Another component was *modularization,* meaning that parts were identical up to a high level of tolerance and thus fully interchangeable. The advantages of modularization had been understood since Christopher Polhem enunciated them in the early eighteenth century, but the precision engineering that made it possible on an almost universal scale required machine tools that became available only in the twentieth century.[51] Modularization was closely related to *standardization,* making all products of a particular type conform to a uniform standard. Standardization, much like modularization, helped not just during the production stage of output but also in the maintenance of durable equipment. Whoever could repair one Model T could repair *any* Model T. It was also essential to mass marketing through catalogs and price lists. Mass production also entailed *acceleration* through continuous flow production. Continuous flow, in which the employer could determine the speed of each worker, could take place in production that involved assembly or *dis*assembly (as in the stockyards), as well as for continuous physical and chemical processes (grain milling, refining).[52] Finally, in some applications there was a trend toward *miniaturization* (space-saving) such as in the design of smaller motors and steadily less clumsy microelectronics culminating in modern nanoelectronics.

Parallel with changes in the organization of production was the growing specialization of labor. Trends in specialization are complex: the routinization of production, as Marx already pointed out, was fundamentally de-skilling, and production employed undifferentiated homogeneous labor to perform simple tasks on machines that were increasingly user-friendly in the sense that they were easy to operate. Yet the division of labor became more and more refined in the twentieth century and led to a myriad of highly specialized occupations and tasks. The advantages of the division of labor and specialization have been commented on ever since Adam Smith wrote *The Wealth of Nations.*

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[51] Hounshell notes that by 1913, when Ford initiated his line assembly techniques, the machine industry was capable—perhaps for the first time—of manufacturing machines that could turn out large amounts of consistently accurate work (1984, pp. 232–33).

[52] Von Tunzelmann (1995), who stresses the importance of time-saving technological changes, has identified at least four components of the speed of production: higher speed of operation, less down-time due to more reliable and easy-to-repair equipment, faster interprocess coordination, and faster intraprocess coordination.

Along with nuclear power and antibiotics, the most spectacular macroinvention of the twentieth century was the semiconductor.[53] Although all three emerged in the 1940s, electronics is the only area in which the continuous feedback between prescriptive and propositional knowledge, as well as recombination with other inventions led to a sustained and continuous growth that to date shows no evidence of slowing down and is believed by many to herald a "new economy." Helpman and Trajtenberg (1998) have pointed to the semiconductor's unusual properties as an innovation: its ability to recombine with other techniques, its complementarity with downstream innovations, and its consequent pervasiveness in many applications, meriting the term general purpose technology (GPT). There have been few comparable macroinventions since the emergence of electricity in the late nineteenth century. A large cluster of separate inventions emerged, with an unusual propensity to recombine with one another and to create synergistic innovations that vastly exceeded the capabilities of individual components. Around 1955, vacuum tubes were replaced by the junction transistors invented by William B. Shockley a few years earlier.[54] In the 1980s and 1990s, such hybrid machines combined high-speed integrated circuits and then microprocessors with lasers, fiber optics, satellites, software technology, and new breakthroughs in material science and electronics that made high-density RAM storage possible. The so-called ICT (information and communication technology) revolution is not identical to the computer and was not implied by it, and many of the debates on the impact of "the computer" on productivity in the 1990s for that reason miss the point. Mainframe computers in the 1950s and 1960s and even the early personal computer (at first little more than a glorified typewriter and calculator) were not really a revolutionary general purpose technology, their many uses notwithstanding.

It always seems rash and imprudent when historians analyze contemporary events as if they occurred sufficiently long ago to be analyzed with some perspective. But the arguments made above suggest that the cluster of innovations around semiconductors and their applications will be viewed by future historians as a macroinvention; they represent the kind of discontinuity that separates one era from another, much like the two pre-

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[53] There are many excellent histories of the computer despite their obvious built-in obsolescence (see, for instance, Campbell-Kelly and Aspray, 1996).

[54] The transistor is a good example of the concepts employed here, as already noted in a classic paper by Nelson (1996). The epistemic base consisted of the natural regularity of the behavior of silicons as semiconducting materials, and the work of A. H. Wilson explained this in terms of quantum mechanics in 1931. Much of the theory, however, was not fully understood until Shockley wrote his 1949 book in which he showed how and why the junction transistor would work. As Nelson remarks, "the theory was the invention" (p. 170).

vious Industrial Revolutions. For a true technological watershed to take place, there has to be more than a GPT such as steam power or electricity or chemical engineering (Rosenberg, 1998a). There has to be a profound change in the generation and deployment of knowledge. The significance of the information revolution is not that we can read on a screen things that we previously read in the newspaper or looked up in the library, but that marginal access costs to codified knowledge of every kind have declined dramatically. The hugely improved communications, the decline in storage and access costs to knowledge, may turn out to be a pivotal event.

The significance of ICT is not just its direct impact on productivity but that it is a *knowledge technology* and thus affects every other technique in use precisely because it affects the level of access costs, which, as I argued in chapter 1, is one of the critical properties of Ω. Given the huge dimensions that the set of propositional knowledge attained in the twentieth century (and its continuing exponential growth), ever-increasing specialization and narrow-based expertise are inevitable. The existence of search engines that allow an individual to find some known piece of propositional knowledge at low cost becomes critical, but other technologies to sort and assess the information to prevent overload are becoming essential. Indeed, it must be true that if useful knowledge had grown at the rate it did without changes in the technology of access, diminishing returns would have set in due to the difficulty in information management. After all, there is one immutable fixed factor: the human cranium. Although the flexibility of the human mind is remarkable, it remains true that the segment of total social knowledge that each person possesses is declining proportionally (even if it increases in total terms) over time. Specialization is the only way to deal with the current size of useful knowledge. An increasingly fine division of knowledge requires better and better access relations between people, and between individuals and storage devices. The Internet may seem to be the culmination of this process, but in fact access has been improving for decades in the form of computer-based information such as library catalogs, databases, and online access devices such as Medline. As some—if by no means all—of the people who carry out technological instructions (let alone those who write new ones) need access to more and more useful knowledge, the means by which they can find, access, sort, evaluate, and filter this knowledge is crucial.

That aspect of information technology holds the key to the future of technological creativity in our time. The uniqueness of the late twentieth century is that this body has become vast and depends on access-cost-reducing technology, without which it could never have advanced as fast as it did. The Internet and its "search engines"are but one element of this information revolution. Equally important is the institutional element: the establishment of social conventions of rhetoric and acceptability, coupled with growing professionalization and the formalization of expertise. The resource cost learning something is not the only variable that determines how easy access to knowledge is; there is also the matter of the reliability of the information.

Declining access costs are instrumental in the rapid diffusion of new techniques, not just because they cannot be employed before their existence is known, but also because in many cases each user has idiosyncratic needs and uses and has to adapt the technique to his or her specific conditions. This is surely true for agriculture, but it holds with equal force in the service industries and manufacturing. Someone executing a technique whose instructions were written elsewhere needs a way of answering specific questions that arise while actually implementing the technique, and these questions can often be answered using rapid and cheap communications.

Furthermore, falling access costs have stimulated technological progress through another phenomenon, technological hybrids and recombinations (what one might call technological compounds). If we consider each technique in λ to be a "unit" of analysis, these units can interact with other units to produce entirely new entities. Most modern devices represent such compound bundles of knowledge, often scores or even hundreds of them.[55]

The notion that existing techniques can recombine into new ones is not novel (Weitzman, 1996), but in our framework it has deeper significance. It means that techniques can not only incorporate other techniques whole (which we might call "hybrids") but also import subsets of their instructions and their epistemic bases and combine these with their own (which would more properly be thought of as a recombination).[56] Hybrids and recombinations are not quite the same: there is a conceptual difference between joining together an internal combustion engine, a propeller, and a glider to make an airplane, and the application of mechanical knowledge underlying bicycle repairs in solving the specific problems that occur in

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[55] The degree to which technology is "recombinant" can be approximated, however imperfectly, by citations to other patents and scientific literature in patent applications. Considerable research has gone into the topic of patent citations, and recent work shows that a fair number of citations refer to other patents that are not closely related. Unfortunately this information had to be attained from an ex post survey of the patentees, and thus the inference is from a small sample and for 1993 only. It is striking, however, that on a rank from 1 (unrelated) to 5 (closely related), 44 percent of the citations did not rank above 2. The data pertain to 1993 patents and therefore predate the Internet (see Jaffe, Trajtenberg, and Fogarty, 2000).

[56] Just as we can define "general purpose technology" as techniques that can readily hybridize with others (electric power being an obvious example), we can think of "general purpose knowledge" mapping into a large number of techniques and allowing them to recombine. I am indebted for this point to Richard G. Lipsey.

airplane construction.[57] Either way, however, better access to knowledge not only will make it more likely that best-practice techniques are widely employed, but will also generate the emergence of such compound innovations.

But what, exactly, does "better access" mean? Even scientific knowledge in the public domain needs to be found, interpreted by specialists, and reprocessed for use. In recent years, economists have returned to Michael Polanyi's juxtaposition of tacit vs. codified knowledge (Cowan and Foray, 1997). Modern technology may be more codified and is thus more accessible by normal channels. In any event, even in the twenty-first century there is still a great deal of tacit knowledge that cannot be readily acquired from storage devices and can be accessed only by hiring the people who possess it. Nevertheless, modern ICT makes it easier to find the people who possess that tacit knowledge, and hire them, if possible, on an ad hoc basis. Technical consultants and subcontractors with "just-in-time expertise" have become pervasive. One reason, I suggest, is that modern ICT makes it easier to track down where this knowledge can be found (or, one step removed, easier to track down *who knows* where this knowledge can be found, and so on).

Modern information technology has also produced new tools for conducting research, and thus an immensely powerful positive feedback effect from prescriptive to propositional knowledge. As I have argued repeatedly, a great deal of knowledge still consists of cataloging phenomena of great underlying complexity rather than coming to grips with their underlying mechanisms. Invention remains a pragmatic and empirical process of informed and systematic experiments, and looking what works. The process of drug discovery, although not as dependent on serendipity and intuition as it was in the age of Hoffman and Ehrlich, still often relies on "brute force" rather than on strategy. Molecular structures of proteins are so complex that the old and crude methods of search-and-see-what-works are still in place, albeit in a highly sophisticated form. Databases on genes, proteins, and their mind-boggling interactions require computer memories measured in petabytes (billions of megabytes). Molecular biology

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[57] Many techniques are particularly amenable to recombination. Historically in the West, watchmaking is probably the best example as a set of techniques with considerable spillovers of this kind. Watchmaking knowledge found its way into instruments and fine machinery of all kinds and some watchmakers made important inventions. The best-known inventors trained as clockmakers were Benjamin Huntsman, the originator of the crucible steel technique, and John Kay (not to be confused with the inventor of the flying shuttle of the same name), who helped Arkwright develop the water frame. Gunmaking played a somewhat similar role, such as when John Wilkinson's boring machines helped Watt build his cylinders. In a modern context, Nelson has pointed to the theory on which semiconductors were based as the source of better thermoelectric devices and the Bell solar battery (1996, p. 171).

has expanded our knowledge of the natural world, and the modern pharmaceutic R&D based on it may well be called "guided discovery," but it still represents a streamlined version of a traditional empirical discovery technique. Computers likewise have become indispensable in engineering. In the past, the difficulty of solving differential equations limited the application of theoretical models to engineering. A clever physicist, it has been said, is somebody who can rearrange the parameters of an insoluble equation so that it does not have to be solved. Computer simulation can evade that difficulty and help us see relations in the absence of exact closed-form solutions and may represent the ultimate example of Bacon's "vexing" of nature.[58] In recent years simulation models have been extended to include the effects of chemical compounds on human bodies. It is easy to see how the mutual reinforcement of computers and their epistemic base can produce a virtuous circle that spirals uncontrollably away from its basin of attraction. Such instability is the hallmark of Kuznets's vision of the role of "useful knowledge" in economic growth. Yet it would be as futile to search directly for these effects of ICT on national income statistics as it would be to search for the effects of the *Encyclopédie* on eighteenth-century French economic growth.

Useful Knowledge and Growth

The productivity and growth implications of revolutions in knowledge are at the core of much of the literature in the economics of technological change and productivity measurement. Oddly, however, economistshave not gotten into the "black box" of knowledge evolution in the past (with a few notable exceptions such as F. M. Scherer, Richard Nelson, and Nathan Rosenberg). Instead, total productivity measures generally take technological progress as exogenous. Models of endogenous growth have attempted to open these black boxes, but have just found another black box inside. The analysis of human knowledge as defined here takes a small step toward understanding what is inside this black box. As has been argued by many analysts in the evolutionary epistemology school (e.g., Plotkin, 1993; Wuketits, 1990) as well as by evolutionary psychologists (Nelson and Nelson, 2002), human knowledge can be and needs to be analyzed as part

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[58] Many of the hardest problems still await the development of more powerful computers. Direct numerical simulation of a statistically isotropic turbulent flow (a highly idealized and simplified version of turbulence) is proportional to the Reynolds number (a parameter measuring density, velocity, and the size of the vessel) raised to the power of 3. To perform a simulation on today's fastest computers of a system approximating the simplest form of turbulence would take 5,000 years of CPU. I am grateful to my colleague Moshe Matalon of the Department of Applied Mathematics at Northwestern for his help on this matter.

of a larger evolutionary paradigm. This effort was started in economics by Nelson and Winter in 1982, but so far has been little applied to economic history, where its marginal product seems particularly high.

The interaction between propositional and prescriptive knowledge grew stronger in the nineteenth century. It created a positive feedback mechanism that had never existed before, not among the scientists of the Hellenistic world, not among the engineers of Song China, and not even in seventeenth-century Europe. In that sense, Kuznets's insight is fully vindicated. The useful knowledge as it emerged in the decades after 1850 was truly *social*, but the "society" in question was international—though not global. Societies that could overcome their own reluctance and the inertia of their institutions could "join the club," if at considerable cost. Japan and Russia, in very different manners, made that decision.

The economic history of knowledge suggests that an emphasis on aggregate output figures and their analysis in terms of productivity growth may be of limited use in understanding rapid growth over long periods. The full *economic* impact of some of the most significant inventions in the past two centuries would be almost entirely missed in that way. One reason for that has been restated by DeLong (2000). Income and productivity measurement cannot deal very well with the appearance of entirely new products. The Laspeyre index of income measures a basket from some year in the past and asks how much it would cost today; that is, comparing the current standard of living with that at some point in the past asks essentially how much *our* income would have bought then. But the whole point of technological progress is not just that goods can be made more cheaply. If that were all that was going on, such indices would measure progress accurately. In fact, new consumer goods not even dreamed of in an earlier age are making direct welfare comparisons otiose. In that regard we see a progression from the first to the second Industrial Revolution and even more into the twentieth century. The Industrial Revolution in the early nineteenth century created few new consumer goods, and consumption baskets in 1830 were not radically different from those in 1760. This was no longer the case in 1914, and by the end of the century new goods that satisfied needs hitherto unsuspected (Walkman radios, Internet service providers) or needs that simply could not have been satisfied earlier (laser vision-correction surgery) keep emerging at an accelerating pace. Traditional measures underestimate the rate of progress and do so at a rate that grows over time.

Moreover, goods become different, and they improve in ways that are very difficult to quantify.[59] Some aspects are difficult to quantify: reduced wear and tear, ease of repair and maintenance, and improved user-friendliness come to mind.[60] It has also been pointed out repeatedly that increased diversity and choice by themselves represent welfare improvements, and that modern technology makes mass customization possible by allowing customers to "design" their own final product from modular components (Cox and Alm, 1998).

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[59] DeLong (2000, p. 7) chooses a particularly felicitous example. In 1895 a copy of the *Encyclopedia Britannica* cost US $35, whereas today a print version costs $1,250, about one quarter in terms of labor costs. But a different good, the *Encyclopedia Britannica* on CD-ROM today costs only $50.00. How are we to compare the two? Assuming that in both cases the content reflects an equally exhaustive and reliable picture of the world, the CD-ROM has some major advantages besides cost: it is easier to store, and access to information is a bit faster and more convenient. It also includes more powerful imagery (through video clips) and audio. In short, readers in 1895 with a fast computer would have in all likelihood preferred the CD-ROM version.

[60] This point is insufficiently stressed in William Nordhaus's (1997) otherwise pathbreaking paper on the real cost of lighting and strengthens his conclusion that the gains to consumers are understated by standard measures. The true benefit from switching from candles or oil lamps to electric light was not just that electric light was cheaper, lumen per lumen. It is also that electric light was easier to switch on and off, minimized fire hazard, reduced flickering, did not create an offensive smell and smoke, and was easier to direct.

Chapter 4

Technology and the Factory System

The consequences which accompanied the introduction of the modern factory are extraordinarily far-reaching.... Workshop industry meant the employment of the worker in a place which was separate both from the dwelling of the consumer and from his own.

—Max Weber, 1923

In half a century's time, it may well seem extraordinary that millions of people once trooped from one building (their home) to another (their office) each morning, only to reverse the procedure each evening... Commuting wastes time and building capacity. One building—the home—often stands empty all day; another—the office—usually stands empty all night. All this may strike our grandchildren as bizarre.

—Frances Cairncross, 1997

Introduction

What does technology really do to our lives and well-being? Much of the history of technological revolutions in the past two centuries is written as if the only things that technology affected were output, productivity, and economic welfare as approximated by income. This is of course the best-understood and most widely analyzed aspect of technological progress. Yet technological progress also affected other aspects of the economy that may be significant. Among those is the optimal scale of the basic economic production unit and the location where production takes place. These in turn determine whether "work" will be carried out in a specialized location and thus whether households and firms will be separate physical entities.

The stylized fact is that the Industrial Revolution of 1760–1830 witnessed the "rise of the factory." Like all historical "facts" of its kind, it is only an approximation. In reality, there were numerous precedents for large-scale enterprise and for people working in large plants even before the classical Industrial Revolution. But there can be no doubt that the Industrial Revolution meant the ever-growing physical separation of the unit of consumption (the household) from the unit of production (the plant).[1] The term "factories" mixes up two economic phenomena: one is the concentration of former artisans and domestic workers under one roof, in which workers more or less continued what they were doing before, only away from home. These are sometimes known as "manufactories." The other involves a more radical change in production technique, with mechanization and a substantial investment in fixed capital combined with strict supervision and rigid discipline resulting in what became known as "mills." In practice, of course, this neat dual division did not hold, and most of the new plants were blends of the "ideal" types, with the relative importance of the "manufactories" declining over time.

The purpose of this chapter is to argue that technology and knowledge to a large extent drove the emergence of the factory, by determining the relative costs and the benefits of moving people as opposed to moving information. These costs overlap only in small part with the "transaction costs" postulated to explain the existence of firms by Ronald Coase and Oliver Williamson. The modern distinction between firm and plant should be kept firmly in mind: I am interested here primarily in the location where the work is carried out. What matters is location rather than ownership or organization per se.

In the standard theory of the firm, firm hierarchies substitute for formal contracts to reduce uncertainty and opportunistic behavior, and

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[1] Max Weber, as cited in the epigraph to this chapter, was not the first to emphasize this aspect. Paul Mantoux opened his still classic work on the Industrial Revolution (first published in 1905) with the words, "The modern factory system originated in England in the last third of the eighteenth century. From the beginning its effects were so quickly felt and gave rise to such important results that it has been aptly compared to a revolution, though it may be confidently asserted that few political revolutions have ever had such far-reaching consequences" ([1905] 1961, p. 25).

they set incentives to elicit efficient responses from agents. Firms can hire workers or transact with suppliers in a long-term, repeated relationship or on a one-shot basis. This theory, however, does not fully specify the location of production. Whether workers work at home or in a central location depends, among other things, on the relative costs and benefits of moving people versus moving information and on changes in the composition of output and capital-labor ratios that change labor demand toward or away from activities requiring workers to be physically present on the shopfloor or in the office.[2] Although the costs of both transporting people and transporting information have declined in the past two centuries, a change in their ratio affected the location of production in a complex manner.

Furthermore, the benefits of concentration may be moving in a different direction as the result of changes in the technology and product mix. These benefits are directly related to the size and complexity of the knowledge needed for production to take place. This knowledge (or "competence") is what it takes to execute the instructions contained in a technique. It differs from the knowledge in the epistemic base required to invent, develop, and design a technique. Indeed, part of the improvement in technology may consist of making complex techniques simpler to carry out by making them more user-friendly and thus de-skilling the labor force in some sense.

Large firms were quite widespread before the Industrial Revolution, but most of their employees were domestic laborers (working in a cottage industry), much of it on a putting-out basis. In this system, the "firm" (that is, the merchant-entrepreneur) owned the raw materials, the goods in process, and often the tools and equipment as well, and outsourced physical production to workers in their homes. This "domestic system" may well have been more efficient if raw materials and the tools had been strongly complementary, but capital markets were underdeveloped. In that kind of world, the theory of the firm associated with the work of Oliver Hart and Sanford Grossman suggests that ownership confers residual rights of control and decision so that the merchant-entrepreneur or capitalist owner could decide what, how, and how much would be produced. In most cases, however, the technology may not have required physical production to take place in a central location, and hence the existence of large firms without large plants.

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[2] In a recent paper, Lamoreaux, Raff, and Temin (2002) note that information and transportation costs determine the location and organization of economic activity but worry that these costs all decline monotonically over time; yet the organization of business shows anything but a unidirectional trend. Part of the reason for this phenomenon, as they correctly point out, is the emergence of new techniques of coordination.

Most workers in pre–Industrial Revolution western Europe, in any case, were independent farmers or craftsmen, and the distinction between "firm," "plant," and "household" is otiose. For those who had become part of larger firms, putting-out was the answer. A condition for the putting-out system to exist was for labor to be paid a piece wage, because working at home made the monitoring of time impossible. In the stylized version, then, the factory, factory towns, and an industrial wage labor force or proletariat were all created in the closing decades of the eighteenth century and the first half of the nineteenth. The transition was long, drawn out, and never quite complete, but by 1914, as far as we can tell, the majority of the labor force was no longer working at home.

In the late twentieth century the pendulum started to swing back. Some telecommuting enthusiasts are predicting a return to pre–Industrial Revolution conditions, in which suitably networked households will once again become the main location in which human work will be carried out. The "death of distance" may mean that more and more production can take place at *any* location, and hence the need for employees to be present at some central facility may be reduced. To be sure, the reported demise of the industrial plant may be premature, and in any event it is not my intent here to engage in prediction, much less futurism. Instead, I propose to reexamine the causes and effects of the rise of the factory, and specifically to sort out the role of technological change in this process, to examine the beginnings of the reversal in recent years, and then to apply some of the insights to issues of current policy relevance.

The Industrial Revolution and the Rise of the Factory

Manufacturing before the Industrial Revolution was, in François Crouzet's words, an industry without industrialists (1985, p. 4). This was surely true for the independent craftsmen who worked on their own account with the help of their family members and a few apprentices who were co-opted into the household. Workers employed by capitalists in one form or another also worked, predominantly, in their own homes. Max Weber stated it most clearly, that the distinguishing characteristics of the modern factory were "labor discipline within the shop...combined with technical specialization and co-ordination and the application of non-human power....The concentration of ownership of workplace, means of work, source of power and raw material in one and the same hand. This combination was only rarely met before the eighteenth century" ([1923]1961, pp. 133, 224).

As noted earlier, large industrial plants were not entirely unknown before the Industrial Revolution. For instance, Pollard (1968) in his classic work on the rise of the factory, mentions three large British plants, each employing more than 500 employees before 1750.[3] Perhaps the most "modern" of all industries was silk throwing. The silk mills in Derby built by Thomas Lombe in 1718 employed 300 workers and were located in a five-story building. After Lombe's patent expired, large mills patterned after his were built in other places as well. Equally famous was the Crowley ironworks, established in 1682 in Stourbridge in the Midlands (not far from Birmingham), which at its peak employed 800 employees. Yet these atypical firms were still quite different from modern factories. Much of the work was put out to master workmen who worked the iron in their own homes or workshops. Ambrose Crowley was unusual in having set up a system of supervision, monitoring, and arbitration with his workers unlike anyone else.[4] Blast furnaces, breweries, shipyards, mines, paper mills, construction, and a few other industries had long been producing outside the domestic system because they could not operate economically at the scale of a household.[5] In textiles, supervised workshop production could be found before 1770 in the Devon woollen industry and in calico printing (Chapman, 1974) . Yet in industries such as the Yorkshire wool and the Midland metal trades, centralized workshop production controlled only a few stages of output and rarely displayed the control and discipline we associate with real "factories." Wherever possible, work was outsourced to small-scale artisans working at home who at times ran cooperatives when scale economies were important.[6] Even these early factories, then, were a compromise between the domestic system and the need to produce away from home.

The Industrial Revolution thus did not quite "invent" the factory system, but gradually and relentlessly it brought about factories where none were before. Most firms did not switch abruptly from the domestic system to a factory system but continued to farm out some processes to domestic workers, until mechanization and technological complexity had expanded sufficiently to make it worthwhile to bring the workers under one roof. The cotton industry provides the best example of this mixed factory system. In

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[3] Tann (1970, p. 3) mentions a number of large works in the seventeenth century, but designates them as "exceptional cases."

[4] The insightful biography by Flinn (1962, p. 252) calls Crowley's firm "a giant in an age of pygmies" and notes that his example of successful large-scale industrial organization was not followed until a century later.

[5] One of the largest firms was the Neath colliery in Wales. Coal mines by their very nature required a presence away from home, of course, but even coal miners were often employed with their families and paid a piece wage. In a sense, then, many coal mine employees could be regarded as subcontractors.

[6] Thus in the woollen industry of West Yorkshire, the finishing stages of the output required a powered mill and was carried out in cooperatives (Berg, 1994b, p. 128).

1760 cotton was overwhelmingly a domestic industry. The water frame spinning machine changed all that. Richard Arkwright's works in Cromford employed about 300 workers; he also helped found the New Lanark mills in Scotland, which employed a workforce of 1,600 in 1815 (most of whom worked indoors). Such huge firms were unusual, perhaps, but by 1800, there were in Britain around 900 cotton-spinning factories, of which a third were "mills" employing more than fifty workers and the rest small sheds and workshops with a handful of workers—though even those were larger than households. The mule, especially after it was coupled to steam power, changed the distribution of firm sizes quickly: at first, in the early 1790s the majority of cotton mills were still small firms employing ten or fewer workers, with a few Arkwright-type mills of 300–400 workers. By the early 1830s, when reasonable statistics rather than guesswork and pronouncements of contemporaries become the basis of our estimates, the average Manchester mill had about 400 workers. The very large and very small plants made room for medium-sized ones, with between 150 and 400 workers. The domestic spinner had by that time long disappeared.

Some of the other branches of the cotton industry were also quick to move into factories: carding, calico printing, and bleaching were all absorbed. Weaving, however, was a different matter. Although inventors experimented with a variety of mechanical looms, the power loom did not make its effective entry on the scene until the 1820s. Until then, the handloom weaver, operating from his own home, not only was not threatened by the factory, but actually prospered. With the spread of power looms after the 1820s, home weaving rapidly disappeared. Many of the former handloom weavers simply joined the factories they could not beat.

In textiles other than cotton, the factories marched on as well. In worsteds, spinning was mechanized early and followed the trajectory of cotton toward a rapid transition to factories; combing, however, proved difficult to mechanize and was left to domestic or small-scale producers until the mid- nineteenth century even when the yarn was spun in factories. Once again, we see a "mixed" system in which some stages of the production were carried out domestically, whereas others were concentrated in factories. Wool lagged even further behind, because spinning of carded wool proved difficult to mechanize. In flax spinning, large-scale factories emerged using the wet-spinning process invented in France and adopted in Britain in about 1825.[7] Hand looms in linen persisted until deep into the second half of the nineteenth century. On the whole, the transition

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[7] John Marshall of Leeds was the leading flax spinner in Britain, and his large mill was world- famous. The building was designed by an architect who based it on the single-story temple of Karnak in upper Egypt.

from domestic manufacture to factory was the most dramatic in textiles, but even there it took a century or more to complete.

In other industries, the transition was less spectacular because some large-scale establishments already existed by 1760, or because for one reason or another domestic manufacturing could linger on. This was especially the case in iron. The few large ironworks around 1750 notwithstanding, this was still primarily a small-scale industry, with much of the work carried out in little forges adjacent to the homes of blacksmiths and nailers. Cort's great invention of puddling and rolling around 1785 changed the face of the industry and made large-scale production in the refinement process efficient. Some of the new ironworks grew to unprecedented proportions, such as the Cyfarthfa ironworks in Wales, which employed 1,500 men in 1810 and 5,000 in 1830, and the Dowlais works, which were of comparable size. At the same time in the hardware and engineering trades, small workshops predominated (Berg, 1994b). In the metal trades of Sheffield and Birmingham such as cutleries, toymakers, armorers, nailers, and bucklemakers, large factories were rare and much of the production was located in small workshops and houses, interspersed with a few larger establishments.

It is sometimes felt that the rise of the factory in which workers were concentrated under one roof and subjected to discipline and supervision was not a significant break with the past. The discontinuity of the Industrial Revolution has at times been overstated. It was not the beginning of "capitalist" production; the putting-out system could be quite hierarchical and tightly controlled. It was not the beginning of mechanized production, because various types of machines were widely employed in the Middle Ages. Moreover, pre–Industrial Revolution manufacturing produced organizational forms that could accommodate a variety of technical needs. For instance, it could and did practice a division of labor at a fairly high level.[8] Yet the Industrial Revolution marked the beginning of the process in which the household would eventually lose its position as the prevalent locus of production. For that to be true, perhaps it did not matter much whether people worked in workshops of 20 or 400 employees. The welfare and other economic implications of this change were far-reaching.

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[8] Furthermore, Berg (1994b) has argued that decentralized organization forms lent themselves well to innovation and that small firms that practiced "flexible specialization" were a viable alternative to the factory.

Some Implications

The rise of the modern business plant as a locational unit has had an enormous social impact first fully identified and described by Marx. He developed the notion of "alienation" and stressed the historical significance of the emergence of an industrial proletariat, the need to form a docile and malleable labor force, and the significance of people spending much of their life interacting with strangers, subjecting themselves to the hardships of the shop floor and to the coercion of the factory clock.[9] Many modern writers echo Marx's views.[10]

The full welfare implications of the rise of the factory for the household go beyond the social phenomena Marx was interested in. They include the social cost of commuting. Little is known about the frequency and average distance of commuting in the early factory days.[11] Before urban mass transit, the only way for laborers to commute was by walking, which limited the commuting distance and led many factory masters to supply living quarters in so-called factory villages. But these were rare in urban areas. Technologically-driven changes in the number of hours spent commuting reduced overall economic welfare in ways not wholly captured in national income statistics, because some commuting crowds out leisure. Insofar as the time costs of commuting were compensated for in higher wages, these welfare costs were borne by others, but society as a whole still had to pay the cost. A change in the level of commuting does not "distort" the measurement of GNP as such, but any replacement of leisure with commuting time will change welfare without changing the measured aggregates. This distortion was small before 1850, and relative to the growth of incomes, probably not very large afterward either.[12] A sudden change in commuting time, however, could have significant implications for economic welfare.

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[9] It might have seemed a good idea to hire factory labor in family units just as some of the pre-Industrial Revolution industries had done, and some authors have in fact argued that the practice was quite common (Smelser, 1959), but others have shown that it involved only a small portion of the labor force (Landes, 1986, p. 610, n.60).

[10] Pollard cites Ashton's laconic comment that "there was no strong desire on the part of the workers to congregate in large establishments" as "an understatement to the point of travesty" (1968, p. 195).

[11] The distances cited in Parliamentary Papers (1831–32) are quite striking: There are repeated mentions of workers living one full hour's walk away (pp. 5, 19, 95, 98, 350, 365). The source makes it difficult to conclude how typical this distance was, but in any case, the time cost of the commute represented a social cost that was rare before the Industrial Revolution.

[12] The same point is made by Nordhaus and Tobin (1973, p. 521), one of the few attempts to adjust the National Income accounts to the many ambiguities that modernization throws in their path.

A related but different welfare reduction due to the rise of the factory is the collapse of the leisure-income choice to something close to a single point. Under the old regime, domestic workers could choose essentially any point on the leisure-income trade-off—that is, they could choose to work less if they liked, at the cost of less income. This freedom of choice was much reduced once workers had to submit to the factory regime. Part-time employees were rare, and absenteeism was usually a cause for fines or dismissal. Even a combination of higher wage with lower leisure, it can readily be shown, could be welfare-reducing if it became an "all or nothing" choice.[13] In addition to losing the choice over the quantity of leisure, workers lost control over the *timing* of leisure. The factory system regimented the allocation of time and left no opportunity for individual preferences and flexibility. Moreover, insofar as the factories drove the employees to work faster and harder to keep up with machinery, they reduced the workers' choice-set even more by curtailing "on-the-job" leisure consumption. Factory owners often severely limited what workers could and could not do outside their break periods, such as leave the room without permission. This decline in the laborers' options was compounded by the relentless erosion of the undeniable opportunities for joint production of income and household services within the home, especially as far as child care was concerned. The loss of this opportunity for domestic multitasking further increased the upward bias in the income statistics as a measure of welfare.

Beyond that, of course, were the nonpecuniary characteristics of the factory relative to the home. Although actual factory conditions varied a great deal, and the "dark, Satanic mills" and large coal mines did not employ a majority of the workers, the shift to the noisy and dangerous conditions of many new mills probably reduced most workers' well-being. If factory work and life in industrial towns and villages became more onerous, risky, or disagreeable, rising real wages should be interpreted as a compensating differential.[14] The evidence for a significant nationwide increase in real wages, however, has been called into question (Feinstein, 1998). If real wages failed to rise appreciably, yet working conditions worsened, a decline in overall economic well-being cannot be ruled out.

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[13] In practice, of course, workers could exercise more freedom of choice than the grim all-or-nothing regimes suggest. The frequent complaints about absenteeism, especially on "St. Monday," suggest that the conditioning of workers took generations. All the same, the evidence suggests that by the early nineteenth century, the practice of taking Mondays off was in decline (Voth, 1998).

[14] This effect has been measured in an ingenious paper by John Brown (1990), who concludes that despite rising real wages "there was virtually no improvement in living standards until at least the 1840s and perhaps the entire first half of the nineteenth century" (pp. 612–13).

For the economist, it is a logical puzzle why, in the absence of coercion, workers would voluntarily agree to work in factories if doing so reduced their utility. Many workers were paid a factory or coal-mine premium as a compensating differential, and workers were provided with benefits such as housing, schooling for their children, and even milch cows (Chapman, 1967, pp. 159–60). Insofar as this was inadequate, however, factory owners, especially in the countryside, relied on pauper children and orphans "borrowed" from workhouses.[15] Beyond that, however, the economic logic of the Industrial Revolution implied that workers might end up working in factories even if it made them worse off than they were before (though not worse off than if they stayed home). The reason is that the opportunity cost of many of these potential factory employees was set by what they could earn in cottage industry. This alternative declined rapidly because of factory competition and by 1850 was, in most cases, no longer available. The factories, by relentlessly driving down the price of manufactured goods, reduced the earnings of those working at home and thus forced them (or their offspring) to abandon their cottages and seek work in the mills or emigrate.[16]

The separation of worker from household also meant that human capital formation began following different rules: before the emergence of the factory, the only agent with any interest in training and human capital formation beside the agent herself was his or her parent.[17] With the proliferation of factories, employers increasingly took an active interest in the education and training of their labor force. There was an obvious complementarity between the fixed capital in the plant and the human capital necessary to operate it (see Galor and Moav, 2001). There is evidence suggesting that worker training initiated by the capitalist class became increasingly important with the Industrial Revolution. The skills that were in abundant supply around 1750 were largely the skills of the

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[15] Some of the transactions between poor law authorities and mill owners resembled nothing as much as the slave trade; e.g., the purchase of seventy children from the parish of Clerkenwell by Samuel Oldknow in 1796 (Mantoux, 1928, p. 411). Recruiting agents were often sent to scour the surrounding countryside in search of workhouse labor, and some of these children were brought in from the other end of the country, indicating that for some industrialists pauper apprentices were indeed a cheap and satisfactory but hardly voluntary form of labor.

[16] The model showing this result assumes only that labor productivity in a factory setting is higher than in a domestic setting. For a formal demonstration of this general equilibrium model of the Industrial Revolution see Mokyr (1976).

[17] The large-scale putting-out industry usually required low levels of skills; the more skilled craftsmen were by and large independent.

blacksmith, not those of the mathematical instrument maker. The machines required levels of competence that were scarce, even in Britain.[18]

Much of the education, however, was not technical in nature but social and moral. Workers who had always spent their working days in a domestic setting had to be taught to follow orders, to respect the space and property rights of others, and to be punctual, docile, and sober. The early industrial capitalists spent a great deal of effort and time in the social conditioning of their labor force, especially in Sunday schools, which were designed to inculcate middle-class values and attitudes, so as to make the workers more susceptible to the incentives that the factory needed and to "train the lower classes in the habits of industry and piety" (Mitch, 1998, p. 245). At the same time, a gap emerged between "firm-specific" human capital (with the factories training workers in the skills needed for the core competencies of that firm) and "general" human capital such as literacy and middle-class values of diligence and docility that the worker could take anywhere. Factory masters thus began subsidizing schools, but students' families were almost always expected to pay part of the cost. Some factory masters signed up their workers for long contracts or indentures ranging from five to twelve years (Chapman, 1967, p. 173).

The transition from household to plant involved a more subtle issue of the changing nature of competition. In a classical world, in which firms produce and households consume, firms compete with each other in a Schumpeterian sense. Firms that pick best-practice techniques prosper and expand. Those who choose inefficient techniques lose market share and profits and eventually shrink and disappear. An inefficient owner/manager of a large competitive firm will see his firm go under or his assets bought out and labor hired away by another. This kind of Darwinian mechanism does not work very well for a world of family firms in which the home is the plant and the household is the unit of production, because households are constrained from growing too large and there is no well-defined exit process. Households that employ inefficient techniques may have lower income and utility, but only in extreme cases will these bad techniques lead

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[18] James Watt, often impatient with his workmen, complained that Soho people had no accuracy and that he never could leave the firm without some gross inaccuracy or blunder occurring (Pollard, 1968, p. 206). It is less clear to what extent the new cotton industry required training: some elite spinners surely possessed skills that had to be acquired over long periods, but they tended to be exceptional (Mitch, 1998, p. 261). By using the existing institution of seven-year apprenticeships —a medieval legacy—Britain's craftsmen bred their own and supplied the needs of a growing modern sector. Factories also practiced "migration," the rotation of workers from job to job. This system of accumulating human capital probably did not work as fast and efficiently as the factory masters would have liked, but surely worked better than in any other country at the time.

to their elimination in a Darwinian sense.[19] Household-firms competed in various markets, but mechanisms that eliminated efficiency differences between them worked only poorly: social learning and emulation may have led to changes in technical choices if households had a chance to observe each other closely and compare notes, as happened in craft guilds. The more efficient and industrious producers enjoyed higher incomes, but they could neither grow nor rapidly expand their numbers.[20] Inefficient or lazy household-firms may not have "died" unless their inefficiency reached truly disastrous dimensions.

If there were economies of scale in just learning about new techniques, households were at a further disadvantage, and an economy that consisted of home producers might experience a slower rate of diffusion of new technology. To be sure, such problems were to some extent overcome by informal networks, and later in the century by farm cooperatives. Moreover, even if somehow households observed that their income was different from others, they could not easily distinguish between differences in the techniques chosen and pure rents (that is, income differences due to differences in endowments that they could not change). Concentrating all workers under one roof allowed an immediate comparison between workers of different productivities and the remediation of obvious problems through instruction and the creation of better incentives. Factory masters, knowing that they might go under if they did not choose the right techniques, could whip workers (sometimes literally) into using the most efficient techniques.

In the real world of economic history, things were rarely that extreme. Urban artisans did pool their knowledge and compared techniques in use.[21] In the early stages of the Industrial Revolution there was a considerable variety among the practices used by factories, and shaking out the inefficient was itself an imperfect process. All the same, the rise of the factory represented a growing stringency of the competitive environment

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[19] In a putting-out setup, the entrepreneurs who owned the capital and marketed the final product would prefer to employ more efficient workers if there was a substantial cost in terms of capital utilization and product quality due to lower technical ability by bad workers, and if they were unable to recognize such workers and vary their piece rates accordingly.

[20] One "Darwinian" mechanism did work to some extent: very successful and able craftsmen would attract more apprentices than their competitors, and thus transmit superior skills that in the long run would drive out inferior ones.

[21] Recent research suggests that the enhancement and transmission of human capital was—at least in the early stages—the main purpose of urban craft guilds (Epstein, 1998). But with the growing migration of manufacturing to the countryside in the centuries before the Industrial Revolution, craft guilds lost much of this function and more commonly acted as a barrier to innovation.

and thus increased allocative efficiency and speeded up the adoption of new best-practice techniques.

Explanations

Why did the factory arise when it did? I submit that its rise is inseparable from the growth in the knowledge-base of production. I do *not* maintain here that knowledge in the sense I use it is the single explanation, but that it has hitherto not received sufficient emphasis. Moreover, it interacts with the other arguments and compounds them.

There are three main explanations in the current literature for the unprecedented phenomenon we now call the rise of the factory.[22] One relies on fixed costs and technical and physical economies of scale and scope, which might have caused the minimum efficient size of plants to become larger than the household. A second explanation is drawn from the modern micro-economics of the firm: because of asymmetric information and the division of labor, costs were higher in decentralized households, and the new technology changed the benefits and costs of monitoring and the incentives to self-monitor. A third argument is that by concentrating all workers under one roof and placing them under supervision, actual labor effort is enhanced. I briefly survey each of these explanations and then propose a fourth one.[23]

Fixed costs and scale economies. The most obvious explanation of a shift in plant size is that the new technologies changed the optimal scale of the producing unit and introduced increasing returns where once there were constant returns. Some equipment, for purely physical reasons, could not be made equally efficiently in small models that fit into the living rooms of workers' cottages and thus required large plants: iron puddling furnaces and rollers, steam and water engines, silk-throwing mills, and chemical and gas works all required relatively large production units. Heating, lighting, power supply, security, equipment maintenance, storage facilities, and inventory control were all activities in which scale economies were the result of technical considerations. In addition, there were nontechnical economies of scale such as marketing and finance, but many of these advantages were at the level of the firm, not the plant. To some extent they had been resolved by the pre–Industrial Revolution putting-out firms. What

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[22] It might be noted here that this question was raised in very explicit form by Charles Babbage (1835) in a chapter entitled "On the causes and consequences of large factories."

[23] Some of what follows below is adapted from Mokyr (1998c). For a more elaborate and detailed survey of the literature, see Geraghty, 2001.

made the difference for the locus of production in this view is large-scale mechanization.[24]

Machinery and other technological changes meant that fixed costs at the level of the plant went up. As soon as fixed costs become important, the employer has an interest in supervising the workers, because shirking and volatility in labor supply reduce the utilization rate of the fixed capital and are costly to the employer.[25] By the force of this argument, the rise of the factory was a wholly technological event. Of course, "fixed costs" were heterogeneous: if the main attraction was a heated, lighted room, in which relatively inexpensive equipment could be placed, raw materials and parts supplied, and some instruction given, the most likely outcome would be setups in which workers rented equipment, worked on their own account, and chose their own hours, as still could be seen throughout Britain in the nineteenth century. If, on the other hand, the raw materials and the equipment were valuable and complex, factory discipline (setting the hours worked, controlling the effort put in, and managing the allocation of time and effort over different tasks) would increasingly be the norm.

Information costs and incentives. And yet this cannot be the whole story. If it were, we would see a tighter correlation between mechanization and the transition to "manufactories." Berg (1980), Jon S. Cohen (1981), and Szostak (1989, 1991), among many others, have maintained that technological change and mechanization were not necessary for the establishment of centralized workshops, which in fact preceded the great inventions

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[24] Long ago, Usher wrote that "machinery made the factory a successful and general form of organization....Its introduction ultimately forced the workman to accept the discipline of the factory" (Usher, 1920, p. 350). Landes has restated this argument in unambiguous terms: "What made the factory successful in Britain was not the wish but the muscle: the machine and the engines. We do not have factories until these were available" (1986, p. 606) . Even Maxine Berg, who has argued forcefully that small-scale production was viable until the 1830s and beyond, concludes that the transition to the factory system "proceeded at a much faster pace where it was combined with rapid power-using technological innovation" (1994b, p. 207).

[25] This insight is hardly indebted to modern theory: Karl Marx, in a famous passage, cites an industrialist telling the economist Nassau Senior that "if a labourer lays down his spade, he renders useless, for that period, a capital worth 18 pence. When one of our people leaves the mill, he renders useless a capital that has cost £100,000" Marx (1967, Vol. I, pp. 405–06). William Smith, a Glasgow cotton spinner, noted that "when a mantua maker [a typical domestic industry, employing at most two or three workers] chooses to rise from her seat and take the fresh air, her seam goes a little back, that is all; there are no other hands waiting on her...but in cotton mills all the machinery is going on which they must attend to...when there are a great number of people congregated together, there is a necessity for the rules of discipline being a little more severe... because the profits of the master depend upon the attention of those employed" (Great Britain, 1831–32, p. 239).

of the last third of the eighteenth century.[26] One explanation suggests that factories, by saving on transaction costs, were simply more efficient than cottage industries (whether putting-out or independent producers), and thus their rise was inexorable (Williamson, 1980). Such a simplistic approach cannot possibly do justice to the historical reality (S. R. H. Jones, 1982, 1987; Szostak, 1989). After all, the domestic system survived for many centuries, and its demise was drawn out over a very long period. Cottage industry practiced a fairly fine and sophisticated division of labor, and the proximity of cottages to each other makes the reliance on physical transaction costs a weak reed. Industry studies (e.g., S. R. H. Jones, 1987) confirm the importance of mechanization and technology as a *primum movens* in the emergence of factories, although they rarely specify through which mechanisms machinery brought about the factory and do not explain the emergence of centralized workshops in the absence of technological breakthroughs.

Some answers must come from the economics of information and especially principal-agent problems. Paying workers a piece rate—uniformly practiced in putting-out industries—solves this problem if the employer can assess the quality and quantity of the final product and if there are no cross effects between workers' productivity (so that the effort of one worker does not affect the output of another). In a world in which each worker makes a homogeneous product with simple tools, the employer has no interest in effort enhancement because workers who are inefficient will be automatically penalized *pro rata.*[27] The proportionality between output and wage provides what is called a "high-powered incentive": each worker will provide the level of effort he or she prefers. But in a more complex world of expensive equipment that needs to be used and maintained, or in which product quality is important but hard for the employer to measure, employers want to monitor and control the efforts of their employees and not just the fruits of these efforts. Effort enhancement meant setting up incentives, but in domestic industry it was impossible to observe labor input (either hours worked or the effort expended). The

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[26] Berg (1994b, p. 196–97), Hudson (1992, p. 28), and Szostak (1989, p. 345) point to industry after industry that established centralized workshops employing practically the same techniques as cottage industries: wool, pottery, metal trades, even handloom weaving and framework knitting. Clark shows how certain industries—including pin making —practiced a fine division of labor in central workshops but did little to enforce discipline and punctuality (1994, p. 155) . Rosenberg and Birdzell feel that "the spirit of the times was centralizing management before any mechanical changes of a revolutionary character had been devised." Had the steam engine and semiautomatic machinery never been invented, "more and more control would have devolved upon the factory master"(1986, p. 186).

[27] *Within* the domestic system, of course, master weavers and similar artisans had very good information on the quality of the work of their family members and apprentices, and for that reason it was "considered better than having the weaving done in a factory" (Partridge, 1823, p. 19).

merchant-entrepreneurs who managed the putting-out system—if they cared at all—had to infer input from output. For all practical purposes, employers who wanted to pay time wages had to move workers to factories (where they still had the option to pay some of the workers piece wages as well). But why would they want to?

In a classic paper, Edward Lazear (1986) analyzed the conditions conducive to an employer's choosing between a time and a piece wage. In his model, once there is fixed capital in production, the owner will care about the effort put in by the worker. Owners then will have to either pay a piece wage and bear the expense of monitoring the quality-adjusted quantity of output, or pay a time wage and monitor the input directly, which could not be carried out outside a factory setting.[28] Given that monitoring costs varied from activity to activity and product to product, it is not surprising that we see a bewildering diversity of piece and time wages was used. Lazear observes that whereas piece wages introduce a direct proportionality between effort and payment, time wages could be and were made contingent on some minimum of effort supplied. It might be added that by paying slightly higher wages than the workers' opportunity costs while threatening dismissal if efforts fell below some level, time wages could be made compatible with optimal levels of effort.

Measuring net productivity in a piece-wage putting-out world thus ran into two difficulties. One was that workers had an incentive to increase their earnings by cutting corners on quality and finish and to make verification by the employer difficult. This is a classic problem of asymmetric information: the worker knows where he can "cheat," making it costly for most employers to monitor the quantity and quality of output but for the simplest processes. Lazear notes that paying a time rate allows the employer to monitor quality by controlling what happens on the shop floor, and he can also persuade the worker that for the same level of wage and effort he or she can trade off quantity for quality to attain the combination the firm desires.

The other difficulty the domestic system encountered was that when the employer owned the capital—as was increasingly if by no means uniformly the case in the putting-out system—he needed to supervise the worker's handling of his property. Embezzlement of raw materials (which usually belonged to the capitalist) was a widespread complaint (Styles,

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[28] In addition to the standard problem of monitoring costs, Lazear points out that paying a piece wage has a sorting function, and if workers are very heterogeneous in their ability, it makes more sense—for a given output-monitoring cost—to pay them a piece wage. In this context, firms with large fixed costs or physical capital will pay a mixed wage; the higher the costs of physical capital, the higher the output-independent (time-dependent) component.

1983).[29] The problem of embezzlement, like quality control, was one of asymmetric information; measuring the precise quantities of yarn supplied to a weaver and comparing those with the final output was itself costly, and had to be assessed against normal quality defects and losses of raw material during production, which the employer did not always observe directly.[30] When the equipment became more expensive and sophisticated, such as the early jennies that were still small enough to fit in a worker's home but cost far more than an ordinary spinning wheel, employers needed to be able to monitor how the worker handled the machines. Even when a piece wage was possible, then, it became increasingly attractive for employers to monitor input as well as output. Observing worker effort became important because a worker could harm his employer by damaging expensive machinery and interfering with other workers, much as he could by pilfering materials.[31] Geraghty puts it well: "Over the course of the Industrial Revolution, the task of a typical industrial worker was transformed from a single-minded focus on producing as much output as possible to a multidimensional job, which also required attention to product quality and maintenance of expensive assets" (2001, ch. 3, p. 40).

Behind the question "will a piece wage be paid?" is of course the classic "team production" problem raised by Alchian and Demsetz (1972): if individual contributions to output cannot be disentangled, supervision and monitoring are necessary just to make sure that the workers have the right incentives and do not shirk.[32] In factories there was the option of paying workers a time rate, which would be necessary if the marginal product of labor were hard to assess or beyond the worker's control. These

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[29] See Berg (1994b, p. 226). Social control gradually invaded the domestic economy during the years of the Industrial Revolution. A series of acts passed between 1777 and 1790 permitted employers to enter the workers' premises to inspect their operations, ostensibly to curb embezzlement. Unwin concludes that by this time "there was not much left of the independence of the small master, except the choice of hours" (1924, p. 35).

[30] Introducing factories , of course, did not eliminate embezzlement altogether but made it possible for employers to set up safeguards against it. Robert Owen noted that when he started to work at the Lanark mills in Scotland, "theft was very general and carried on to an enormous and ruinous extent. To make sufficient profits I adopted checks of various kinds to render theft impracticable...[and] devised a plan by which losses would be at once discovered"([1857], 1920, pp. 79, 111).

[31] This problem will be recognized as a standard multitask principal-agent problem analyzed by Holmstrom and Milgrom (1991), who note that a hard problem for the firm is to allocate efforts and time of workers between their various duties if monitoring costs differ from activity to activity. If it is difficult to measure the performance of an agent in one activity, it makes little sense to produce strong incentives for workers in another. Thus the harder it was to monitor the way the employee treated the equipment and unfinished products he was given, the less the incentive to pay him a piece wage.

[32] A formalization of the problem was presented by Holmström (1982), who pointed out that the need for a "monitor" is created by the fact that unobservable actions by workers lead to nonzero marginal products.

time rates could then be supplemented by various incentive schemes that extracted maximum effort from workers and made them allocate effort correctly among tasks (including maintaining the equipment).

Yet this argument does not, by itself, explain the rise of the factory: why did "team production" become important after 1780 and not a century earlier? The answer must be that the new technology required more team production.[33] In part this change was due to the introduction of continuous-flow production as was used in the large cotton-spinning mills and the Portsmouth blockmaking factory, and in part because of a finer and more closely integrated division of labor. With continuous flow, the speed of the entire production process was set by the plant manager, and the interest in supervision and control of individual workers became obvious, because in its absence the speed of production became equal to the speed of the slowest worker.[34]

The rise of the factory, in this interpretation, was indirectly the result of changing technology. Above all, the new technology required larger amounts of fixed capital, and the joint use by many workers of the same equipment made the measurement of marginal contributions to net, quality-adjusted output more difficult. The movement to factories was reinforced by consumer demand. Szostak (1991) points to the integration of British markets due to falling transportation costs in the second half of the eighteenth century. In an integrated market, he argues, there was growing desire by consumers to purchase a product of standardized quality. Input monitoring became important when consumers insisted on products of easily verifiable quality. Workers were expected to produce more uniform products and to conform to lower tolerance limits on the various dimensions of the final product. Employers had to worry about the variance of the final products not just because a higher variance made the measure-

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[33] Alchian and Demsetz themselves point out that technological development will expand the role of the firm, and add, with some historical license, that "with the development of efficient central sources of power it became economical to perform weaving in proximity to the power source and to engage in team production" (1972, p. 784). They point out that with the invention of steam, the sharing of power sources made team production more important. They confuse "firm" with "plant" (a putting-out merchant was clearly a "firm") and get the history of weaving wrong (factory weaving did not come into being with central power sources as much as with the solving of the complex mechanical problems of making a functional power loom in the 1820s), yet their intuition about the rise of the factory is correct.

[34] Continuous flow was already typical of the early Arkwright-type factories, but in that respect the cotton-spinning industry may have been atypical (Chapman, 1974, p. 470). Batch production was still the rule in the vast majority of early factories, and continuous-flow processes became more widespread in manufacturing only after 1870.

ment of mean quality more costly, but because variance entered independently as a quality attribute.[35]

Labor effort. Stephen Marglin (1974–75) revived a Marxist tradition by arguing that factories emerged when workers were placed under one roof in order to make them work longer hours than they would have if left at home. Because the piece wage was less than the marginal revenue product, he maintained, the more time workers put in, the higher the capitalist profit. This view is little more than a standard left-wing account according to which factories enabled employers to exercise more control over their workers and to squeeze more profits out of them. In this interpretation, then, technological progress is not the *primum movens.* Discipline and supervision in large factories in this view were not the means to adapt to a new technological environment, but constituted the road to increased output and profits. Technological progress was a byproduct of the intensification of social control. Interestingly, after this argument had been effectively demolished (see especially Landes, 1986), it was rejuvenated by Clark (1994). In a clever but ultimately inconclusive argument, Clark turns Marglin's view on its head and maintains that factory discipline was introduced to elicit more effort from workers lacking in self-control, so that they would "coerce themselves" to work harder and earn higher wages.[36] It might be added that Clark's argument works only when there is considerable fixed capital involved (because that allows the capitalist to spread his capital costs over more output when workers' efforts are enhanced, thus enabling him to pay them more) and insofar as the increase in fixed costs in manufacturing was due to new machinery—thus technologically determined—Clark's theory, too, boils down to a technologically driven interpretation.[37]

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[35] Langlois (1995) has argued that as manufacturers produced more standardized products for larger and larger markets, their fixed costs started involving specialized tools designed just for that, such as jigs and dies that make screws and other standardized parts. In other words, larger markets and standardized output made it worthwhile to make Allyn Young's famous hammer (which as he noted would be wasteful to make to hit a single nail).

[36] In his paper, Clark foreshadowed theoretical work by David Laibson (1997) and others following a suggestion by Thomas Schelling (1992), which has reintroduced to economists the issue of self-control and precommitment behavior in dynamic models. These preferences do indeed show why rational agents would voluntarily restrict their choices. Much of that work has been directed at issues of saving, but there seems no reason why the idea cannot be extended to labor supply. At the same time, any direct evidence for such precommitment behavior on the part of British workers—deliberately restricting their own choices—is lacking.

[37] A different interpretation of the need to discipline can be formulated in terms of a Grossman-Hart model of the firm: in a normal situation, employees own no assets and yet have to be made to perform efficiently. Because not all early nineteenth-century workers could be made to respond sufficiently to financial incentives, an element of coercion in the form of harsh discipline (especially for child laborers) was a substitute for an efficient incentive structure.

These explanations are not alternatives, but reinforce one another, creating synergistic effects. Organizational and technological forces interacted to increase the total advantage of the factory by more than just the sum of the individual components (Geraghty, 2001). A simple example of this interaction is the economies of scale in worker supervision, in which increasing returns were amplified by the need to monitor worker input.

The division of knowledge. Adam Smith famously believed that specialization and the division of labor lead to economic progress through three separate processes: the growing familiarity of a worker with the process he is assigned to; his ability to produce improvements on it once he is thoroughly familiar with it; and the savings of time involved in moving from one task to another. The idea of the division of labor proposed by Smith was further picked up by Charles Babbage, who noted that specialization was useful not only for the reasons laid out by Smith, but also because workers had different inherent skill endowments and it would be wasteful for employees to carry out tasks for which they were overqualified. An optimal matching of tasks to (exogenous) ability was a key to efficiency (Babbage, 1835, pp. 175–76; Rosenberg, 1994, pp. 28–29).

Whatever the case may be, the division of labor in and of itself does not explain the emergence of factories. Up to a point, the domestic system lent itself well to a division of labor, including—when necessary—the establishment of larger workshops away from homes, where some stages of production (such as wool finishing) could be carried out when the optimum scale made domestic production impractical. The costs involved in moving intermediate products from worker to worker were not insubstantial, but they have to be weighed against the considerable costs of putting all workers under one roof. After all, under the domestic system the employees themselves were responsible for the costs of their dwellings, and much of the fixed cost of early factory owners consisted of rent. This ratio shifted increasingly in favor of the factory system in the second half of the nineteenth century, when continuous-flow processes became more and more common in manufacturing.

Even together, then, Smith and Babbage did not wholly explain the phenomenon of specialization. As time advanced, more and more knowledge or competence was necessary to operate the best-practice techniques in use. What determines the minimum level of competence needed to operate a technique? Given any epistemic base of technology, increasingly complex instructions and more sophisticated machinery required a higher level of competence. In this way, innovation created the need for a division of labor and thus for larger plants. To be sure, following the initial introduction of a new technique, as the epistemic base expanded and people came to understand better why a technique did what it did, technological progress and refinement often consisted of the emergence of a "dominant design." Over the life of a technique, the minimum competence needed to operate it declined and it became more user-friendly and codifiable even if it required a broader epistemic base to be invented. Increasingly, useful knowledge could be "built into" the artifact or the machine, and the more sophisticated and deep the knowledge of the inventors, the greater the gap between the useful knowledge needed to design and build it and the competence to operate it. Driving an automobile and operating a computer were at first tricky activities, but they could be made accessible to millions even if their operators could not repair, let alone design, the artifacts. In the limit, we could imagine an economy in which technology is designed by geniuses and operated by idiots, as Gavin Wright once remarked.[38] All the same, in the early stages of the Industrial Revolution most machinery was custom-made, demanding in-house expertise and tacit knowledge for operation, repairs, preventive maintenance, and so on. As the amount of technical information (to say nothing of other forms) increased, household-sized firms started to be subject to what we would call today information overload (Bresnahan, Brynjolfsson, and Hitt, 2002). Factories relied first and foremost on the skills and knowledge of the owner or partners, and then on that of machinists, mechanics, chemists, carpenters, filers, foremen, and other specialists. As long as there were enough specialists about, the skills of the other mill-operatives may have less important to productivity.

As the minimum competence requirements in manufacturing increased after 1760, efficient production required more knowledge than a single household could possess. In particular, the new equipment and materials required a fair amount of trial and error and experimentation and were still a distance away from the "off-the-shelf" products that became available later. This was realized early: in the 1806 report to Parliament on the woollen industry, the commissioners noted, "It is obvious, that the little Master Manufacturers cannot afford, like the man who possesses considerable capital, to try the experiments which are requisite, and incur the risks, and even losses, which always occur, in inventing and perfecting new articles of manufacture, or in carrying to a state of greater perfection articles already established....The Owner of a Factory, on the contrary, being commonly possessed of a large capital and having all his workmen employed under his own immediate superintendance may make

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[38] Adam Smith's colleague in Edinburgh, Adam Ferguson wrote in 1767 that "Many mechanical arts require no capacity...ignorance is the mother of industry as well as superstition... Manufactures, accordingly, prosper most where the mind is least consulted" (cited by Schaffer, 1999, p. 129).

experiments, hazard speculation...may introduce new articles and improve and perfect old ones" (Great Britain, 1806, p. 12).

The fixed factor here is not just resources, but the capacity of people to learn and retain information. When the competence needed for production exceeds the normal ability of an individual worker, specialization becomes inevitable. The advantages of specialization were compounded by differences in mental endowment. In the specialized world of the division of knowledge, the smartest workers can be assigned the most complex chunks of knowledge. As long as production was simple and could be summarized in a finite number of rules of thumb, a single household could know all there was to know and effectively serve as the unit of production with all the advantages thereof. But the Industrial Revolution and the subsequent technological developments after 1760 led to many production processes that required a level of competence that was beyond the capability of the individual household.

This point was first recognized by Harold Demsetz (1988) and then formalized and elaborated upon by Gary Becker and Kevin Murphy (1992). It suggested nothing less than a new interpretation of the role of the firm. Given the limitations on how much each worker can know, they maintain, the total competence that the firm has to possess is chopped up into manageable bites and divided among the workers, and their actions are then coordinated by management.[39] As Demsetz puts it, "Those who are to produce on the basis of...knowledge, but not be possessed of it themselves, must have their activities *directed* by those who possess (more of) the knowledge. Direction substitutes for education (that is, for the transfer of knowledge itself)" (1988, p. 157).In addition to Smith's dictum about the division of labor being limited by the size of the market, the division of labor is limited by the size of the knowledge set necessary to execute and operate best-practice techniques. The point is not just that each worker knows what she needs to know to carry out her task, but that she is in charge of a subset of the total knowledge required so that others can ask her for it whenever necessary. Asymmetric information is not a "problem" for the firm but an essential way for it to operate. Not only does specialization in knowledge "exacerbate the problem of asymmetric infor-

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[39] A similar point is made by Pavitt and Steinmueller (2002, pp. 15–16) in the context of the knowledge-*generating* activities in the firm (that is, R&D). They point out that uncertainty and much tacit knowledge require "physical and organizational proximity" that guarantees efficient coordination of the knowledge-generating and the production and marketing functions of the firm. The skills involved in this coordination are themselves tacit, and hence some meetings and personal contact remain important in industries that rely on a high degree of innovation, yet this does not mean that outsourcing to individuals working normally from other locations would not be effective.

mation" but it demands it (Kim, 2001). Not everyone can and should know everything. The organizational problem for the firm is to ensure that agents who possess knowledge reveal it fully and truthfully to those who need it. Putting all workers under one roof ensured repeated interaction and personal contact provides maximal bandwidth to maximize the chances that the information would be transmitted fully and reliably. Inside a plant agents knew and could trust each other, and this familiarity turned out to be an efficient way of sharing knowledge. As long as distance was a critical factor in information transmission, the benefits and costs of proximity had to be traded against each other.

The model predicts that as long as the minimum competence requirement is small, plants can be small and coincide with households with all the associated advantages; when it expands it will require either a sophisticated and efficient network for the distribution of knowledge or a different setup of the unit of production. In an age in which direct contact was the main technique of sharing information, marginal access costs were minimized within a single plant, especially when the exact description and formalization of the technical details of production were more difficult than demonstration and emulation. Factories thus served as repositories for technical knowledge and vastly reduced access costs to this knowledge for individual workers. They were not the only possible solution to this problem: professional associations of mechanics, machinists, engineers, and skilled workers functioned as exchanges of technical knowledge. Technical knowledge moved horizontally and vertically through master-apprentice relations. Beyond these organizations were informal networks that operated as knowledge-exchange mechanisms based on reciprocity and trust. Such networks required cooperation and were always threatened by an "invasion" of free-riders and defectors. The factory represented a solution to this free-rider problem. The model further predicts that when knowledge can be shared and trusted among people by means other than personal contact (say, through repeated electronic communication), firms may survive, but large plants may become less necessary.

The domestic system was thus replaced by the large-scale plant/firm, which brought the workers under one roof, made them specialize, and coordinated the exchange of knowledge between them. In addition to unskilled laborers, such plants employed experts: engineers, mechanics, machinists, chemists, foremen, and dexterous, clever employees who interpreted instructions, read blueprints, could fix things that were broken, and knew which tools were needed for each task. Often, of course, this expertise was supplied by the "master" or entrepreneur himself. Watt worked in Boulton's plant in Soho and personally supervised the production of steam engines. In an age in which there were few alternatives to the exchange of information, direct contact was inevitable if the firm was to practice a division of knowledge. Furthermore, as Babbage had already pointed out, because some of those in-house experts could serve a large number of other workers, specialization inevitably created further economies of scale. When textile machinery became increasingly complex, large on-site machine shops headed by master mechanics appeared. It is hard to say whetther the Industrial Revolution on balance raised or reduced the demand for skills. The factories needed *new* technical competence that had to be created *ab nihilo*, and in all likelihood it increased the variance of the skill distribution.

Providing evidence for this interpretation is far from easy.[40] Microstudies at the firm level demonstrate that the vast majority of firms that can be classified as "factories" and used complex machinery also had a maintenance staff of specialists: machinists, mechanics, engineers, and others.[41] Some of these specialists were in very short supply during the early stages of the Industrial Revolution and there is much evidence complaining about their shortage. In the absence of formal engineering and training schools in England, many of these expert workers in the early stages of the Industrial Revolution were imported from Scotland and foreign countries. Boulton and Watt's great Soho works trained many "engine men" who could install and re-fit steam engines, but for other pieces of machinery most firms had to train their own using the age-old apprenticeship system insofar as what they needed exceeded the skills of ordinary artisans such as carpenters and blacksmiths. The poaching of skilled workers was a common complaint, and entrepreneurs who moved their business saw to it that they took these experts with them (Tann, 1970, p. 81; Pollard, 1965, pp. 197–205). Many of the expert tasks were carried out by overseers, but the larger plants often had adjacent machine workshops in which specialists repaired tools and parts.

The 1841 census of Great Britain, the first to provide a detailed breakdown of occupation, unfortunately reported primarily occupations

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[40] Pollard notes that some of the new skills were merely the result of a successful subdivision of labor and that the most successful industrial entrepreneurs of the time such as Boulton and Wedgwood "obtained virtually all their advantages in production from a skilful use of the division of labour" (1965, p. 210) . Given the difficulty in finding and training such employees as he describes, the implicit model here is clearly more in the spirit of Becker-Murphy than Adam Smith's.

[41] Geraghty (2002), has found in a sample of original records mostly dating from the first half of the nineteenth century, that out of thirty-five firms that could be viewed as factories, ten had evidence of using complex machinery but no visible evidence of a separate maintenance class, twenty had a maintenance staff and complex machinery, four had neither, and one firm had evidence of a maintenance staff and no evidence of machinery. The absence of evidence, needless to say, might simply reflect the quality of the evidence and little more.

such as "cotton spinner" without regard to whether the person was a mule operative or a mechanic or machinist. The only of the census's many hundreds of occupations that seems to fit the bill were "engineers and engine workers"(distinct from engine makers). A simple test of the importance of specialization in factory counties is to divide the ratio of such engineers to the total adult male employment in "commerce, trade and manufacturing" for a county by the same ratio for Great Britain (so that a value of 1.00 would mean a proportion of engineers equal to the national average). We can do this again for the 1851 census, based on a sample of the original records and a consolidation of the occupations constructed by Jason Long (2002).[42] The results are presented in table 1.

It may be too much to expect for the two columns to be unequivocally consistent, given that they are quite different indicators. On the whole, however the top third of the table containing the main "factory countries" has considerably higher ratios than those in the bottom third which were agricultural areas in which the workers in commerce and manufacturing were largely shopkeepers and craftsmen. For the United States, a recent study by Ross Thomson concludes that in the 1830s firms that "printed, sawed, spun, wove and made clocks, guns, and floorboards all had to have the skills to maintain, service and repair machines. Many employed machinists, with distinct skills, functions, and spatial positions in factories that differentiated them from other workers" (Thomson, 2002, p. 6).

The Becker-Murphy framework and the asymmetric information framework both point to the central importance of the costs of moving knowledge relative to moving people. It was costly to move workers from their homes to the factory, but even costlier to supervise, coordinate, and instruct them at home. These relative costs are only one factor in determining the location of labor, but they demonstrate the extent to which exogenous changes in information technology and transport technology affect the place where work is carried out. To be exact, locational decisions using a Becker-Murphy "division of knowledge" approach will depend on the benefits of specialization and the ratio of the full costs of moving information and people. The benefits depend on the complexity and sophistication of the competence needed to execute the technique.

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[42] The published occupational tables of the 1851 Census of Britain (Great Britain, 1852–53) are useless for the purpose of testing the hypothesis of increasing inhouse expertise in factories, because the tables classified workers according to the characteristics of the final product or service they produced or the main raw material processes, rather than by the tasks and responsibillities of the worker, thus for instance grouping machinists and engineers in the cotton industry with unskilled laborers in the manufacture of cotton.

Table 1: Relative ratios of "expert occupations" in Britain, 1841 and 1851.

County	Engineers and Engine Workers, 1841 (relative to Commerce and Manufacturing).	"Expert Occupations," 1851 (Long Sample)
Lanarkshire	1.96	1.97
Lancashire	1.19	2.27
Yorkshire WR	0.71	3.12
Staffordshire	1.88	0.88
Middlesex	0.73	0.52
Cheshire	0.79	1.30
Gloucester	1.17	0.52
Warwick	0.53	0.69
Norfolk	0.27	0.13
Kent	1.02	0.57
Devon	0.08	0.66
Essex	0.34	0.21
Lincoln	0.32	0.47
Wilts	0.55	0.34

Source: 1841: Great Britain (1844), *passim*; 1851: Supplied kindly by Professor Jason Long.

In a world of fairly simple techniques, a single producer could work on his own, in which case there would be no informational reason for him or her to work anywhere else but at home, though there still could be fixed costs and other sources of increasing returns. Once techniques became so complex to execute that no single household could contain all the competence, a coordinated exchange of expertise became inevitable. In the technological context of 1800 or 1850, the only way this could be done effectively was by direct contact because the costs of moving most knowledge expeditiously were normally very high. In that sense the factory became an obvious solution, and would emerge even when economies of scale were modest and problems of asymmetric information and piece wages relatively unimportant. At the same time factories would exist even when minimum competence requirements were small if there were economies of scale or high monitoring costs. There may not have been "four good reasons for anything," but in the case of the rise of the factory there were at least three.

Moreover, knowledge has to be transmitted not only across space but also across time. As in all good evolutionary models, a model of knowledge must take into account that it is embodied in carriers who are subject to wear and tear. Unless they can pass their knowledge on to new generations, it will go extinct. The pre–Industrial Revolution economy had two parallel transmission mechanisms: from parent to child, and from master to apprentice. Such a system worked well when the competence required to operate a best-practice technique was relatively limited and did not change much between generations, and when there were few gains from applying the knowledge in one field to another. By 1750 these assumptions had begun to be eroded, and by 1850 they had become obsolete in many industries. By that time the industrial plant had begun to serve as the unit that transmitted this knowledge over time: new hires learned the trade "on the job" by direct contact with veteran workers, observation, and emulation. Hence the practice of learning through "migration" (or rotation) mentioned. With the formalization and codification of much technical knowledge, the importance of the firm as mechanism of knowledge transmission over time declined to some extent, but as long as tacit knowledge was a large enough component of the firm's competence, its transmission over time remained a main function of the plant (Howells, 1996).[43]

The acceleration of technological progress placed domestic workers at a further disadvantage. As new techniques became available after their learning stage in the life cycle was completed, it would be far more costly for homeworkers to keep up than it would be for a large plant. The diffusion and implementation of new techniques to a group of workers in one building was faster and cheaper than if workers stayed in their homes, dup-

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[43] Pollard notes the change in managerial and organizational requirements that accompanied continuous technological change (1968, p. 124). He regards the improvements in management as "over and against" technical changes and does not fully realize the direct causal connection between the two. And yet modern research establishes exactly that: there was a strong and direct complementarity between organizational and technological change. See Geraghty (2001) for an elaboration on how organizational change enhanced the benefits of technological change and vice versa.

lication could be avoided, and most important, workers taught one another. Workers who learned quickly (often younger ones) might pick up new techniques first and help spread them. In an industry of household-sized, self-contained cottages, such diffusion mechanisms would be more costly.[44]

To be sure, much of the knowledge that firms relied on was codifiable and could be looked up in the ever-increasing stream of technical manuals, engineering textbooks, and encyclopedias that became available during this period and could be accessed or purchased from external sources, including other firms. But much of what the new technology required was uncodified or "tacit" knowledge that was hard to buy, sell, or obtain from books and periodicals (Cowan and Foray, 1997; Cowan, David, and Foray, 1999). Moreover, access to codified knowledge required uncodified knowledge that it existed and where to find it, as well as the ability to read, understand, and apply it. These were all by and large tacit skills.[45] Tacit knowledge was costly to acquire as a separate entity, and large plants could train or hire specialists who possessed it and thus were better settings for easy access than individual households.

Modern economists, in the traditions of evolutionary economics and organization theory, treat the firm as a single unit that "knows things."[46] Firms have "corporate core competencies" and "organizational practices."[47] But one could turn this argument on its head: the optimal size of the firm (or plant, to be accurate) is a function of the access costs of this type of information inside a firm relative to the costs of trading it between firms or acquiring it from other sources, and the total amount of knowledge ("competence") necessary to run a best-practice operation in a competitive world. For a given communications technology, the rapid growth of knowl-

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[44] In a putting-out context, keeping technological secrets was of course impossible, and indeed some factories were set up just to keep industrial processes secret (Chapman, 1967, p. 39).

[45] This point is well made by Cowan and Foray (1997) who point out that tacit knowledge is needed to access codified knowledge and that in many ways the two are complements, not substitutes.

[46] See Sabel and Zeitlin (1985) and Scranton (1997). One of the most perceptive of these theorists, Paolo Saviotti, writes, for example, "Firms scan the external environment in order to detect...possible pieces of external knowledge which are useful for their productive purposes. When they find such useful pieces of knowledge, they have to internalize them....The capacity of firms to learn and internalize knowledge depends on the firm's previous knowledge." (Saviotti, 1996, p. 175). Firms have what he calls "knowledge bases," which consist of the collective knowledge used by the organization.

[47] Much of this very large literature is summarized ably by Pavitt and Steinmueller (2002), and Teece et al. (1994).

edge necessary to use the newest techniques (let alone improve them) meant that household-sized firms became impractical. All the same, the technological and informational trade-offs between different forms of organization were sufficiently multidimensional to allow the survival and coexistence of very different forms of organization. The large prototypical factory was just one of these forms. Another was a cluster of much smaller firms—often artisans working from their homes—working in close proximity and exchanging knowledge through informal cooperative channels (Piore and Sabel, 1984). The picture of mass production of standardized output produced by Chandler and others ignores the many industries that needed the flexibility and agility of specialized production.[48] Large factories and domestic artisans were only extreme forms of industrial organization: in many parts of Europe, such as Lyons, Sheffield, and the industrial districts of northern Italy, complex networks have been observed in which home work and factories were combined in a variety of forms.

The large plant/firm in this setup is thus a substitute for the incomplete markets in technical knowledge.[49] I do not mean that such markets did not exist at the time. Britain in the Industrial Revolution had consulting engineers, instrument makers, machine-tool producers, and a variety of independent inventors and mechanics, of whom John Smeaton and Joseph Bramah were the best known, who could be and were hired to dispense advice. The famous firm of Boulton and Watt, especially in its early days, also should be regarded in part as a consulting firm, although later on it produced more and more of the machines at its Soho works. These consultants had predecessors: by 1718 the mining engineer Henry Beighton was already hiring himself out as an advisor on the operation of Newcomen engines and was much in demand (Stewart, 1992, pp. 242–46). Engineering and other specialized expertise, inevitably, was purchased by firms when in-house machinists were inadequate. Entrepreneurs of the time either hired specialists for a specific task, such as the consulting engineers

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[48] Some of these firms were quite large, others were medium and small. Scranton shows that as late as 1923 "specialty production" employed only slightly fewer workers than "routinized" (mass) production. There is no evidence in Scranton's work that much of this specialty production operated anywhere but in plants and factories that were considerably larger than households, but his work is an antidote to the view that in the late nineteenth century Chandlerian high "throughput" mass production became the rule.

[49] The notion that the role of firms is to be above all a *locus* for specific and tacit knowledge has been proposed by many writers in the so-called neo-Schumpeterian school. For examples, see Saviotti (1996); Antonelli (1999); Nooteboom (1999).

working for Boulton and Watt, or subcontracted out work.[50] Such outside professional consultants included the famous British "coal-viewers" who advised coal mine owners not only on the optimal location and structure of coal mines but also on the use of the Newcomen steam pumps employed in mines in the eighteenth century (Pollard, 1968, pp. 152–53). "Civil engineers" was a term coined by Smeaton, who spent much of his life "consulting" to a large number of customers in need of technical advice. At first civil engineers were combined with mechanical engineers, but with the proliferation of machinery and engines, independent mechanical engineers became a separate category.[51] By the middle of the nineteenth century, it became routine even for leading scientists to assume the role of industrial consultant and advisor (Fox and Guagnini, 1999, p. 18). Nonetheless, consultants were of limited use not only because they possessed general knowledge when often firm-specific knowledge was needed, but because of issues of credibility and trust.

For many of the tasks at hand, then, over-the-counter knowledge was not suitable. Technical knowledge, then as now, combined the understanding of general relations and principles with local problems specific to an industry, to a product, and to a set of routines that a firm had adopted. The more specific and local these technical routines were, and the more tacit the knowledge was, the more production had to rely on an in-house supply of expertise. The practice of knowledge-pooling became increasingly applicable. Even in services, the division of knowledge became more common: physicians were attracted to hospitals where expertise could be pooled despite the relatively high codifiability of much medical knowledge. Lawyers, architects, and teachers formed larger units in part for the same purpose, or created professional associations and cooperatives that did the same.

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[50] The mechanics trained by Boulton and Watt at Soho were sought all over Britain for their expertise. Only Soho graduates knew how to use the special Soho slide rule, and an apprenticeship there was "a recommendation to any firm" (Pollard, 1968, p. 207).

[51] The list of great mechanical engineers after 1815 includes some of the inventors who sustained the technological momentum of the Industrial Revolution: William Murdock, one of the co-inventors of gaslighting and James Watt's most talented lieutenant; Richard Roberts, the miraculously gifted inventor of the self-actor; Arthur Woolf, the inventor of the compound steam engine; Henry Maudslay, the maker of many new machine tools and the first to apply mass production to the production of components for the sailing vessels of the British navy; George and Robert Stephenson of railroad fame; Brian Donkin, the inventor of the tachometer and the metal tin for canned food; James Nasmyth, the inventor of the steamhammer; and the Brunels, shipbuilders and engineers.

Factories after the Industrial Revolution

In the decades that followed the Industrial Revolution, the factory system that sprouted in the years after 1760 came to full fruition. As noted earlier, the concentration of workers under one roof depends on the ratio of costs and benefits of moving information relative to moving people. Before 1850, these costs changed little, and the emergence of the factory was due primarily to changes in production technology and the concomitant rise in the benefits of the division of knowledge. While these changes continued at an accelerated rate during the so-called second Industrial Revolution after 1860 or so, there were some major developments in the technology of moving people and information. The second half of the nineteenth century saw some breakthroughs in communication and information technology: the telegraph and later the telephone, as well as a variety of management devices that facilitated the flow of information inside the firm, such as pneumatic tubes, mimeograph machines, public address systems, and typewriters.[52] All the same, the preponderance of productivity gains was in the movement of people: trains, streetcars, bicycles, and internal-combustion cars clearly reduced the costs of moving people relative to moving information.

Production technology continued to favor large units. The Chandlerian firm, as it is often thought of, came to the fore in the closing decades of the nineteenth century, and technical factors were paramount in its emergence. Among these factors were the railroads, which not only became the standard model for the next generation of large firms, but also created ever larger markets for standardized products. In many other industries associated with the second Industrial Revolution, such as steel, transportation, and chemicals, small and household-sized plants were simply impossible. Moreover, the growing modularization of manufacturing, involving the mass production of products based on interchangeable parts and the use of continuous-flow production on assembly lines, made the large-scale production plant, whether identical to the firm or not, inevitable in many industries.

Simple technological factors that increased minimum efficient scale, however, are not the entire story. For one thing, some technological advances reduced optimal plant size or at least flattened the cost curves

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[52] In fact, as Lamoreaux, Raff, and Temin (2002) argue, the improvements in communications before 1914 made it possible for firms to distribute their output in more remote areas and exploit economies of scale and speed by concentrating production in large plants. This essentially Chandlerian interpretation abstracts from the complex relationship between mass production and the flexible specialization of their suppliers or other firms catering to more specialized needs.

considerably. The most important of these was electricity, which made power supply less bulky and allowed small, household-sized firms to purchase power on the same terms (disregarding quantity discounts) as their large scale competitors. But other inventions pointed in the same direction. In transportation, the growing optimal size of ships and the obvious scale economies of railroads have to be weighed against the democratization of transportation through bicycles and cars that allowed household-sized producers to sell transport services.

The transition was thus more gradual and nuanced than mass-production enthusiasts have allowed for. Studies of firm size during the second Industrial Revolution have noted that very small-scale business still had considerable life in it until well into the nineteenth century.[53] The statistical difficulty that mars this debate is that most industrial and population censuses did not count people working at home or in little workshops attached to it (what the French census, the exception in this case, called *isolés*). The only country that reported the number of such isolated workers with accuracy was France. The 1906 French census estimates that about 33 percent of the manufacturing labor force in France worked in isolation, which to a large extent must have meant in workers' homes.[54] A summary of the proportion of manufacturing workers by industry in France in 1906 is provided in table 2. The German Industrial census of 1895 reported a total of 1.88 million workers who worked by themselves, out of a total "trade and industry" (*Gewerbe*) employment of 10.54 million (17.8 percent) and a manufacturing employment of 7.52 million (25 percent).[55]

Undercounting and inconsistent definitions by statistical services have led to considerable confusion about the average size of firms in the industrialized parts of western Europe. This confusion was sorted out by Kinghorn and Nye (1996), who maintain that the omissions led to Germany's undeserved reputation as a nation of large technologically progressive plants. Adjusting for the omitted firms based on some carefully spelled-out assumptions, they compute that in the decade before World War I, 95 percent of all German industrial establishments still employed

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[53] The British census of 1851 demonstrates that the household-sized firm was far from gone: of the total number of masters (129,002) who made a return, over half (66,497) employed five men or fewer, of whom 41,732 employed nobody but themselves. The 1871 census shows very similar returns. Moreover, these returns were incomplete and understated the number of very small and one-person firms (Musson, 1978, p. 68).

[54] As Kinghorn and Nye (1996, p. 95) point out, the 1906 French census was part of a population census and the evaluators made an all-out effort to count all small establishments.

[55] These numbers probably reflect serious undercounting. More detailed data for Baden show that one worker in six worked in a plant in which there was only one worker present. I am indebted to Dr. Jörg Baten of the University of Munich for making these data available.

Table 2: Factory and Domestic Workers in France, 1906.

Industry	Home-workers (1000's)	Workers away from home	Percentage home workers
Food Processing	37.2	293	11.3
Chemicals	1.4	116.9	1.2
Rubber and paper	2.6	78.1	3.3
Printing	5.2	91.1	5.4
Textiles	162.4	686.1	19.1
Apparel making	890	441.8	66.8
Straw and baskets	13.6	19.6	41.0
Glass and pottery	3.1	153.1	2.0
Stone-cutting	12.9	24.7	34.3
Leather	122.2	155.3	44.0
Wood and carpentry	200.5	361.6	35.7
Iron and steel	0	73.6	0
Metalwork	93.7	552.5	14.5
Fine metals and jewelry	4.5	23.9	15.8
Total	1,550.0	3,071.5	33.5

Source: France (1910), pp. 188–93. The computations refer to workers "travaillant isolément" and those in firms employing more than one worker; the table leaves out the category of *chefs d'établissement*. This procedure tends to understate the number of homeworkers, since many of those "bosses" were small-time artisans employing apprentices or servants.

one to five workers and that these firms employed 67 percent of the workforce. In the United States, the proportion of such firms was smaller

(91 percent) and they employed 33 percent of the labor force.[56] Kinghorn and Nye conclude that "the size of an enterprise is a response not only to the demands of a narrowly defined production technology but also to organizational considerations." Yet such "organizational considerations," too, are a function of technology, if not of the production technology of the firm itself, then of the technology it uses for managers to communicate with workers and with outside suppliers and customers, and for workers to communicate with one another.

Yet as I argued before, the changes in the technology of moving people about set the numerator of the cost ratio of moving people versus moving knowledge. As a result, between 1850 and 1914, the concentration of workers in large factories, department stores, large offices, and similar "mills" continued apace.

A Contemporary Perspective

A headline in *USA Today* (July 5, 2000, p. B-1) read, "Many Companies [Are] Kicking the Bricks-and-Mortar Habit" and the article proceeded to describe a list of firms whose staffers work from their homes and meet only a few times a year. Conference calls, e-mail, and the Internet have begun to replace the water cooler and the meeting room, and the comfort of the living room is threatening the corporate cubicle.[57] Frances Cairncross, in her sensible and informed book, declares that "the falling price of communications will affect where people work and live. The old demarcation between work and home will evaporate" (1997, p. 234). The term "tele-cottages" (coined by futurist Alvin Toffler in 1980) that has cropped up in describing this phenomenon is particularly apt because it clearly implies the connection to a pre-1750 past.[58] In recent years the relation between distance and the cost of transmitting information has weakened. The Internet is only one factor in this story; the sharp decline

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[56] The French census of 1906 carries out a similar exercise and compares average firm size between different countries.

[57] Lamoreaux, Raff, and Temin (2002, p. 46) point out that the internet's impact on specific coordination mechanisms will be profound, but they focus on its role in goods markets, not the labor markets or communications that involve the exchange of technological as opposed to commercial information.

[58] The argument I am making here about factories parallels the argument made about the future of cities. Gaspar and Glaeser (1998) and Mokhtarian (2000) point out that face-to-face communications are in many cases a *complement* to long-distance contact, and that cities may well survive modern information technology. I should add, perhaps unnecessarily, that even though the Industrial Revolution set in motion an unprecedented urbanization movement, large urban concentrations predate the rise of the factory.

in the cost of long-distance phone calls and the explosion in the use of cellular networks is another.[59]

The notion that "distance is dead" is of course not to be taken literally. Even if people work at home, physical goods still have to be moved and most services still need to be provided *in loco*, although technology will determine to what extent "virtual" activities can replace physical presence. It is far from clear whether the sharp decline in communications and information-processing costs reduce or increase the economies of agglomeration. Evidence that the decline of the economies of agglomeration is due to the Internet and lower phone rates is very mixed so far. The assumption that travel and telecommunication are substitutes seems at least questionable (Mokhtarian and Salomon, 2002), and in many instances they are obviously complements.[60] Moreover, travel has a high income elasticity, and as new technology generates growth, the demand for travel is likely to increase. There is hence some justified skepticism about whether telecommuting is the panacea for traffic congestion (Mokhtarian, 1997, 1998, 2000). As Couclelis (2000) has argued, the rapid improvements in information processing have led to a fragmentation of activity, in which work is increasingly carried out in smaller time units, interspersed with leisure activity and at times multitasked with it.

All the same, much work will be capable of being performed outside the rigid confines of the workplace. The interest in telecommuting and working at home is not new. Robert Kraut (1989) describes some of the advantages and possible drawbacks before the appearance of the World Wide Web.[61] The "factory" as a system is in retreat not only as a physical central location of activity, but also as a time-organizing institution in which work begins and ends at given times and the lines between leisure and labor are firmly drawn. Instead, work is dispersed over space as well as time, allowing workers to calibrate their trade-offs to reflect their preferences. The welfare implications of home work are the mirror image of the costs of the factory system: less commuting, more flexibility in the leisure-work trade-off, and the ability to combine work with household-

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[59] The connection between the growth of information technology and the organization of the workplace is explored in Bresnahan, Brynjolfsson, and Hitt (2002). The emphasis here is on the communication aspect of the information revolution rather than on the processing of information.

[60] As Mokhtarian and Salomon point out, the cellular phone is by construction a complement to human travel.

[61] Kraut's pessimism about the future of the option to work from home was based on his assumption that firms and organizations need to coordinate work and thus require co-presence, and that home-based employment is most appropriate in occupations where the need for such coordination is low. He felt that such "routine" jobs are quite rare, and did not address the possibility that information technology might make co-presence less necessary for a large number of other jobs.

services production.[62] For many workers the freedom to design and control the parameters of their physical work space may be equally important.[63]

The direction technological progress has taken since the 1970s should make a partial return to household production quite logical. For one thing, the costs of sending and receiving information relative to the costs of moving people have fallen sharply. The full costs of commuting (including time) have not declined. City and suburban highways are as congested as they were two decades ago, and public transportation has not improved substantially. To be sure, some improvements have made commuting more pleasurable (e.g., better car stereos and walkmen, airconditioned cars) or more productive (cell phones and laptop computers). Yet on the whole the industry that serves commuters and travelers has shown comparatively little technological progress. On the other hand, the ability to store, manipulate, and transmit information keeps expanding at a dazzling rate, and the connections between private homes and other homes and businesses have improved in quality and speed as dramatically as their price has plummeted. Ever faster and cheaper access to huge stores of knowledge has shown little evidence so far of diminishing returns. In some sense, a worker whose work consists largely of reading a computer monitor and interacting with it could be located practically anywhere. At the same time, the large number of married women and single heads-of-household in the formal labor force makes the opportunity costs of working away from home, in terms of the foregone housework multitasked with income-producing work, particularly high.

A large and rapidly growing literature on telecommuting discusses the prospects of this movement taking hold, and it seems reasonable to suggest that the pendulum of the "unit of production," after two centuries, is slowly swinging in the other direction. Exact numbers are hard to come by, and estimates differ. The 1990 census reported that 3.4 million workers aged 16 and above worked "only or mostly at home" (Russell, 1996). In 1997, it was estimated that the number of telecommuters in the United States was about 11 million.[64] Estimates put the number of U.S.-based

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[62] In this respect, however, there is a profound asymmetry with the demographic conditions in the nineteenth century, when single-headed families with small children were rare.

[63] One telecommuter reports that she has just "created the right atmosphere for herself" in her home office, with the TV on at a low volume so that it feels as if there are people in the room with her (*New York Times*, Nov. 2, 2000, p. D-8).

[64] The estimate was based on a survey commissioned by a New York market research company, FIND/SVP, cited by "Telecommute America," a website maintained by AT&T. This figure is also quoted by McCune (1998). The International Telework Association and Council reported that 16.5 million (12 percent of the labor force) now work at home at least one day a month, and 9.3 million of these worked at least one full day a week at home (see http://www. telecommute.org/twa2000/ research _results_key.shtml).

employees telecommuting at some time in 1999 at 19.6 million, but far fewer actually telecommuted on any given day.[65] In addition, there are 21.4 million self-employed homeworkers (Miller, 2000).

The distinction between telecommuters and independent contractors is getting murky, and with the growth of a just-in-time labor force, separate statistical estimates of the two will become hard to interpret. For my present purposes what matters, above all, is where workers work. Recent survey data suggest that all over the industrialized world "teleworking" is catching on.[66]

Just as the Industrial Revolution did not quite create factories *de novo* but turned them from a rarity into the normal way in which production was carried out while preserving some niches of home work, it seems clear that the movement away from factory settings will eventually run into diminishing returns and that the locus of work will remain a mixture of work at home and work away from home. Certain industries and services, from food processing to dental care, will inevitably require a physical presence. But the weights of this mixture will change significantly, and such a transformation, much like the movement in the other direction two centuries ago, will be largely technologically driven, depending on both the production technology itself and the information technology used to communicate with employees and monitor them.

The welfare implications of the decline of the factory go beyond just computing the time cost of commuting. They concern the way we define input and output, efficiency and productivity. The commuting costs in terms of time alone in the United States nowadays can be roughly estimated at about 25.4 billion person hours at an estimated cost of $356 billion.[67] The additional costs in terms of capital goods and fuel and the

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[65] Khaifa and Davidson (2000). Simulations carried out by Mokhtarian (1998) suggest that 6.1 per cent of the workforce may have been telecommuting around 1998, with 1.5 percent doing so on any given day. More recently, Mokhtarian has put the number of telecommuters at about 8 percent *not* including independent home-based businesses (Professor Patricia Mokhtarian, personal communication). The 2000 U.S. census reported only about 4.1 million people working at home out of a labor force of 127 million, but this figure does not seem to take into account people who telecommute part of the time.

[66] The leader in teleworking appears to be Finland, with 10.8 percent of its labor force telecommuting at least once a week, followed by the Netherlands with 8.2 percent (see http://www.telecommute.org/twa2000/ research_results_key.shtml). According to a 2000 estimate for Britain, 1.5 million workers now define themselves as "technology-dependent homeworkers," up from 1.2 million a year earlier, almost 5.5 percent of the workforce (see http://www.analyticadial.pipex.com/twstats00).

[67] The 2000 U.S. census estimates the average commuting trip at twenty-four minutes per day. Imputing the mean hourly earnings at $14.00, at 250 days a year for a labor force of 127 million, produces these numbers. The actual number is considerably higher because the real compensation per hour is higher than earnings and because of the nontime costs of transportation.

costs of environmental damage are at least as large. The inefficient utilization of space is another cost (see the epigraph to this chapter). There is little evidence to date that any of these costs have been reduced. All we know is that in the century and a half after 1750 these costs were gradually imposed on industrializing economies. They are dwarfed, of course, by the enormous gains made in income per capita, but if these costs were reduced rather quickly, they should still be counted as gains.

Whether they are large or small, these costs should be included in our national income accounts, but they rarely are. National income accounting does not actually subtract them from output, but there can be little doubt that in principle it should do so, to preserve the notion that intermediary inputs are subtracted because aggregate output is a *net* measure.[68] As things are, the purchases of transportation services needed for getting to work are treated as consumption. Commuting time does not enter into GNP calculations but is treated as leisure. From a welfare point of view this procedure is mildly absurd, and although economists have long recognized this, the treatment of these items in our national accounts remains an open issue. A considerable amount of time spent on "leisure" is nothing of the sort but is an intermediary cost of production or consumption. The new-economy pessimists who fail to see much evidence of a gain in productivity should keep in mind that the numerator of all productivity measures fails to capture some of the most important effects of the new technology.[69] In short, commuting—much like shopping—is a "friction" that drives a wedge between total output as a measure of effort and as a measure of welfare. Hence, a sharp increase in telecommuting and teleworking would have clear-cut welfare effects but would appear nowhere directly in our national accounts.

To be sure, telecommuting is still a long way off as an economy-wide phenomenon, and many of the people who can work from home do not do so all the time. Predictions of how many people will be telecommuting in the future range widely and depend on assumptions about changes in the

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[68] Kuznets already pointed out that the changing boundary between the costs of producing income and that income itself imparts an upward bias on the long-term series of national product as measures of economic well-being (1971, pp. 7–8).

[69] This particular aspect of Information and Communications Technology (ICT) is often overlooked by the new-economy-skeptics such as R. J. Gordon (2000a, 2000b), who maintains that this technology is less dramatic than the great breakthroughs of the late nineteenth century in steel, electricity, the telegraph, and indoor plumbing. Yet computerized access to large stores of useful knowledge and the ability to observe, coordinate, and monitor production activities taking place far away can restore the home as a location of work, with all the concomitant social and economic ramifications.

costs and efficacy of data transmission.[70] Changing technology will not necessarily eliminate the workplace as an institution, but it will make commuting to work increasingly optional and part-time. The unbundling of "going to work" from "working" is unambiguously welfare-improving: it will separate those whose net marginal utility from going to work exceeds the costs from those who commute out of necessity.[71] It could be argued that the factory or office provides what one might call a "tavern effect." The medieval tavern and the modern pub provided the social institution in which people who worked apart got together and interacted. Maybe the last thing an economy in which loneliness is already a national affliction, and in which people, in Robert Putnam's term, are "bowling alone," needs is to get rid of the workplace, with its water coolers and cafeteria to compensate for the solitude of the corporate cubicle. The simple response to this argument is that people in need of social interaction can still arrange to meet for lunches or conversations at places and times of their choice. Community life has not done well in America in the second half of the twentieth century, but perhaps the reason is in part that community life and the workplace are substitutes, competing for the same time and serving similar needs. If the workplace and the commute were to claim less time and effort, people might re-invent the social institutions associated with life before the Industrial Revolution as well as create entirely new forms of social interaction, as witnessed by the growth of e-mail pals and Internet chatrooms.

Most scholars looking into the issue agree that there is considerable heterogeneity among workers, and that by allowing them to sort themselves according to their preferences aggregate welfare must increase. In addition, workers can mix: they can go to the office at odd hours, avoid rush-hour traffic and bad weather, stay home to attend to domestic needs, and so on. Finally, to repeat, some level of multitasking is feasible when one works at home. Baby-sitting and cooking are two activities that can be thought of as compatible with simultaneous work, but the advantages of such jointness should not be overstated, and many employers of telecommuters demand that small children be placed in child care. It is reason-

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[70] Mokhtarian (1998) decomposes the proportion of telecommuters into the intersection of those whose jobs are amenable to telecommuting, those who prefer to work at home, and those who are not prevented by inertia or fear on the part of their employers from working at home. Over time, however, these proportions cannot but go up. Not only will more and more workers end up in the "information sector," but more and more of these jobs will become sufficiently integrated with information technology to raise the proportion of jobs that can be done from home.

[71] As Cairncross predicts (1997, p. 237), the office will become a "club" where people congregate for networking and gossip, where firms motivate workers and embue them with loyalty to the firm, much like the early capitalists, only doing so with the help of health clubs and "retreats" rather than religious and moralistic preaching.

able to ask whether the total full output of a worker watching a child is less or more than that of a worker away from home concentrating fully, and whether employers can adjust their payments for the reduced but still positive productivity of a parent. Switching to some kind of piece wage might resolve this, much as it did before the Industrial Revolution.

Flexibility in the hours away from home is probably as important for parents and homeowners as the actual numbers (Humble et al., 1995). An increase in the technological opportunity to telecommute will thus allow an increase in housework (child care, food preparation, and so on) at little or no cost in "real" output. Again, however, our convention of not including housework in our measures of national income means that any such change will be welfare-improving without registering in our national income accounts.

The degree to which a postindustrial economy will return to a home-production economy will be determined by technology. It seems natural that some jobs lend themselves to telecommuting and others do not (Handy and Mokhtarian, 1996). But that is conditional on the continuous progress of technology, especially on the supply of bandwidth. If the trends of the 1990s continue, it is likely that few jobs will be entirely immune from radical changes in location and the geography of labor supply. This is not to say that face-to-face contact will disappear. If communication techniques can be devised that provide a "virtual meeting" of acceptable quality, location may become indeterminate. Until then, just as the emergence of the factory system in its early days produced a "mixed system" in which a single firm employed both factory workers and domestic workers, our economy might find such a combination attractive, perhaps through workers who work at home three days a week and go to the office the other two.

How do the four causal roots of the emergence of the factory discussed above perform in analyzing the impact of modern technology on the future of the workplace? Economies of scale at the plant level have not been eliminated, but as a result of increasing automation, robotization, and the substitution of capital for labor, in industrialized economies fewer and fewer workers are employed in manufacturing, and the remaining ones are increasingly monitoring and controlling production through automated processes. Some scale effects are weakened by modern information technology: inventories can be kept at lower levels, and the advantages of mainframe computers, once the sole prerogative of large firms, have melted away. It seems unlikely that wholly robotized factories, supervised by remote monitors, will become dominant in our near future, but the number of workers whose physical presence is required on the shopfloor has been declining.[72] For services, a similar phenomenon is increasingly visible on the horizon. The twentieth century witnessed the virtual demise of the household-sized mom-and-pop corner stores, replaced by large-scale department and specialty stores. The trend toward e-tailing may well encounter some teething problems, but if it continues, little in the industry besides warehousing and shipping cannot be outsourced to independent agents or assigned to employees working from their homes. The same holds true for banks, law firms, insurance companies, and higher education.

The monitoring of effort put in by workers is trickier. The new technology will require one of two things: the ability of firms to monitor a worker's productivity, or when that is not feasible to observe somehow what the worker does even if she is not in the same location (say, through remote closed-circuit digital cameras). Improved information technology should make measuring output easier and thus re-institute piece wages ("tele-piece-rates"), that is, subcontracting and payment per project. The ability of employers to monitor remote workers by electronic means may help solve other monitoring problems. Thus the employer can observe from a distance how many hours a worker has been online, which activities were carried out, and how the work has been performed. This kind of monitoring will make it possible for employers to pay a time wage to domestic workers if necessary, removing one of the most potent reasons for factory settings. Modern information technology is thus a large step toward reducing the information and transaction costs that made "firms" necessary in the classic Coasian formulation. In other words, the principal-agent problem is one of asymmetrical information, assuming information technology to be given. Insofar as modern information technology "symmetrizes" the distribution of knowledge inside the firm, it may make the organizational structures devised to cope with asymmetrical information less necessary.

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[72] Pavitt and Steinmueller (2002) discuss the options of "informatizing the factory" which must eventually spell the decline of the importance of distance there as well. The use of so-called intelligent agents that control robotized operations may sharply reduce the number of workers present on the shop floor, and may eventually lead to so-called "lights-out" factories (plants with no human workers present). Factory equipment often comes with a built-in Internet connection, so machines can be monitored and controlled from a remote location (see "Thinking Machines," *Business Week*, Aug. 7, 2000, pp.78–86; and "Brave New Factory," *Business Week*, July 23, 2001, pp. 75–76). An example are VEC's (virtual engineering composites), which allow the manufacturing of molded products through Internet remote control. This technology allows the production of virtually any molded product anywhere with a minimum of labor present (ee "The Revolution in a Box," *Time* July 31, 2000, p. 30). Another example is a new tire-making technology introduced by Pirelli known as MIRS (modular integrated robotized system), in which 125,000 tires a year are produced by an automated system monitored and run by three white-collar employees behind their computers (*Le Monde*, July 15, 2000, p. 13).

The Marglin-Clark view of factories regards them as places where workers are controlled and disciplined so as to increase their work effort and productivity. It seems likely that in the twenty-first century motivational problems may be less of a concern if the conditioning that makes workers self-motivated can be provided through the education system. This approach will not work for all, and firms will have to learn to sort workers into those who can be relied upon to work effectively in a home setting and those who must be watched.[73] What little anecdotal evidence there is points uniformly to an increase in productivity resulting from telecommuting.[74] It is hard to know precisely what these increases reflect. In part it may be selection bias: the workers most likely to benefit from telecommuting should be expected to be the first to switch. Other causes may be a reduction of commuting-related fatigue and stress and fewer distractions by fellow workers. On the other hand, more telecommuting may negatively affect the workers who stay in the office or the store. More detailed information about relevant variables such as changes in absenteeism and turnover rates is unavailable. All the same, even if it turns out that productivity and related measures are not much improved by a change in location, the increase in total social welfare due to a reduction in friction costs is enough to make it significant, to say nothing of the nonpecuniary aspects of work.[75]

Finally, the function of the plant or office as a unit in which knowledge is divided and shared has been widely discussed in the business literature.[76] It seems plausible that if employees mostly communicate with each other electronically anyway, there may be little point in making them drive to work and putting them in little cubicles next to each other. But things are not quite that easy. For one thing, in addition to ease of access, proximity in a plant or office creates personal familiarity and thus conditions of trust and believability. Body language, intonation, and general demeanor always

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[73] McCune (1998) argues that a home office tends to reinforce an employee's tendencies: it will make a workaholic labor harder and longer and give a procrastinator ample opportunity to delay work. Some firms have recently taken a more skeptical view of telecommuting, "believing that telecommuting causes resentment among office-bound colleagues and weakens corporate loyalty" (see *Wall Street Journal,* Oct. 31, 2000, p. 1).

[74] The estimates tend to be all over the map. At Nortel Networks, productivity increases were estimated at 10 percent (Strickland, 1999). Humble et al. (1995) report a range of 10–200 percent with the mean at 30 percent, which is consistent with the survey used by DuBrin and Barnard (1993). McCune (1998) reports productivity increases ranging from 4 to 25 percent. All these figures are based on small samples and suffer from poor controls and selection biases.

[75] The Nortel survey reports that 90 percent of work-from-home employees reported "increased job satisfaction" and 73 percent "decreased stress levels" (McCune, 1998).

[76] Hudson (1998) makes this point clearly: "Telecommunications networks now link manufacturers with assembly plants, designers with factories, engineers with hardware vendors, suppliers with retailers, retailers with customers. No longer is it necessary to have all the expertise in house."

play a role in human interaction.[77] Even with vastly improved communications, for many purposes direct personal contact with in-house experts may still be necessary. All the same, much of the ICT revolution was born in industrial districts such as Silicon Valley; but the next stage may be the virtual industrial district, a network of workers all over the globe.

The amount of personal contact relative to long-distance communications depends on the ratio of codified to uncodified (tacit) knowledge. If the new information is increasingly codified, as Cowan and Foray (1997) suggest, access through impersonal contact may well render much personal physical presence unnecessary. It is true, of course, that in order to access codified knowledge we need the codebook, and the knowledge of the code itself may be largely tacit. Improved access to technological knowledge may make it advantageous to produce more widely accessible codebooks (Cowan, David, and Foray, 1999). But modern communications and search engines not only permit quick and easy access to codified information, they also make it easier for agents to locate and hire people who possess the tacit knowledge that interprets the codified knowledge. Such people do not have to be employed by the firm, and are often hired as subcontractors and consultants. Moreover, firms that need to produce something that requires access to specialized knowledge they do not possess tend to subcontract out that whole stage of production to specialists. Such vertical disintegration, if driven to extremes, may jeopardize the entire notion of a "firm" as we understand it. To some extent, firms may be replaced by virtual "teams," assembled on an ad hoc basis for specific projects. This practice will require some kind of reputation-maintaining technology, which is precisely what the Internet provides.

Does the introduction of modern ICT enhance the competitiveness of the economy and the diffusion of new techniques? The return to household-plants and even household-firms will not mean a return to a world of peasants and artisans with loose selection standards. Modern ICT will make it easy to establish or lose a reputation for expertise and reliability. Establishing standards for veracity will be one of the challenges of the world of cheap access to knowledge. Such a world, however, will contain few pre-1750-type household-producers muddling on without continuously keeping up with best-practice techniques. As access costs continue to decline, codifiable knowledge will flow to where it can be used. All the same, it is not clear how society will handle individuals who cannot or will not stay up to date.

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[77] See Leamer and Storper (2001). In the late nineteenth and early twentieth century it was believed, similarly, that the telephone could replace face-to-face meetings and that telecommunications would reduce transit congestion (Mokhtarian, 1997).

To sum up, modern communications and information technology are weakening many of the advantages that the "factory" has had over the household. With increased female participation in the labor force and little improvement in commuting technology, the costs of factories relative to home production have gone up. It is hard to make predictions about the trend, especially given how little hard information we have about the state of telecommuting in the twenty-first century.[78] The changeover will be slow, much as the full establishment of the factory was and for much the same reason: a major social constraint is that the baby-boom generation grew up using typewriters, telephones, and cars to commute to work and will have a difficult time changing its lifestyle.[79] It will have to await workers who grew up in hard-wired homes, and for whom the Internet comes naturally, to accept fully the new lifestyle implied.

Technology, now as in the past, opens doors; it does not force society to walk through them. On the whole, however, the contemporary changes may mean a social transformation quite comparable in magnitude to the rise of the factory in its impact on society in the eighteenth and nineteenth centuries. The difference between the two eras is that in the modern age, a sorting principle will be operational: more and more of those workers who want to work at home will be able to, whereas those who prefer to work in centralized settings, or who would not be as productive at home for one reason or another, will be able to maintain the status quo. This is an option the handloom weavers, the frame knitters, and the nailmakers of the nineteenth century never had.

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[78] It is worthwhile to cite the 1806 British Select Committee that predicted confidently that it was their "decided opinion that the apprehensions entertained of [the Domestic System] being rooted out by the Factory system are, at present at least, wholly without foundation" (Great Britain,1806, p. 10).

[79] Andrew Ure's words in 1835 resonate with the modern experience: It was found "nearly impossible to convert persons past the age of puberty, whether drawn from rural or from handicraft occupations, into useful factory hands" (p. 15).

Chapter 5

Knowledge, Health, and the Household

Our House is clean enough to be healthy and dirty enough to be happy.

—Nineteenth-century poster inscription in American kitchens

Until such time as science shall illuminate the housewife's path, she must walk in the twilight of traditional opinion.

—Wesley Clair Mitchell, 1912

Introduction

Thus far, I have discussed *techniques,* that is the procedures with which we manipulate nature to produce goods and services. We typically do not think of households as units that employ prescriptive knowledge and select techniques, but a moment's reflection reveals that they do so all the time. In the consumption process, households do not just purchase consumer goods but convert them into their final uses by using a set of techniques I call *recipes.*[1] These final uses include the satisfaction of the biological and psychological needs underlying demand as well as the indirect effect of consumption on health and longevity. Recipes are thus comparable to the production techniques of firms, representing knowledge available to the household. They determine the composition of the bundles purchased as well as the efficiency with which the inputs into the household production function (that is, the goods the household buys at the market) are converted into final services. The idea that households actually "produce" in this way and thus employ technology is by now a standard part of neoclassical theory, the protestations of sociologists notwithstanding (e.g., Thomas, 1995, p. 333). Hence useful knowledge, in the sense I employ it in this book applies to households as much as to firms. Yet the generation and diffusion of recipes follows different rules than firm-level technology. The historical implications of these differences are profound.

The most obvious difference between firms and households is that firms are pressed into using efficient techniques because they compete with each other for scarce resources, profits, and eventually survival. Households compete with each other for resources as well, but once they have been given an allocation and purchased a bundle of commodities, there are no comparable competitive pressures on them to use these resources efficiently when they make their consumption decisions and when they convert goods they have bought into the market to yield utility-enhancing services. This is not to say that no such pressures exist altogether. Partners with poor household skills using low-efficiency recipes may have found themselves at a disadvantage in the marriage market and failed to reproduce. Conformism and imitation may have been more important than selection: in all ages social conventions evolved that pressured households to follow certain practices customary in a society or risk social ostracism. If such social conventions increased fitness, they would help move society toward an optimum. Yet there is no evidence that they invariably did so, as the adoption of smoking and narcotics use and changing fashion in clothing suggest.

It might be thought that differential survival would ensure the eventual extinction of inferior and harmful recipes because badly managed households that use them will suffer higher mortality rates and vanish in the long run just as badly managed firms do. If vertical transmission of useful household knowledge is more important than horizontal or oblique

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[1] Recipes should be distinguished from technologies that are used by the household but generated outside it. Thus the invention of the vacuum cleaner is not a change in household recipe, but learning to use one properly is. In what follows I use the term "household technologies" for technologies that are purchased by the household and "recipes" for the knowledge possessed by the household.

transmission, the children of poorly managed households are more likely to be bad homemakers themselves. If "bad" is defined in terms of "fitness" —that is, survival or life expectancy—natural selection will eventually provide an advantage to those "germ lines" with better household techniques. In that case selection takes place in its most literal Darwinian sense. However, the "correct" choices of techniques in the best-managed households would involve better contraceptive as well as better health techniques, meaning that well-managed households would have both lower birth rates and lower death rates, with the net result unknown (Galor and Moav, 2002). Moreover, one implication of the social changes over the past two centuries is that vertical transmission of knowledge from parent to child learning) has become relatively less important. Finally, the objection could be raised that even in highly competitive environments evolutionary models imply that the techniques picked are not necessarily globally optimal, and for that reason we will observe a distribution of techniques rather than a single best practice in use.[2]

Households and firms also differ in their ability and the criteria employed to choose among competing techniques. Households select recipes based on certain prior beliefs about the effects and side-effects of different alternatives. To be sure, many household chores are repeated over and over again and thus would be revised if they were visibly inefficient. Almost every household learns how long to boil pasta, and if it cannot accomplish this, how to purchase ready-made food. More complex information, however, particularly the impact of consumption on long-term health, is more difficult to evaluate. The questions the consumer needs the answer to are of the type "is this quantity of a given consumption good best for my health and that of my family?" and "is the recipe I use to transform this good into its final form optimal?" Such knowledge is often complicated and hard to verify. Comparing the performance of a given household with that of others or with some standard of performance is difficult not only because households are often poorly informed about others, but because there is no single number like a "bottom line" by which performance can be evaluated.

Although the difference between households and firms is thus one of degree, the degree is of decisive importance. Firms are, at first approximation, constrained by what best-practice technology can do. If a much

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[2] This is a standard result in evolutionary theory. Optimizing selection by itself only guarantees that the system will come to an equilibrium at a *local* peak in the fitness landscape. For a recent re-statement, see for instance Kauffman (1995, pp. 149–89, 248). There is no current consensus on the issue of optimality in the theory of evolution. See the essays in Dupré (1987), especially the ones by Philip Kitcher and Richard Lewontin.

better way to produce, say, tires or green peppers became known, some firms would adopt it and the others would follow suit or vanish. But the knowledge base of household recipes is more complex. Some people exercise daily or refuse to eat beef because they believe these practices will make their bodies better. There exists an epistemic base for the technique that prescribes eating garlic or drinking grapefruit juice, just as there is one for building diesel engines. It is based on often rather untight beliefs (or as I shall refer to them, "priors") about how nature (in this case, the human body) works. But unlike firms, households may find it difficult to verify or refute these priors or assess and rank outcomes. There are too few observations and the lag structure may be complex and unknown: consuming garlic may reduce the chance of stroke, but at some point in the remote future and only if other things remain constant. As a result, the selection of household techniques is dominated, far more than that of firms, by persuasion, social conditioning, and emulation. People choose many recipes, from toothbrushing to jogging to the consumption of broccoli, because of untested beliefs that they improve health in some way. In many cases, it is simply impossible for the household to experiment and verify whether these priors are correct; they have to follow authority. The idea that "the surgeon general has determined that..." blaring from every cigarette pack is paradigmatic of a large number of choices that households make on the basis of epistemic bases they accept but cannot verify.

In a post-Enlightenment age of growing rationalism and empiricism, authority and tradition were challenged and people started to question age-old beliefs. Yet consumers, by and large, continued to rely on authorities. Testing the effect of consumption goods on health, from garlic to hard soap to quinine, ran into inference problems because the number of variables usually was large, the number of observations small, and the effects of consumption often followed with a long and unknown time lag. Comparing alternatives, let alone evaluating the costs of type I and type II errors, was thus difficult, and many consumers continued to rely on traditional knowledge and old wives' tales in choosing recipes. Many of those practices may have been sound, and some of them are being confirmed in our own age by multivariate research. Yet in the absence of an understanding of what makes one ill, consumers also made some astonishingly persistent and prevalent errors, such as practicing utterly useless procedures and services, of which bloodletting was but the most notorious. All told, then, households and firms are subject to quite different competitive pressures and information constraints in their choice of techniques, and we should not be surprised to see the proliferation and persistence of long-term practices and techniques that appear to be inefficient and inferior given certain objective functions.

The approach I apply below is akin to the so-called cognitive limitations model in which consumers are neither perfectly informed nor totally ignorant of the implications of their choices, a concept closely related to Herbert Simon's bounded rationality idea. In making their choices, they try to process the available knowledge rationally. Yet in so doing, they are limited in at least four ways. First, the best knowledge available may be defective or even completely false. Second, best-practice knowledge may fail to reach large segments of society. Third, best-practice prescriptive knowledge may be untight: alternative and competing dogmas (scientific or otherwise) may exist, making it difficult for consumers to decide which one to prefer. Consequently, they may have access to best-practice knowledge and yet refuse to follow its recommendations, not having been convinced that the health advantages of a particular good are worth the costs or effort. Finally, because often the costs or benefits were evaluated in terms of changed probabilities rather than certain effects, consumers may make systematic errors in assessing the stochastic impact of their behavior.

Changes in household knowledge and behavior explain what may well be the greatest shock to Western demographic history (at least since the Black Death), namely the decline in infectious disease in the industrialized West after 1870 or so. The fall in infectious disease drove down mortality rates, so that when effective cures to infectious diseases appeared after 1945, the demographic impact of these diseases had already been attenuated and mortality rates had been declining for many decades, as table 3 demonstrates. Adult mortality rates declined for most of the nineteenth century, but infant mortality rates in many Western countries stayed stubbornly high until the late 1890s and then fell abruptly by around a third between 1900 and 1914 and to half their 1900 levels by the mid 1920s.

The framework I delineated above serves well to explain this event. The rise in income, as McKeown (1976) and others have steadfastly maintained, increased the consumption of goods that improved health: fresh fruits and vegetables, high-protein foods, home heating, hot water, cleaning materials and so on. At the same time, growing government intervention and improving public health reduced the relative price of clean and safe water, as well as the cost of waste disposal, protection against insects, and verifying the safety of food and drink. Not all changes in relative prices were the result of public health measures: technological progress contributed as well: filtration and chlorination of drinking water, refrigerated ships, pasteurization techniques, and electrical stoves and home heating, all reduced the price of "health-enhancing foods." This decline has

Table 3: Indicators of Mortality in the Industrialized West, 1850–1950

	Life Expectancy at birth			Infant mortality rate (per 1000)		
	c 1850	c 1900	c 1950	c 1850	c 1900	c 1950
England and Wales	40	48.2	69.2	162	154	30
France	39.8	47.4	66.5	146	136	52
Italy	32.0	42.8	66.0	232	174	64
Spain	29.8	34.8	63.9	204	175	64
Germany	37.2	44.4	67.5	297	229	55
Netherlands	36.8	49.9	71.8	169	155	25

Source: Livi Bacci (1989), p. 109; Mitchell (1975), pp. 127–132.

remained one of the most lively subjects in the literature of economic history and historical demography, as well it should be. Surely, from the point of view of the standard of living, it ranks among the most momentous events in history. With some exceptions (Mokyr, 1993; Easterlin, 1995, 1996), scholars have failed to take technology properly into account in explaining this event. Once it became clear that medical science could not take credit for the decline in infectious disease, some economic historians hastened to support McKeown's notion that rising incomes led to rising nutritional status. Improved nutrition, in turn, strengthened the body's immune system's ability to ward off infection, and thus reduced mortality. Others, especially Johansson (1994), and Szreter (1988) have rejected that notion altogether and in its stead accepted the "reduced exposure" notion according to which public works improved the environment in which most people lived enough to reduce the incidence of killer diseases. The framework proposed below combines elements of both these approaches and then adds a third explanation based on the impact of useful knowledge on household behavior. A simple model is enough to show how these approaches can be logically distinguished.

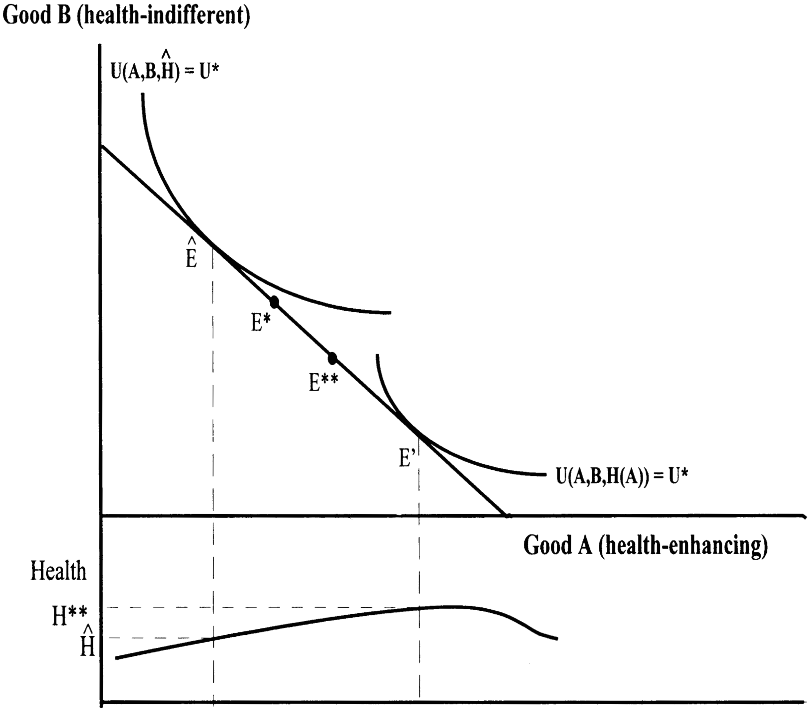

Figure 3: Household knowledge and health

A Simple Model of Health and Household Knowledge

To illustrate the insight that this model provides for the decline of mortality in Europe, assume there are two goods: *A* which enhances health in addition to being desirable (say, grapefruits), and *B*, which does not affect it one way or another.[3] This simple set-up is drawn in figure 3. If the

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[3] The assumption that *B* and *H* are independent is not innocuous. As shown in the appendix, if *both* goods affect health in ways that are imperfectly understood, there is no unambiguous relation between learning and health improvement, and in those cases "a little learning could be

consumer is totally unaware of the effect of A on his health, she will choose point $\hat{E}$, ignoring the indirect effect of A on H (health) in the process, implying an overall level of H of $\hat{H}$ which is taken parametrically. We may call this "primitive" consumption, since the consumer only cares about the direct and immediate gratification of the good. A consumer who is *fully* aware of the healthy effect of A will optimize over A, B, and $H(A)$, choosing E' with the corresponding level of health H^{**}. A consumer who operates somewhere in between will choose a point like E^* or E^{**}.

Figure 4 illustrates that there are in fact three ways in which health can improve. One is through rising income, holding knowledge constant. If A is a normal good, consumption of A rises with income (from E_1 to E_2), and thus health improves (the McKeown effect). A second change is a change in relative prices, favoring A over B. Technological change biased toward A would have this effect, as did the public works projects in the late nineteenth century that provided sewage works, clean running water and inspection of food. All can all be viewed as a decline in the relative price of goods with a high health elasticity, causing a substitution effect that improved health.[4] This move is described by the move from E_1 to E_3. Finally, we can view the change as a learning effect in which consumers increase their consumption of A at the expense of B, going from E^* to E^{**} in terms of figure 3. This would cause them to shift from an initial point like E_1 to a healthier point like E_4. Such a movement would be tantamount to an increase in efficiency and implies a very high rate of return on government programs in nutrition, health education, and propaganda.[5] How should we assess the choices made by consumers in the past? One reasonable approach might be that the "best-practice" science at the time be introduced as a constraint. No consumer in the past could be said to have made suboptimal choices by failing to follow rules nobody knew at that time. Yet

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a dangerous thing."

[4] At times, changes in relative prices had unintended side effects on health. Economic reforms in post-communist Central Europe drove up prices of fatty meat, encouraging Czechs and Slovaks to eat more fruits and vegetables; the result was a drop in cholesterol intake and obesity and a decline in heart disease (*The Economist*, Jan. 7–13, 1995, p. 42).

[5] A World Bank study estimates that micronutrient deficiencies (of suchsubstances as vitamins, iodine, iron, etc.) in third-world diets cost these countries 5 percent of their GDP and that they could be remedied at a cost of 0.3 percent of GDP —a rate of return of 1,600 percent. But even today many governments are unaware, for example, that traces of iodine in the food prevent blindness and cretinism. Very small redeployments of resources can, at times, provide technological fixes for serious medical problems, such as the addition of Vitamin D to margarine that eliminated rickets in Europe early in the twentieth century (*The Economist*, Nov. 23, 1996, p. 100).

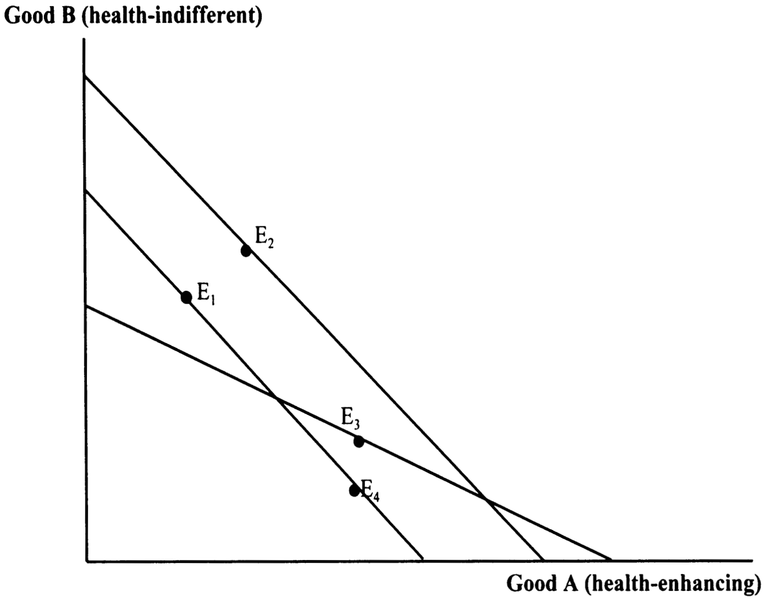

Figure 4: Income, Price, and Knowledge Effects in Mortality Decline

any consumer who did not use the best available knowledge could have done better than she did, if—a big if—best practice knowledge at that time mapped into recipes that actually improved health. That many did not do so is neither surprising nor necessarily evidence of irrational behavior. The fact that something is known to somebody at a given point in time does not mean that this knowledge was accessible to everybody or that the beliefs were sufficiently tight and widely shared. Access costs and tightness in the knowledge of health and the human body were and are to this day of critical importance. The diffusion of best-practice techniques may have led to better health and higher life expectancy even without rising living standards.

In practice, distinguishing between changes in household behavior and relative prices is not always easy, and decomposing observed changes between movements from E_1 to E_2 and E_3 in terms of figure 4 in historical reality may prove tricky. In many cases, improved understanding simultaneously affected the demand and the supply sides, and the shifts were often coordinated.[6] Yet this should not blind us to the fundamental difference between households responding to a change in their knowledge, which is a demand side phenomenon, and a change in relative prices or income faced by the household, which is on the supply side.

To distinguish between the alternatives, it is useful to set up the problem a little more formally.[7] The advantage of this model, which is just a modification of standard consumer theory, is that it isolates with some precision the exact variables at play and their relationship with each other even if they cannot be measured directly in the historical record. As in standard theory, the consumer *j* maximizes a utility function:

$$(1)\quad U_j = U_j(X_{1j} \ldots X_{nj}, H_{j,} L_{E,} L_D),$$

where *H* is a composite variable of family life expectancy and health, the *X*'s are goods purchased in the market, the *L*'s are time spent on leisure and domestic work respectively and consumption is subject to the usual budget constraints $\Sigma X_i P_i = Y$ and $L_E + L_D + L_W = L^*$ (time is allocated between leisure, housework, and work for income).[8] The special characteristic of this setup is that *H* is determined by the household production function:

$$(2)\quad H_j = E + f(X_{ij} \ldots X_{nj}; L_D)\,.$$

or in simple additive form

$$(2')\ H_j = E + \sum_i f_i\,(X_{ij}, L_{Dj})$$

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[6] In some cases, the technical problems were easily solved once the benefits were recognized. An example is the increase in demand for hot water. As Siegfried Giedion has pointed out, the early nineteenth-century household still heated most of its hot water in buckets in the kitchen, as it had done in Homeric times. This changed suddenly after 1850 or so, when a variety of boiler designs started to appear. Few of these incorporated technical knowledge that had not been available at the time of Louis XIV, but the universal understanding that hot water was essential to hygiene and thus good health became the driving force behind these changes in technology.

[7] For a more detailed exposition, see Mokyr and Stein (1997). The approach here is a special case of home production, and I have not bothered to include most of the comparative statics results, as they are well known. The seminal work here is Becker (1981). For a good summary, see Cigno (1993). For an early example, see Grossman (1972).

[8] Whether H measures life expectancy alone, "health" (the absence of morbidity) or some combination is a difficult issue. The issue seems more perplexing for today's medical environment in which morbidity and mortality are less closely connected. In the age in which infectious diseases were the main causes of death, the distinction seems less acute, though Riley (1991) suggests that while mortality declined during the nineteenth century morbidity was rising.

where E is a common factor independent of the consumption basket ("environment"), f is the vector of household production functions that transforms the goods consumed and time spent producing them into better health and longer lives for the members of the household. Each good X_i is converted by household j into "health" using f_i in conjunction with a dose of L_D. The functions f are unobserved technical relationships. They tend to be complex beyond the household's full comprehension at almost any level of bounded rationality. The food component should take account not only of caloric intake but also of vitamins, minerals, fiber, substances combating free radicals such as anti-oxidants, and so on. Home heating, cleanliness, child- and medical care, and physical exercise are other examples of X's that enter equation 2. The function f describes such effects as exposure to harmful microorganisms and chemicals, the impact of behavior and nutrition on the cardiovascular system, as well as the interaction between consumption and the human immune system. Moreover, f is assumed to satisfy the condition that the conversion is *efficient* (that is, no X's are wasted in the production process), though this assumption is not necessary for the present purpose.[9] The shape of f is, however, not fully known to best-practice science, much less to the household. Indeed its complexity is such that it seems safe to maintain that its precise form is *unknowable*. Behavior is therefore determined by the function:

$$(3) \quad H_j^e = E + \sum_i [A_i - \epsilon_{ij}] F_i(X_{ij}, L_{Di}) \qquad \forall j,$$

where H_j^e is the prior that the consumer has over the determination of H, and E is an environment over which the consumer has no control. F_i is the best-practice knowledge on how the goods X and their associated household labor L_{Di} jointly produce H. The sum of all L_{Di} is total household labor, L_D. For my purpose here, it is important to realize that best practice knowledge could still be far from the accurate truth. A_i is a shift factor that measures the degree to which the "best-practice" grasps the true effects of good i on health. $A = 1$ means that best practice fully understands the impact of a particular X on health. $A = 0$ means that nobody has any idea that X has any effect on health at all (and thus the only reason why it is consumed is because it conveys direct utility). Moreover, individuals lag in

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[9] By this I mean that each X is directed toward the use where it can achieve the best effect on H. For instance, if the household purchases fruits and vegetables because it is believed that these product contain health-enhancing substances, the household does not then destroy these substances by overcooking the food. This assumption is required so that for each set of X's and L_D there exists a unique level of H for each individual. This implies that the crucial part of each recipe is the quantity and quality of the ingredients and not the details of preparation—clearly a simplifying assumption.

their knowledge behind best practice technique. ϵ_j is an individual-specific measure of the difference between individual *j*'s technology and the best-practice technology regarding good *i*. It may be best viewed as a "gap" between the best that anyone can do in this society and what an individual actually believes. This is a function not only of the dissemination of the Ω-knowledge from those who possess it to those who use it, but also of its tightness: do the consumers actually believe these recommendations? How well do scientists persuade consumers that dairy products prevent osteoporosis and that olive oil prevents coronary disease? As noted, the term $A-\epsilon$ measures the degree to which each consumer takes the indirect effect of the X's and L_D on H into account. The term $A_i-\epsilon_{ij}$, then, measures the degree to which consumer j is aware of and believes the mapping of the i-th X (and L_D) into H and is defined here for simplicity as a multiplicative deviation from "ideal" priors. Normally we would expect that term to be somewhere between 0 and 1, though it could be negative.[10] An increase in $A-\epsilon$ within that interval means that a consumer can do better in terms of overall utility than before simply by redeploying the resources available. If $A-\epsilon = 1$, the consumer follows best practice by some kind of ideal standard. If $\epsilon = 0$ but $A < 1$, she follows best practice by the imperfect standards of the time. The possibility that $A-\epsilon > 1$ is especially interesting. This means that the consumer is exaggerating the perceived effect of the good on her health and thus *over*consuming it to the point where its quantity is superoptimal. In the multigood model, $A-\epsilon > 1$ for a particular good means that the consumer *under*consumes other goods, and thus reduces her utility from those goods and in all likelihood even suffers worse health. By substituting equations like 3 into 1, we obtain demand functions for each good X and for the L_D associated with it.

A few further remarks on equation 3 are in order. First, we can define a level of consumption: X^{**}, which is the vector of consumption that maximizes U after substituting equation 2 into 1. This assumes a world of perfect knowledge in which all A's equal unity and all ϵ's zero, corresponding to point E' in figure 3. This means not only that scientists have figured out the exact functional relation between H and every X, but that everyone has access to that knowledge, believes it, and uses it flawlessly so that the consumer maximizes $U(X,H, L_D,L_E)$ "correctly" subject only to the budget constraint. Second, we may define $\hat{X}$, a vector of consumption for a consumer who is completely ignorant of the effect of

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[10] For example, the smoking of tobacco was widely prescribed by seventeenth-century doctors as a cure for a variety of respiratory afflictions; marijuana, in our own age, may be an example of the reverse: namely, a harmless and possibly benign substance (at least for some individuals) denounced and proscribed as unhealthy for moral reasons. In both cases A , and possibly $A-\epsilon$, are negative.

consumption on health, so that $A – \epsilon_j = 0$ for all X's, corresponding to $\hat{E}$ in fig. 1. Here consumption is entirely based on "primitive" utility maximization *strictu sensu* disregarding the effect of the X's on H. We define the actual consumption, conditional on $A_i – \epsilon_{ij}$ of consumer j of good i, as X^* where normally for each good $X^* \neq X^{**}$, $\hat{X}$. It is possible that the completely ignorant consumer would consume by coincidence just the right amount of some X's ($\hat{X} = X_i^{**}$), which holds for example if $F'(\hat{X}) = 0$, so that X_i has exactly zero marginal impact on health.[11] It is also possible that $\hat{X}$ is such that its average impact on health is significant even when A is quite low. In some historical cases, consumption patterns did lead to high levels of health as an unintended by-product. Perhaps the best-known example is the heavy dependence of the pre-famine Irish on potatoes, which produced a comparatively healthy and tall population despite the economy's low levels of income and the absence of any systematic knowledge of the nutritional qualities of the potato. Furthermore, if a good satisfies $X^* > 0$ and $\hat{X} = 0$, we have what we may call a pure health good, such as snake oil or antibiotics, which conveys no utility except its putative medical effects. If a good satisfies $F'(\hat{X}) = 0$, even a completely ignorant consumer receives the full health-enhancing effect of that good merely as a by-product of his or her appetite.

Second, it may be noted that, because when $X^* \neq X^{**}$ we are looking at a "second best" situation, a partial improvement (an increase in A or a decline in ϵ) cannot be guaranteed to raise the objective function H (although it is likely to). The formal demonstration of this proposition in a simple two-good model is presented in the appendix to this chapter, but the intuition is straightforward: since the consumer has to spend her income, she will pick a certain combination of goods according to her taste and partial knowledge. By updating her knowledge about one particular good, and learning that this good is better for her health than she had previously thought, she will increase consumption of this good, but therefore by necessity reduce consumption of another good. There is no

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[11] This would occur if, for any X^* that maximizes utility, the following condition happened to hold:

$$\frac{\frac{\partial U}{\partial H}\frac{\partial H}{\partial X_i} + \frac{\partial U}{\partial X_i}}{\frac{\partial U}{\partial H}\frac{\partial H}{\partial X_i} + \frac{\partial U}{\partial X_j}} = \frac{P_i}{P_j}$$

where P_i is the full price of X_i (including time cost) and $\partial H/\partial X_i = F'_i$.

guarantee that the loss in health from curtailing consumption on other goods is less than the gain from increasing the good in question.

The framework described here is simplified in many ways. It abstracts from the historical reality in that it makes no distinction between the household and the individual. In the actual historical experience, households made decisions and allocations that affected their members in different ways, and complex bargaining may have been involved in determining how the X's would be allocated. This is especially important because the new recipes for cleanliness and good housekeeping tended to be costly in terms of time, but this time cost was disproportionately borne by women. There may be a difference in the identity of the person whose beliefs are incorporated in equation 3 and the person who carries out the work. In other words, the L_D may be supplied by a different person than this person whose ϵ appears in equation 3. If different members of the household disagree about ϵ, it is far from clear how to aggregate the different values of the H^{ϵ}'s and thus how the actual decisions are made.[12] This is compounded by the nature of H itself: rather than a composite variable, it really is a matrix of variables, with a vector of health characteristics defined for each member of the household. How one trades off the health of one member against another remains an intra-household bargaining problem.

There are, however, deeper difficulties with the neoclassical approach advocated here. The entire structure of the household decision-making model needs to be specified in probabilistic rather than deterministic terms. The simple model ignores the stochastic nature of equation 2. When we say that $F'(X_i) > 0$, we really mean that prob $(H > H^*)|X^* >$ prob $(H>H^*)| X^{**}$ if $X^* > X^{**}$. That is, if the consumer consumes more of X, his or her chances of being healthier are better, but there is no certainty. Health is a stochastic variable, but the probabilities of disease and mortality are conditional on consumption and housework. Whether households can form accurate perceptions of these probabilities and can thus optimize their behavior if only provided with the "correct" knowledge is unclear. The work by Kahneman, Tversky, and their associates, controversial as it may be among economists, suggests at the very least that there are serious psychological difficulties that individuals experience in assessing differences in conditional probability leading to consistent and serious biases in the assessment of the F's in equation 3 above. The probabilities remain subjective and have often alarmingly diffuse prior distributions. Low probability

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[12] Interestingly, recent work on intra-household bargaining deal with cooperative and non-cooperative solutions to the consumption of common (public) goods over which the members have different preferences, but do not deal with the possibility that they may have different views on *how* common preferences are to be achieved (Lundberg and Pollak, 1997).

events are often either under- or overestimated by consumers depending on how the matter is brought to their attention; high-probability risks are systematically underestimated. There is abundant evidence that most people use "judgmental rules" or "heuristics" to assess these probabilities, which at times lead to erroneous inferences.[13] Modern writers about household practices describe the state of knowledge among housewives about hygiene as "a general state of vague anxiety...[and] even the dismissive doubters are rarely absolutely confident of their position" (Horsfield, 1998, p. 171).

A further difficulty in applying rational choice modeling to household work is that it involves dynamic decisions—that is, benefits (or the avoidance of pains) in the future are compared to costs at the present—and thus relies implicitly on discounted utility models. While such models are widely used in economics, they have weak empirical and theoretical foundations in psychology. It is well known that time consistency requires special (exponential) forms of discounting and that discounting asymmetries are often observed; that is, future benefits and future pains are discounted at time-dependent rates. Furthermore, as Thomas Schelling has noted, there is a universal problem of self-management, to behave the way one has resolved to behave for the sake of future benefits, which must be all the more acute for homemakers who do not face competitive pressures to discipline them into best-practice choices.[14] Self-discipline for homemakers was reinforced through education, propaganda, and other methods of persuasion. Calculating the correct rates with which to discount the future is further complicated by the feedback from health to discount rates (as life expectancy went up, discount rates should have fallen). All the same, for many of the infectious diseases of the late nineteenth century, the lag between act and penalty was sufficiently short to make discounting a secondary consideration—in contrast with modern afflictions such as

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[13] A good introduction can be found in the papers in Kahneman, Slovic, and Tversky (1982). Among those errors noticed in modern studies are the tendency to attach a higher probability to an explicit event than to a non-specified one and people's tendency to perceive correlations (and then infer causality) where none exist (see Redelmeier et al., 1995; and Redelmeier and Tversky, 1995). For examples of systematic underestimation of risk, see Viscusi (1992, pp. 22–24) and sources cited there. In regard to the utilization of "judgment rules" and "heuristics" in making erroneous inferences, see Slovic, Fischoff, and Lichtenstein (1982). The psychology literature has long noted that individuals tend to overweight "salient" information that is conveyed to them in a vivid and effective manner. Especially if the health effects of unsanitary behavior follow rather quickly (as is the case with many infectious diseases), the way the information about germs was communicated to the working classes may have led them to err consistently in the direction of over-cleaning and spending more effort housework than was warranted (Ross and Anderson, 1982).

[14] For details, see the essays in Loewenstein and Elster (1992), especially Schelling (1992).

cancer and cardiovascular diseases. Many of the X's thus have the interpretation of investment, because consumption today may affect health many years in the future (Grossman, 1972). The future health benefits of any investment are discounted by economic agents. The discount factor itself becomes an endogenous variable here: as life expectancy improves in society as a whole, each consumer will believe that he or she has a greater probability of survival. The subjective discount factor will fall, and as a result the consumer may wish to participate more in health-enhancing efforts. Thus, improvements in knowledge produce positive feedback in the investment in health beyond their original impact.

Another dimension in which this analysis oversimplifies is that the consumption of health-enhancing goods may be constrained even if the consumer is aware of their benefits. This would occur if there are, for example, indivisibilities in the consumption of certain goods. One cannot have half a toilet, of course, and the sharing of toilets and kitchens between families gave rise to serious externalities. A clean water supply piped in from a distance was something that households could not provide for themselves individually. Many private goods were complementary with these publicly provided goods: a flush toilet was a private good but could not be used without publicly provided sewage and running water networks. Information about the safety of food and drugs has clear-cut public good properties. Thus, some of the X's with the most favorable impact on H had a public good character, from the drainage of swamps to the inspection of milk quality. Epidemics are a classic example of negative externalities: by taking preventive action, a consumer reduces his neighbor's chance of contracting an infectious disease in addition to his own.

Yet the realization that some of the X's were not easily provided by the market and belong to public rather than to private health does not invalidate the analysis. Instead, it focuses the attention on the political economy of public health: once consumers are aware and convinced of the beneficial effects of certain public works, they will resort to political action (possibly at real cost) and demand from their politicians the provision of the goods with the desirable characteristics, shifting the action from the commodity market to the political market (Brown, 1988).[15] Moreover, political decision makers themselves were subject to learning and persuasion, and a function similar to equation 3 above can be written down to describe what policy makers' priors are and how they were persuaded by

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[15] Brown's work suggests, intriguingly, that the more democratic regime in Britain (that is, the broader franchise) held back sanitation projects as middle class taxpayers displayed less enthusiasm for the projects than the business elites. The Swedish experience suggests, however, that other political factors, such as the presence of activist lobbies, could also make an important difference (Nelson and Rogers, 1992).

new knowledge to change the bundle of public goods they provided. In that case, the initiative came from them, but if the projects involved large outlays, they needed to convince voters of their merits. Clearly, then, the growth of useful knowledge in this area has as much a private dimension as it does a public one. Much of the literature has, however, focused on this public dimension of health improvement, neglecting almost entirely the private learning by households (with the exception of Preston and Haines, 1991, p. 20; and Riley, 2001). Many of the important changes, however, were occurring at the household level.

Three Scientific Revolutions

The model in the previous section suggests that there does not necessarily have to be a "true" value of the optimal consumption, or that if there is, it may not be knowable. What counts, above all, is what people *believe* to be true about the material world around them and how their actions and the way they run their lives affect their physical state. People can, however, be closer to or further from the truth (or what appears to us to be the truth) in measurable amounts. The household choices regarding matters that affect their health depend in part on what they know, of course, but there must be more to it than that. As biologist Richard Lewontin has observed, "the reason that people do not have a correct view of nature is not because they are ignorant of this or that fact about the material world but that they look to the wrong sources in their attempt to understand it" (1997). The point, however, is that one can follow better recipes even on a narrow epistemic base, that is, without having a "correct view of nature," as long as one is willing to accept techniques and rules of thumb designed by authorities and trusted experts, if these actually improve health. In that sense the notion proposed in chapter 1 regarding the social character of the epistemic base of techniques applies. Homemakers do not have to know *why* certain kinds of prescriptive knowledge work, they just have to be *persuaded* to follow the instructions. Decision makers have to be believe that if $\partial H/\partial X_i < 0$ (the good is unhealthy), they should reduce the consumption of the otherwise desirable good X_i. Persuasion normally does not play much of a role in standard economic models of technological change. Rational agents make up their own minds.[16] It is at this juncture

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[16] Innovation in agriculture in premodern Europe, precisely because it too depended on decisions made by households in a weakly competitive environment, is comparable to the framework discussed here. Agricultural innovations usually led to higher yield of a given crop or a higher income in case of a new crop. Yet the outcome of an innovation is a change in one of many independent variables in an equation where some "income" variable is the dependent variable. The proper test of whether an innovation is profitable is whether its partial effect on the

that the social construction of technology of Bruno Latour (1987) and Wiebe Bijker (1995) meets the selection models advocated by evolutionary epistemologists such as Donald Campbell (1960) and Robert Richards (1987). At the level of the firm, economists would argue, the selection issue is quite simple, since profit maximization provides an a priori overriding criterion. Whether this view is quite realistic is another issue, but in any event, it does not apply in the same way to households.

How do households pick and choose from the vast menu of techniques that they believe enhance their health? Rhetoric, marketing skills, political influence, and prejudice, as well as emulation and social learning, come into play. Persuasion requires shared standards of evidence, chains of authority, networks of trust, and accepted rules of logic and evidence. Changes in the rules of discourse and communication, no less than the knowledge unearthed by science, are the background to the changes in health and longevity that are the mark of the "modern" age.

In the past two centuries household behavior has been affected by formal and informal Ω-knowledge far more than has been realized by social historians.[17] This is not necessarily because science has gotten it "right" more often than it used to, but because scientists have increasingly influenced the way common people think about the natural world. The propositional knowledge relevant to household recipes was generated of course by a few men and women whose work helped map into new best-practice techniques, denoted here by A. Increases in A were followed by changes in individual behavior, that is, declines in ϵ, the gap between best- and average-practice techniques. To get households to change consumption bundles requires considerable persuasion because any movement, say, from E^* to E^{**} (see figure 3) involves a redeployment of the consumption basket. Furthermore, an increase in H thanks to cleaner homes, improved child care, and better prepared food required more work at home, that is, it required a reallocation from L_E to L_D. What was responsible for these changes? We can readily identify the advances in best-practice techniques. Describing what exactly households knew and believed and how they were

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farmer's objective function is positive. A formal definition of an improvement would be that the distribution of output conditional on the innovation is in some way more desirable than the distribution conditional on the old technique. However, to persuade the farmers of past centuries to adopt new techniques must have been difficult given their limited opportunities to experiment and their inability to conceptualize, let alone carry out the kind of statistical analysis that modern researchers have at their disposal. When someone truly believed in a new technique, he or she tried to persuade other practitioners. Propagandists such as Jethro Tull and Arthur Young employed a rhetoric in which the net effects of certain new techniques were sold to British farmers. These efforts at persuasion were slow and highly uneven. Technological progress in agriculture, according to one witticism, advanced at the rate of a mile a year.

[17] A notable exception is Tomes (1990).

persuaded to change their behavior is a more complex task. The decomposition proposed in equation 3 suggests that two elements can be examined separately: the expanding Ω-knowledge that people in authority possessed about disease and health, and changes in the behavior and the deployment of household resources resulting from the influence experts exerted on daily consumer behavior and household management.

Changes in useful knowledge were thus responsible for many of the changes in household behavior in the period between 1815 and 1945. These changes account for a substantial portion of the decline in morbidity and mortality rates in the West. The abruptness of the changes should not be overstated: medical knowledge is notoriously untight, and alternative practices, including herbal medicine, folk remedies, Christian Science, and a variety of non-standard practices have survived.[18]

Three major scientific revolutions affected the value of A in the past two centuries. The first was the sanitarian and hygienic movement that began after 1815, which picked up enormous momentum between 1830 and 1870 and swept the later Victorian era, leading to a widespread if unfocused war against dirt based on a vague perception that dirt and disease were correlated.[19] Pre-1870 preventive health provides a textbook example of the high cost of techniques that rest on a narrow epistemic base. It was widely believed that filth was a source of disease, but that disease spores traveled through odors. Hence the enormous emphasis on ventilation and refuse removal, a technique that worked to some extent, but at a high cost. Vinegar spraying was widely applied to remove odors, in addition to refuse removal. Diseases such as typhoid and cholera were not affected by these measures and needed a different approach.

The war against filth, which had eighteenth-century roots, drew new strength and focus from the statistical revolution that grew out of the Enlightenment and led to the development of nineteenth-century epidemiology. It provided data to support the close relation, long suspected, among consumption patterns, personal habits, and disease. The statistical movement presented one way out of the household's logical dilemma: how can an individual verify that a given recipe affects the health of its members without being able to carry out an experiment in laboratory conditions? Even today, inferences from large samples have remained the logical foundation of much research in epidemiology and public health.

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[18] Medical anthropologists such as Helman (1978) have argued that there is a great deal of continuity between biomedical treatment and the "folk" model that has remained ensconced in patients' minds.

[19] For some insights in the emergence of the statistical method in post 1830 Europe, see especially Porter (1986); Eyler (1979); Gigerenzer et al.(1989); Coleman (1982); and Cullen (1975).

The roots of this movement went back more than a century, especially to the debates around the efficacy of the smallpox inoculation procedure, the beneficial effects of breast-feeding, and the bad effects of miasmas (putative disease-causing elements in the atmosphere).[20] The empirical regularities discovered by the statisticians reinforced earlier middle-class notions that cleanliness enhances health. By the middle of the nineteenth century, these notions were filtering down vertically through the social layers of society. But their persuasiveness was vastly extended by the growing interest in statistics and the analysis of what we today would call "data" dating to the decades after 1815.[21] The founding of the Statistical Society of London in 1834 led to an enormous upsurge in statistical work on public health. In Britain, William Farr, William Guy, and Edwin Chadwick were the leaders of this sanitarian movement, but it encompassed many others (Flinn, 1965). On the continent, the leaders of the statistical movement included such notables as Adolphe Quetelet, René Villermé, and Charles-Alexandre Louis clustered around the *Annales d'hygiène publique*. The connection between the sanitarian movement and the statistical revolution was fundamental to the changes in the perceived health effects of consumption and behavior. Between 1853 and 1862 no less than a quarter of the papers read before the Statistical Society of London dealt directly with public health and vital statistics.[22]

Much of the statistical work of the sanitarian movement was concerned with the correlates of the incidence and virulence of specific infectious diseases. As such they were meant not only to increase knowledge (increase A) but also to persuade (reduce ϵ). We will come to persuasion in the next section, but the contribution of a more systematic search for patterns in data had some remarkable attainments. Statisticians looked for empirical regularities in the geographical, seasonal, and social patterns of major illnesses in an attempt to find the etiology and transmission mechanisms. Often they were led down blind alleys and clutched at statistical artifacts, but their search for regularities led to advances in epidemiology and public health with profound implications for the practice of preventive medicine. As I have argued, statistics were also a way of

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[20] Sheila Johansson (1999) has argued that the decline in the mortality rates of the British aristocracy after 1700 indicates that some of the knowledge that helped prevent infectious diseases preceded the sanitarian movement. This could be the case for smallpox and possibly childhood diarrhea. It also is likely that the very wealthy chose better values of E in equation 3—that is, to live in low-exposure environments.

[21] For the roots of the movement, see Rusnock (1990); and Riley (1987). The growth of the movement's persuasiveness is well documented in Headrick (2001).

[22] Many social reformers and activists such as Henry Mayhew and Florence Nightingale were life-long and enthusiastic members of the Statistical Society.

tightening some beliefs that may have been held by some but did not carry the day.

Among the other great triumphs of this methodology were the discoveries of John Snow and William Budd in the 1850s that water was the transmission mechanism of cholera and typhoid, and in 1878 that milk was a carrier of diphtheria by correlating the incidence of the disease with milk-walks (Hardy, 1993, p. 90). In clinical medicine, the use of statistical tools was critical to the insight of C. A. Louis, who developed a "numerical method" for evaluating therapy and around 1840 provided statistical "proof" that bloodletting was useless, leading to the gradual demise of this technique (R. P. Hudson, 1983, p. 206). Louis's work and the decline of bloodletting was an excellent example of how statistical methodology could make Ω-knowledge tighter and subsequently persuade others to change their techniques. Similar work on breast-feeding led to a campaign to persuade women to nurse longer.

The methodology that recognizes the narrow epistemic base of techniques it advocates and formalizes the inductive approach to establish natural regularities even without understanding much about the underlying natural processes of work turned out to be unusually fruitful in public and private health technology. In Germany, the great founder of modern physiology, Rudolf Virchow, called for more medical statistics: "we will weigh death and life and see where death lies thicker," insisted Virchow (cited in Rosen, 1947, p. 684). Early Victorian Britain witnessed the transformation of eighteenth-century political arithmetic into a body of knowledge that combined a quantitative approach with social reform. Systematic empirical observations allowed observers, notwithstanding erroneous theories, to draw the correct policy implications for the wrong reasons—another parallelism between technological change and medical progress. Hudson indeed notes that the "great sanitary awakening" after 1840 was a remarkable but not unique example of doing the right thing for the wrong reasons (1983, p. 179).[23] One could add that it was a classic case of a large number of new techniques based on a relatively narrow epistemic base, relying on poorly understood empirical regularities.

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[23] Even those who resisted the new science often made life-extending recommendations: the influential German physician Max von Pettenkofer fought the microscopic theory of disease tooth and nail, yet advocated radical public health measures to prevent the spreading of infectious disease in the city of Munich. As late as 1900, eighteen years after the discovery of the tubercle microorganism, a prominent British physician recommended improving the homes and living conditions of the working classes to reduce the incidence of tuberculosis, yet added that "the insane hunt after the tubercle bacillus is the insanest crusade ever instituted on illogical lines" (cited by Wohl, 1983, p. 131).

The second breakthrough of the nineteenth century, (or, using the notation in this chapter, the increase in *A*), was the germ theory of disease. Bacteriology was more than just a way of attributing certain symptoms to certain microorganisms. The germ theory provided an entirely new concept of disease: how it was caused, how to differentiate between symptom and cause, and how infection occurred. As is well known, the germ theory was not quite "invented" in the decades after Pasteur's famous work on silkworm disease. It had been proposed repeatedly since the sixteenth century, and in 1840 Jacob Henle revived the theory in Germany. The theory remained, however, on the fringes of medical science, and in the following decades Henle was regarded by the medical profession as fighting a "rearguard action in defense of an obsolete idea" (Rosen, 1993, p. 277). But the germ theory prior to Pasteur and Koch was untight. It might be true, but for contemporaries there was no way of knowing for sure. The triumph of the germ theory after 1865 should be regarded above all as a victory of scientific persuasion in which brilliant scientists were able to combine scientific insights with considerable academic prestige and a good understanding of how power and influence in the scientific community work (Latour, 1988). It relied on an experimental method widely touted to be a failsafe way of unearthing "truth" and was thus accepted by increasing numbers of people with the same blind faith previously reserved for religion. Rhetorically, then, it was useful knowledge that was powerful and persuasive enough to change the recipes used by households in the West even if many of the details of the new theory of disease remained highly controversial for decades.

The revolution in preventive medicine of the decades before 1914 serves as an illustration of the interactive dynamics between propositional and prescriptive knowledge. This is the period when the idea that diseases were transmitted by vectors emerged, and specifically the hypothesis that mosquitoes spread infectious diseases such as yellow fever. This murderous disease devastated much of the American South and the Caribbean in the nineteenth century. During the cleanliness campaigns of the mid-nineteenth century standing water and open sewage in cities were reduced, and with them the mosquitoes. The decline of the disease was attributed to the disappearance of the stench. Memphis, for example, was free of yellow fever after the sanitation campaign, but since the epistemic base was essentially empty, this experience could not put to good use elsewhere (Spielman and d'Antonio, 2001, pp. 72–73). The suspicion that mosquitoes might be involved in the transmission of some diseases had already been raised in 1771 by an Italian physician named Giovanni Lancisi (for the case of malaria), and in 1848 a physician from Mobile, Alabama, Dr. Josiah Nott, extended the idea to yellow fever. A more detailed hypothesis that the disease was spread by the mosquito *Aedes aegypti* was put forward by a Cuban doctor, Carlos Finlay, in 1878, but his experiments failed to carry conviction, in part because the notion that insects carried disease was too novel and revolutionary for many physicians to accept (Humphreys, 1992, pp. 35–36). Only in 1900 did Walter Reed demonstrate the infection mechanism by persuasive experimental methods (costing the lives of three volunteers) and also show his interpretation to be consistent with many of the findings of the existing literature. Meanwhile the work of Patrick Manson, Ronald Ross, and G. B. Grassi had demonstrated in the 1890s the culpability of the anopheles mosquito of malaria, and in 1909 Charles Nicholl discovered the louse vector of typhus, five years before the causative germ itself was isolated. Once this knowledge had become consensual and could serve as an epistemic base—even if it was not very wide, since the virus responsible was not identified until decades later—an effective war against the vectors could be launched and the lives of thousands were saved. For a public health campaign to gain support it required, among other things, to be grounded in "undisputed medical theory" and to have a mode of action comprehensible to the lay mind (Humphreys, 1992, p. 180) . The war on insects was launched jointly by the public sector and households, and exactly because the epistemic base was still narrow, it seems at times to have been overzealous (Rogers, 1989).

In terms of its direct impact on human physical well-being, the victory of the germ theory must be counted as one of the most significant technological breakthroughs in history. The bacteriological revolution heralded a concentrated and focused scientific campaign to once and for all identify pathogenic agents responsible for infectious diseases. Between 1880 and 1900 researchers discovered pathogenic organisms at about the rate of one a year and gradually identified many of the transmission mechanisms, although many mistaken notions survived and a few new ones were created. The age-old debates between contagionists and anticontagionists and between miasma and anti-miasma theories slowly evaporated, although the belief that "bad air" was somehow responsible for diseases such as diarrhea was still prevalent in the 1890s. The refutation of the Aristotelian notion of "spontaneous generation" of life from lifeless matter by Pasteur demonstrated that bacterial infection was contracted exclusively from a source outside the body. It provided a much wider epistemic base for a large number of household techniques that were thought to prevent disease, thus making them both more effective and more persuasive. The widening of the epistemic base thus made the techniques employed more accurate and more efficient. As long as all that was known was that poverty and filth were associated with disease, public health was closely linked to income redistribution and the elimination of poverty, as many early public medicine pioneers such as Rudolf Virchow advocated. As more useful knowledge accumulated, this changed: proper child care, domestic and personal cleanliness, and adequate nutrition on the other hand were no longer regarded as the essential domain of policy measures since they were not incompatible with poverty and were properly regarded as part of household choice. The poor did not get sick because they were poor, but because germs infected them. Eliminate the germs and you will have healthy poor as long as they do not fall below a level where their physical well-being cannot be supported. Beyond that, however, the interaction between social problems and medical issues could be defined with some precision. In 1893 the great bacteriologist Emil Behring wrote laconically that, thanks to the methods of Robert Koch, the study of infectious disease could now be pursued without being side-tracked by social considerations and welfare policies (Rosen, 1947, p. 675).

The third revolution consisted of the knowledge that small traces of certain substances are crucial to human health. The realization that some crucial substances cannot be manufactured by the body from other nutrients and need to be supplied by the diet is of special interest here, because often these techniques involved relatively minor and inexpensive reallocations of household resources. It may seem that once this part of Ω is known, the mapping of this knowledge to household techniques would be obvious and changes in behavior would be forthcoming rapidly. But historically this was not quite the case. Physicians in the West had discovered in the nineteenth century that cod liver oil was an effective treatment for rickets, but this was a purely empirical procedure, a typical singleton technique not based on any notion of why it worked (Rosen, 1993, p. 383). Hence mistakes were made and further development was blocked, as was often the case with techniques that rested on a narrow epistemic base. Another example is the history of scurvy. The importance of fresh fruit in the prevention of scurvy had been realized even before James Lind published his *Treatise on Scurvy* in 1746. The Dutch East India Company kept citrus trees on the Cape of Good Hope in the middle of the seventeenth century, yet despite the obvious effectiveness of the remedy, the idea did not catch on and "kept on being rediscovered and lost" (Porter, 1995, p. 228). Scurvy kept reappearing during the Irish Famine, the Crimean War and the Russian army during World War I. Infantile scurvy was still prevalent in the early twentieth century among wealthier families who weaned their children earlier than poorer ones.

Apart from the observation that there was an apparent connection between the consumption of fresh fruit and vegetables and the occurrence of scurvy, little was added to Ω until a century and a half after Lind published his treatise. Again, the case illustrates how a narrow epistemic base led to the untightness of the related technique: nobody quite understood what it was in fresh fruits and vegetables that performed the miracle of scurvy prevention, and thus alternative prescriptions circulated. When the epistemic base is narrow, a great deal of unnecessary research is carried out and many blind alleys are entered: following the discovery of the germ theory, scientists spent decades of futile search looking for a causative microorganism for scurvy. Only after the seminal paper by Axel Holst and T. Fröhlich in 1907, which reported the inducement of scurvy in dietarily deprived guinea pigs, did it become clear that certain diseases were not caused by infectious agents but by deficiencies of trace elements, and only in 1928–32 was ascorbic acid isolated as the crucial ingredient (Carpenter, 1986; French, 1993). Before the epistemic base of nutritional deficiency diseases was recognized and became tight, the techniques dealing with these diseases were simply pathetic.[24]

Knowledge, Persuasion, and Household Behavior

In terms of our model, we can regard the discoveries as a sudden leap in the value of A, equivalent to a large expansion in the knowledge set Ω. To be sure, there is a difference between the discovery of a pathogenic microorganism responsible for a disease and the mapping of this knowledge into recipes implied by it. However, once the epistemic base has been extended and it is clear which microbe causes a disease and how it is transmitted, the means of prevention become easier, and the recommended adjustment in household techniques can be inferred. The discovery of the HIV virus in 1984 had a comparable effect. Yet recall that any expansion in Ω (a discovery) in and of itself initially leaves $A-\epsilon$ unchanged (that is, ϵ rises at first to match the increase in A). It is only when the new knowledge was disseminated to the population and when the public was sufficiently persuaded by it to act upon it and alter its behavior, that the value of ϵ started to decline, consumption and time-allocation behavior were modified, and mortality declined (Mokyr and Stein, 1997). The decline in ϵ (that is, the rate at which the new technique is adopted) depended on the persuasiveness of knowledge, that is, people's willingness to act upon it. The experimental methods deployed by the bacteriologists coupled with the tabulations of the statisticians created a powerful assault on age-old prejudices and notions about what made people ill.

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[24] As late as the 1920s, farmers whose cattle suffered from Bedforshire disease were counseled to burn frogs in their gateways as a cure, instead of using the mineral licks that eventually got rid of the problem (E. L. Jones, 2002, p. x).

Moreover, a combination of the paternalism of the educated classes and the greed of commercial salesmen created an apparatus that diffused the new knowledge rapidly among the working classes in the industrialized West. Although the absorption of the full behavioral implications of the germ theory took decades to complete, what is surprising is how relatively quick and complete its triumph was by 1914; the changed behavior led to sharp declines in infectious disease decades before the introduction of antibiotics. The new knowledge provided the proverbial ounces of prevention that explain the almost miraculous decline in mortality.

It is easy to underrate the rhetorical power that statistics lent to the spread of hygiene. Literally hundreds of tracts, newspaper articles, pamphlets, lectures, and government reports were published in the nineteenth century, all pointing to the direction of improved health if the consumer chose to practice the rules of cleanliness. Statistics were used to persuade the masses, but more important, they persuaded people of authority in key positions to influence others. The findings of William Farr and Edwin Chadwick, two civil servants and leaders in the statistical movement, were disseminated by influential people: the Metropolitan Health of Towns Association was founded in 1844 to "diffuse among the people the valuable information elicited by recent inquiries and the advancement of science [and] the physical and moral evils that result from the present defective sewerage, drainage, supply of water, air, and light, and construction of dwelling houses." Among its early members were T. R. Malthus, Charles Babbage, Earl Grey, Benjamin Disraeli, Bulwer Lytton, and the Earl of Shaftesbury, a leader of the factory reform movement (Wohl, 1983, p. 144). The Manchester Statistical Society (founded in 1833) consisted primarily of members of the industrial and commercial bourgeoisie, people who in many ways were social models, to be followed and emulated by their lessers. The empirical regularities discovered by the statisticians thus filtered down through the social layers of society.

The impact of statistical knowledge was considerable. Chadwick's famous 1842 report, "a masterpiece of persuasion, subtly blending fact and fiction," is only one example of this power. Although Chadwick's work may have been theoretically flawed, his use of statistics lent his report persuasive weight.[25] The statistics and data collected in the mid-nineteenth

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[25] Chadwick cited by Cullen,(1975, p. 56). Statistical fallacies were not of great import, and some of the finer points were lost in the rhetorical noise. Thus, Chadwick used average age at death to drive home his point that poorly drained and congested urban areas had far higher mortality rates than other regions. Cullen points out that already at the time it was realized that this particular statistic is sensitive to the age structure and thus a poor proxy for life expectancy at birth; yet this fine point ignores the more important one that Chadwick was able to associate health with sanitary conditions.

century should not be judged by today's more exacting standards. Many of the statistics consisted of tabulations in which "numerators came from the registration materials and the denominators from the census."[26] There was little realization that correlation did not imply causation, that there was a need to hold some factors constant to isolate the net effect of each variable, to say nothing of an awareness of the problems of multicollinearity, omitted variables, and specification bias. Yet these data allowed inferences, however crude, by increasing the sample size beyond the individual experimentation space. Faced with this growing sense of statistics, medical practicioners and household decision-makers began to re-examine age-old beliefs and practices, including child care, drinking water purity, hygiene, and nutrition. Chadwick was aware that "domestic mismanagement," as he called it, was a "predisposing cause of disease." He cited with approval a set of reports that maintained that workers' wages would have been sufficient to supply the domestic comforts that would keep them in good health, but that these funds were spent "viciously or improvidently" and that "thoughtless extravagance" prevailed in their consumption habits (Chadwick, 1843, pp. 204–5).

Once the scientists and statisticians had persuaded the literate and educated public to modify *their* behavior, well-meaning organizations run by middle-class ladies such as the British Ladies' National Association for the Diffusion of Sanitary Knowledge (founded in 1857) took over the task of persuading the masses.[27] Between 1857 and 1881 this association distributed a million and a half tracts loaded with advice on pre- and postnatal care, made millions of house visits, and spread the gospel of soap and clean water. In the late Victorian period, the poor were receptive to these volunteers (Wohl, 1983, pp. 36–37). The association also published tracts on diet and either taught cooking classes or campaigned to have it taught in elementary schools (Williams, 1991, p. 70). Later, statistics and numbers were used with powerful effect on the masses directly. Contemporary pamphlets used statistical rhetoric to underline especially one crucial recipe, the importance of breast-feeding.[28]

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[26] Eyler (1979, p. 68). William Farr, one of the founders of the statistical movement in Britain, wrote to Florence Nightingale in 1861, "We want facts...the statistician has nothing to do with causation, statistics should be the dryest of reading" (cited in Porter, 1986, p. 36).

[27] The underlying assumption was that a "principal cause of a low physical condition is ignorance of the *laws of health*" (cited by Williams, 1991, emphasis added). These laws, Williams points out, were the laws of "physiology and chemistry" as well as the ethical commandments of a divine lawgiver. These organizations promoted the idea that households should take responsibility for their own health and well-being rather than accept their misfortunes fatalistically.

[28] Home economics textbooks such as Hitching 's *Home Management* (1912) emphasized the fact that babies fed on mother's milk have a ten times larger chance of surviving than bottle fed children (p. 148). One of the most effective rhetorical tools of the authorities in England was

The long-run implications of the new knowledge were outlined by George Rosen but are worth restating: responsibility for the health of household members was shifted from Providence or "fate" to the homemaker. Diseases were controllable and preventable provided households changed their behavior. Infant morbidity or mortality, if it occurred, was to be blamed on the homemaker.[29] While it was recognized that because of certain imperfections such as local public goods and the externalities associated with epidemics there remained a role for the public sector, this role was from now on circumscribed: public health shifted from an environmental view of health and disease to a behavioral one in which the habits of the individual became the focus of health policy.[30] Such political recommendations masked a fundamental uncertainty about the causation of diseases, and while the germ theory made it clear that for certain diseases there were necessary causes (tuberculosis required the presence of the tubercle germ), not all diseases had such necessary causes and few had sufficient causes. In short, the techniques preventing human disease were still supported by a fairly narrow epistemic base, and much of the underlying knowledge (especially relating to non-infectious diseases) was and still is untight (Kunitz, 1987).[31]

Homemakers had to be persuaded that they were the primary guardian at the household gate, armed with mop and sponge, charged with keeping out the microscopic enemy. Mrs. Plunkett spoke for a new set of beliefs when she wrote in 1885 that "the full acceptance of the germ theory of contagious disease shows exactly where to combat it. Destroy the seed, you prevent the crop, and where this is impossible the next best thing to do is the neutralize the conditions of their growth" (Plunkett, 1885, p. 164). Yet by 1885 this new knowledge was still concentrated among a few educated men and women. The challenge was to spread this knowledge to the masses. Public policy was aimed at reducing the lag of the population at

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to convince the population that working mothers jeopardized the lives of their babies by citing a strong correlation between working mothers and infant mortality. This notion received an official imprimatur from the 1904 Physical Deterioration Committee established after the Boer Wars, although the absence of any serious evidence caused it to become more controversial in subsequent years (see Dyhouse, 1981, p. 96).

[29] Rosen (1947, p. 675). This point is made in some detail by Ball and Swedlund (1996). It is hard to understand why this sudden change in the assignment of responsibility took place without the changes in medical knowledge. The responsibility of homemakers to keep the domestic environment germ-free is the main logical prerequisite to "blaming" inadequate maternal care for the high infant and child mortality rates that still plagued the United States and Britain by the late nineteenth century. See also Meckel (1990, pp. 92–123) and Tomes (1998, pp. 65–66, 150–54).

[30] Rogers (1992, p. 16); see also Brown (1988).

[31] Ziman points out that while epidemiology may have great value as the epistemic base of preventive medicine techniques, it is a crude research strategy because there is no obvious way of filtering the signal from the noise and unscramble the causal mechanism (1978, p. 70).

large behind "best-practice knowledge," and to induce wider implementation of the recipes implied by the new bacteriology.

The statistical movement led to the launching of a variety of public campaigns to reform consumption habits, but its full effects on the population's health remained limited until late in the nineteenth century.[32] It seems plausible that attempts of science to reform consumption habits based on empirical regularities alone would ultimately be limited in their effectiveness. Persuasion based on statistics depends on the susceptibility of society to such arguments and thus on education. The reliance on quantitative data indicates how little the medical world really knew of the real sources of disease and the distrust with which much of the public still regarded medical experts. Moreover, statistical information was viewed as furthering our understanding of aggregates while obscuring the peculiarities of individual households, so its findings might not provide sound advice to each decision maker. The concept of expected utilitarianism, in which the probabilities were determined from population means, was still not widely accepted. What was needed was a model that could tighten the Ω-knowledge attained from the data to show what mechanism was responsible for disease and provide guidance in making choices. Without the benefit of such a model, it was difficult for households and the authorities to choose correctly because correlation was perceived to be different from causation. As long as the new knowledge was untight, it was more difficult to persuade governments and individuals to spend money to prevent it.[33] If disease was correlated with poverty, was the only answer to the threats of infectious disease to eliminate poverty?

Even when the statistical evidence is so abundant as to be overwhelming (as is the case with smoking in our own time), the rhetorical strength of statistical logic is limited. One perceptive historian has noted that "preventive medicine is an extraordinarily difficult concept to convey, given that if one is successful, nothing happens—the disease does not come, the baby does not die" (Humphreys, 1992, p. 181). For that reason, the sanitarian movement declared hygiene to be virtuous in the "cleanliness is next to Godliness" mode. Such campaigns, much like the temperance

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[32] See, for example, the essays in Woods and Woodward (1984), esp. pp. 148–202.

[33] An example is typhoid fever, shown in the 1850s by William Budd to be spread by water and food. Yet there was enough uncertainty about the exact etiology of the disease to delay the implementation of his recommendations until the Public Health Act of 1875 (LeBaron and Taylor, 1993, p. 1075). It might be added that Budd himself also warned against the dangers of "sewage air," a widespread culprit of ill health in nineteenth-century beliefs (Hardy, 1993, p. 166). Even after the discovery of the typhoid germ by Karl Eberth in 1880, mistaken theories remained popular at least until 1900 and the disease remained a threat. One fifth of the soldiers participating in the Spanish-American War in 1898 still contracted the disease; during World War I the proportion who contracted it was 0.05 percent.

movement, were as often based on moralistic arguments as on empirical and logical reasoning, and as such their impact was widespread among those susceptible to this type of rhetoric. As Tomes points out, heavy-handed appeals to guilt did not apply to both sexes equally, and women were expected to be in charge of housekeeping and carried greater responsibility for preserving health (Tomes, 1990, p. 527). Arguably, the sanitarian movement needed an ally that would also appeal to the men. This ally was experimental science and the authority of men in white labcoats. The power of empirical regularities by themselves to persuade people to change their behavior, no matter how sophisticated the statistical methods employed, runs into diminishing returns.

Nineteenth-century empirical data were, moreover, highly deficient and incomplete. Contemporary writers, such as Henry Rumsey (1875), were aware of their weaknesses. Most of the statistical inferences were drawn from simple tabulations, had no controls, and almost never recognized the distinction between partial and total effects, to say nothing of endogeneity and omitted variables biases. Consequently the movement confronted the dilemma that a cluster of social problems—poverty, urban congestion, lack of sanitary facilities, bad nutrition—were correlated with high mortality rates and epidemics, but it did not know how and why. It thus ended up recommending the wholesale elimination of poverty and slums as the only possible remedy for disease.

However, the bumbling, groping, purely empirical approach to the prevention of disease of the sanitarians and statisticians prior to the appearance of a model provided by the bacteriologists should not be sneered at. Even today, empirical regularities have not been abandoned as a method of understanding health and disease as our age struggles in rather similar ways with coronary disease, cancer, certain viruses (including HIV), and autoimmune disorders. The continuous rise and fall of red wine, green cabbage, garlic, hot chili peppers, cholesterol, antioxidants, beta-carotenes, megadoses of vitamin, selenium, and so-called phytochemicals are a sufficient indication that even today the modi operandi of consumption on our health and longevity are far from properly understood and we have to fall back on statistical patterns. Empirical regularities drawn from large samples—the famous Framingham heart study begun in the late 1940s is one of the early examples—that establish putative connections between the consumption of certain goods and health keep augmenting the Ω set, even if the mechanisms involved are still largely a mystery. With the decline of infectious and nutrition-deficient disease, non-infectious diseases took their place, and their causal mechanisms are at present almost as poorly understood as those of infectious diseases before 1860.

The success of the nineteenth-century sanitarian movement was slow in the making. Many of the antiquated recommendations to avoid odors and to maximize sunlight and ventilation survived for many decades. Mrs. Plunkett (1885) was well aware of the bacteriological advances of her age, yet in her book she reproduces advice inconsistent with it and recounts tales reflecting miasma theory. As late as the 1920s, household manuals railed against "sewer gas" as much as they did against deadly germs (Tomes, 1990, p. 538). The triumphs of the new recipes in displacing less effective older ones at the household level were not nearly as thorough as what happened in production technology. Indeed, the survival today of "alternative" medical paradigms such as homeopathy, chiropractic, and herbal medicine, suggests that the victory of "modern" medicine is far from complete and that the selection mechanism does not work very thoroughly.

What was needed to complement the insights of statistics was a model. A theory of disease that identified a clear-cut enemy, such as microbes that could be fought with mop, sponge and kitchen range, focused the efforts of European homemakers. To be sure, here too the speed of the transition should not be overstated. Bacteriology took decades to become a coherent body of knowledge, and until the insights of immunology came along it remained unclear why some infected people did not get sick, as Shaw's *The Doctor's Dilemma* (1913) illustrates.[34] Furthermore, the slow rate of adoption and the disagreement reflects the difficulties in the practical application of bacteriology to household decisions. Even when it was wholly understood how impure drinking water could transmit disease, it was not clear how to define standards for purity and how to go about achieving them. Even more difficult was the issue of clean milk: while the dangers of possible infection through milk were increasingly understood, the "right" preventive measures (boiling, pasteurization, breast- versus bottle-feeding) were a source of great confusion deep into the twentieth century.[35] It is also worth stressing that a belief in hygiene did not imply acceptance of the germ theory: from Florence Nightingale to Max von Pettenkofer, leading sanitarians rejected the new gospel of germs and yet preached cleanliness.[36]

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[34] B.B. *Though the germ is there, it's invisible...can you for instance show me a case of diphtheria without the bacillus?*

Sir Patrick. *No, but I'll show you the same bacillus without the disease, in your own throat.*

B.B. *No, not the same, Sir Patrick. It is an entirely different bacillus; only the two are so exactly alike that you cannot see the difference.* (Shaw, *The Doctor's Dilemma*, p. 23).

[35] On the debate around impure drinking water, see Hamlin (1990). On milk, important works are Dwork (1987) and Apple (1987).

[36] Helman (1978, p. 123) asserts that "the biomedical germ theory seems to have only gained widespread currency among the lay public after the influenza pandemics of 1918." He produces no support for this statement, and it seems to fly in the face of most of the evidence.

All the same, the rhetorical power of the germ theory was immense. It was based on two components. One, emphasized by Latour (1988), is that the microbial theory came in the wake of the sanitarian movement which had prepared the ground for many of its recommendations.[37] The experimental method and the scientific aura around the discoveries made the new knowledge more persuasive and difficult to challenge. The other was the powerful rhetorical image that microbes provided, an image that is hard to replicate with more elusive pathogenic substances like ozone or cholesterol. Microbes were an invisible, omnipresent evil agent, a live monster threatening with infinite malice to attack the most vulnerable members of society (Campbell, 1900, p. 196). They lent themselves like nothing before to the demonization of dirt and dust. One author, Ferdinand Papillon, warned that "these baneful toilers for disease lie ever in wait to pierce the internal machinery of living beings to create disturbances" (1874, p. 551). After 1890 an anti-bacterial obsession took shape. Samuel Hart, M.D., wrote in 1890 that "pathogenic microbes cause four fifths of all diseases and destroy more lives than war, famine, fire, murder, ship wreck and all casualties... they actually abbreviate the average natural term of human life by three fourths" (Hart, 1890). Home economics textbooks, aimed at women, pulled out all stops: "a dirty house is full of poison germs....Try to imbue the children with a horror of dirt in any shape or form" exhorted one author in a handbook for teachers in girls' schools. Another volume published at about that time warned students that "dirt...is the soil in which plants grow... some very small kinds of colorless plants grow in dirt... known as microbes" and the obvious conclusion was that "our safest course is to keep all the things we have anything to do with very clean."[38] In his masterful analysis of the impact of the bacteriological revolution on the idea of cleanliness in France, George Vigarello speaks of the "emotional power of the discoveries of Pasteur" which led to the change in the meaning of cleanliness—"to be clean meant primarily to be free of bacteria...to cleanse was to operate on these invisible agents" (1988, p. 207). In full cooperation with statistics and moralizing, the rhetoric of the germ convinced the masses that the new recipes it implied were truly beneficial. It was by such imagery and language and the authority of science that civil servants, educators, and medical people were able to reduce ϵ: they persuaded large segments of the population to act upon their new knowledge and alter their recipes and thus time and budget

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[37] As Tomes (1990, p. 529) notes, "popular hygiene writers had little trouble...in associating dirt, infection, and germs... The ability of microorganisms to produce dangerous toxins or poisons could be easily assimilated into older notions of decay and putrefaction as sources of infection."

[38] Hart (1890, p. 808). See also Hitching (1912, pp. 26, 33, 64) and O'Shea and Kellogg (1921, p. 6).

allocations. Perhaps the most shocking discovery was Koch's identification of the tubercle bacillus (1882), which changed the outlook on one of the great scourges of Western civilization, hitherto believed to be hereditary and beyond the control of humans.[39] A middle-class belief in cleanliness and hygiene was not novel, but the new bacteriology provided it with focus and accuracy, and because it was effective it was persuasive, and the recipes it implied spread to large segments of the population.

The diffusion mechanisms of the new anti-infection movement to the mass of lower-middle- and working-class consumers were of course diverse. The persuasive powers of bacteriology were especially effective when the authority of science was combined with fear, guilt, and old-fashioned moral authority. But teaching and advising were just as important. Because babies were particularly vulnerable victims of infectious disease, much of the campaign was directed toward new mothers, in such organizations as Goutte de Lait and the Consultations de Nourissons in France, infant consultation clinics in Germany, and the Mothers and Babies Welcomes in Britain that were patterned after them. These organizations specialized in distributing free clean milk and instructing mothers in infant care. They also attacked infectious disease on every front they could think of. In Ireland, the Women's National Health Association sent out caravans with slogans to fight "bad air, bad food, bad drink and dirt."[40]

Another agent of diffusion was the medical profession. The Pasteur revolution, despite some pockets of resistance, had by 1890 been embraced by the majority of the medical profession and led to a re-definition of the tasks of medical personnel.[41] Physicians and nurses could now assume the new role of household consultants, advising families on how to avoid disease by following new sets of recipes in the preparation of food, cleaning, and child care. These professionals, most of whom had fully bought into the germ theory by 1890, insisted on making home visits and teaching the working class about matters of health and hygiene in their

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[39] Tomes (1998, p. 113). It is this aspect of the germ theory that refutes Latour's view that without the Pasteur revolution the "hygienists" would still have achieved essentially the same results (1988, p. 23). Indeed one scholar puts it well: "Miasma was entirely concerned with breath and fetidity, the microbe...became a more precise cause which could be both located and logged...the microbe thus materialized the risk and identified it. Hence the new role of cleanliness" (Vigarello, 1988, p. 201).

[40] Bourke (1993, p. 238). Dr. Josephine Baker, head of the newly created New York City Health Department, organized a "Little Mother's League" among school girls who in many poor families were in charge of their siblings' hygiene. These girls, in Rosen's words, "served as missionaries of the new gospel" (see Rosen, 1993, p. 334).

[41] Latour (1988). Tomes describes the long struggle between proponents and opponents of the germ theory as a "virtual civil war" (1990, p. 28). Much like the theory of evolution, the germ theory took about a generation to be accepted by scientists.

kitchens and bathrooms. At least some of those health visitors were drawn from the same social class they were to teach and persuade, but their training and background often varied.[42] In every industrialized country some intrusive form of such domestic counseling by "sanitary missionaries" (as Tomes has aptly termed them) was set up, in which professionals imposed themselves on working-class families to instruct them in the ways of prevention and health.[43] Not all of the advice given out was sound, and certainly not all of it was followed; but there was enough to alter the perception of the role of homemakers permanently. Although cures for infectious diseases were still elusive, prevention became a reality. Many of the old prescriptions such as ventilation (to avoid miasmas) and bleeding were abandoned. Instead, asepsis and hygiene became the watchwords. The gradual realization of the existence and operation of an immune system led to more controlled environments ("avoid drafts") to prevent opportunistic diseases. The understanding of contagion led people to value living space and privacy and to eschew customs such as putting children in the same bed and the sharing of facilities with other families.

Of particular importance to consumer health were the insights that the germ theory provided about contaminated food. During the nineteenth century in general unwholesome food was sold to the poor at low prices: until the 1880s, for example, the poor in Britain could buy "third-day" fish, such as mackerel with a "horrid stench" at six for a shilling. Bacon became cheaper when its fat had turned yellow and it showed black spots (caused by anthrax) (Smith, 1979, pp. 204–7).[44] During the nineteenth century, authorities made efforts to curb the worst excesses of these markets, and clearly people did not have to wait for Louis Pasteur to tell them that eating spoiled foods was dangerous. Since 1857 there had been attempts to control the sale of diseased meat, and in the 1860s there were repeated seizures of spoiled food in London (Smith, 1979, p. 206). Yet the germ theory added enormous impetus to the intuitive and empirical insights that made authorities concerned about food quality, made them enforce the law with greater energy, taught them that some substances could be dangerous even without the signals of color and odor, and convinced increasing numbers

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[42] Rosen (1993, p. 354). The "army of middle-class visitors" became at times so numerous that according to one anecdote a woman busy at her washtub called out to her visitor "You are the fifth here this morning" (cited by Lewis, 1984, p. 36).

[43] A detailed description of the characteristically state-run system of child protection and mother education in France between 1875 and 1939 is provided by Rollet-Echalier (1990, ch. VIII).

[44] The negative relation between price and wholesomeness does not always hold, as in the case of bread; the more expensive white varieties were adulterated with chemical bleaching agents such as alum.

of consumers that cheap milk, fish, and meats may not have been such a bargain after all.

The revolution in nutrition was inspired by the bacteriological revolution. The authority of science in advising and instructing people had increased immensely. If learned persons in white labcoats could see the little organisms causing the dreaded typhoid fever and tuberculosis, surely they could tell the masses what foods were good for them. The idea that nutrition affected health in some way goes back to antiquity, but the epistemic base that had supported it, as we have seen, was narrow. In the nineteenth century some diseases could be tentatively associated with a deficiency of specific trace chemicals, but a systematic exploration of these relations was not possible until animal models were combined with biochemistry. In many cases, households were slowly persuaded to change their habits. Since most of the vitamins and minerals were only needed in small quantities, such changes did not usually add much to household expenses. In a few cases, when policy makers felt that the risks and costs were low relative to the benefits, they did not wait for households and took matters into their own hands. The addition of iodine to common salt to prevent goiter is one example; the fluoridation of drinking water is another.[45] Less well known is the addition of thiamin-rich pills to machine-milled white rice, which eliminated beri-beri in the Philippines.

The discovery of vitamins and minerals and their effects on the body further raised the awareness of the health benefits and risks of various consumer goods and environmental factors. The realization of the beneficial effects of "an apple a day" had unambiguous effects on consumer behavior. An organic molecule is defined as being a vitamin if an organism needs to have it but cannot make it for itself (Carpenter, 1993, p. 477). Most animals can, for instance, make niacin out of the amino acid tryptophan (which is a part of all proteins), but it needs to be supplied in large quantities. Seemingly minor changes in food processing may alter the availability of these substances in usable form. Thus the milling of maize led to an epidemic of pellagra in the U.S. after 1905. The source of the problem was suggested when it was observed that pellagra was absent in other maize-eating regions in Central America. Vitamin C oxidizes easily

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[45] The history of fluoridation is an interesting example of how a chance observation of empirical regularities combined with an epistemic base in chemistry and the understanding that a large database is necessary to establish the benefits of a single agent. In 1905 Frederick McKay discovered oddities in the teeth of the inhabitants of Colorado Springs, but it took the photospectographic analysis at ALCOA's chemical laboratories to identify fluoride as the unique component in that water, and the famous social experiment between 1945 and 1960 in Grand Rapids, Michigan, to demonstrate that fluoridation resulted in a 60 percent decline in tooth decay in 30,000 schoolchildren.

at high temperatures, and thus boiled cabbage contains only a small fraction of the Vitamin C in raw cabbage. Such simple insights made huge differences to mortality and health, but they had to be inferred from data and experiments. Now that the simple nutritional deficiency diseases such as rickets and scurvy have vanished, there is a growing interest in the connection between nutrition and more complex diseases such as cancer and heart disease. The impact of megadoses of vitamins on the immune system remains a matter of controversy and despite the considerable authority of such scientific giants as Linus Pauling, this therapy has remained an untight technique. Yet, as any visit to a health-food store will show, large number of consumers have been persuaded to alter their behavior.

Household choices of technique, as I have noted, are slower and more difficult to change than those of firms. Households need to be persuaded to change their behavior, rather than be forced to do so by competition. Despite the huge advances in knowledge about the causes of diseases and the many triumphs that medicine has enjoyed in the past century, traditional and alternative forms of medicine are still alive. In part this is because the epistemic base on which modern medicine rests is still narrow—perhaps not compared to what it was in 1850, but certainly in comparison with engineering or chemistry. Moreover, much of this knowledge is still untight, as is demonstrated by some radical and dramatic reversals in recent years. For example, best-practice medicine for many decades attributed peptic ulcers to stress under the firmly held belief that bacteria could not survive in the stomach—until it was proven otherwise. Modern medical techniques represent a blending of the biomedicine of the twentieth century with much more venerable notions that have survived even if their epistemic base is untight (see Riley, 2001, p. 89). This is in part because biological systems are inherently very complex and in part because the ability to do research on human bodies is limited by social and moral conventions.

Domestic Science and Domestic Labor

Knowledge matters not only for what is produced and how efficiently and cheaply goods are made; it also has deeply affected the allocation of resources and distribution of consumption *within* the households of the industrialized West over the past century and a half. The implications of changes in useful knowledge on the inner workings of the most basic unit of the economic system are profound. One especially remarkable example is what may well be called the Ruth Schwartz Cowan problem. In her classic book *More Work for Mother*, published in 1983, Cowan raised a fundamental conundrum: why did homemakers work longer hours in their homes in the century after 1870, despite the growing mechanization of household activities? Despite the obvious technological changes in household appliances (most of them presumably labor-saving), married women worked as long if not as hard in their homes, and until World War II very few of them worked outside the home. It has been maintained that the number of hours worked by the homemaker in U.S. households was around fifty-two hours a week at the beginning of the century, fifty-six in the late 1960s, and about fifty in 1987.[46] Strictly speaking, the uncertainties surrounding these numbers suggest that perhaps the "more" in Cowan's title should be interpreted cautiously as "not less." In view of the technological progress in household implements and declining fertility in industrialized countries, however, the phenomenon is still rather amazing. This is not to say that labor-saving innovations in domestic technology had no beneficial effect. Cowan notes that the American housewife of 1950 produced single-handedly what her counterpart in 1850 needed a staff of three or four to produce: a middle- class standard of cleanliness, health, and comfort for herself and her family. Cowan's observation holds one of the keys to the paradox. The point is that when three or four servants were needed to attain this standard for one household, only a fraction of the population could enjoy it. Technological advances allowed a growing fraction of the population to enjoy these standards, thus substituting capital for labor.[47]

The Cowan problem, not much discussed by economic historians, is one of the more intriguing puzzles of modern economic history.[48] There are other persuasive explanations for the paradox. For one thing, when the effort required to carry out an activity is reduced (and possibly made less unpleasant), the volume of the activity may expand, offsetting the labor-saving effect. The decline in the supply of domestic servants forced housewives to carry out activities previously bought in the market. At the

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[46] Cowan (1983, p. 178); Vanek (1974, pp. 116–20) and Schor (1991, p. 87). Stanley Lebergott disputes these numbers and estimates that weekly chores fell from seventy hours in 1900 to thirty in 1970 (see Lebergott, 1993, p. 58). A recent study finds a far more moderate decline (14 percent) in housework time between the 1920s and the 1960s, of which about one-third can be attributed to composition effects (see Bryant, 1996; Gershuny and Robinson, 1988). Robinson and Godbey (1997, pp. 103–20) show that since 1965, time spent in household work has declined in the United States and United Kingdom, largely, they believe, on account of growing productivity rather than reduced volume). Research by Roberts and Rupert shows a further decline in housework in more recent years (Roberts and Rupert, 1995).

[47] Cowan (1983, p. 100). Formally, the problem is similar to the question whether labor-saving innovation reduces total employment. It is of course no paradox to note that by and large any innovation that increases the capital-labor ratio does *not* create unemployment in and of itself, because the total demand for labor depends on the demand for final goods.

[48] An exception, written before Cowan's book appeared, is Brownlee (1979). The idea that home production of household services is an economic activity worthy of analysis has been widely accepted since Folbre's comprehensive analysis of the issue (see Folbre, 1986).

same time, if housework and market goods or services were close substitutes for each other, the invention of labor-saving devices may simply have meant an additional shift from market purchases toward home production. Demand for female labor may have remained low, thus leaving women with little choice but to stay home and either consume leisure or engage in housework. This observation adds another dimension to the question of why so few married women worked outside their homes: the *perceived* marginal product of housework increased sharply in the last third of the nineteenth century.

The changes in the formal participation rates of married women have long puzzled economic historians. The exact timing in the nineteenth century is not easy to establish because of the ambiguous meaning of statistics on "participation" in economies where much production is still carried out by self-employed workers in their homes. Yet two facts seem well established: first, in comparison with the standards of our own time, these participation rates in the industrialized West were quite low.[49] Second, what little evidence we have is consistent with a *decline* in the participation rates of married women in the last third of the nineteenth century.[50] The leading specialist on the subject has stated that "what cries out for an explanation in these [female participation] data is not dramatic change over the period of the Industrial Revolution, but a retreat much later in the nineteenth century that is then maintained through the first 30

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[49] The evidence that only a small (if variable) proportion of married women worked outside the house is summarized for the United States by Brownlee (1979). Goldin shows that for the cohort of women born between 1866 and 1895, participation rates of married white women did not exceed 10 percent over their lifetime (see Goldin, 1990, p. 121).

[50] Data for England are difficult to interpret because of inconsistent census definitions. Whereas in 1851 about a quarter of all married women reported a "specific occupation" other than domestic work (not, of course, quite the same as working outside the house), the rate declined to 10 percent by 1901 and remains there till 1931. Hakim concludes from these data that in the mid-twentieth century "women returned to work after almost a century of being primarily engaged in unpaid work at home and excluded from the labour market" (Hakim, 1980, p. 560). In France, things may have been different. Until 1931 the participation rates of French women did not decline and remained unusually high, and yet in 1931, only 19.4 percent of French married women outside agriculture were "active." One historian concludes that "French women were far less likely to leave their jobs upon marriage than English women" (Rollet-Echalier, 1990, p. 491). In the Netherlands, budget studies show that the percentage of married women working fell from 55 percent in 1886–87 to 26 percent in 1910–11 and the contribution of the wife to total family income fell from 7.2 percent to 3.4 percent in the same period (unpublished data kindly supplied by Dr. Arthur Van Riel, University of Utrecht). The convincing evidence amassed for Ireland shows that female labor participation in that nation declined quite significantly before 1914, indicating that the phenomenon was not confined to the industrialized countries (see Bourke, 1993).

years of the twentieth."[51] It turns out that the explanation of this retreat is much the same as the resolution of the Cowan paradox.

The literature on the topic has mostly abstracted from the profound change in knowledge and beliefs that affected household behavior, although recent research has begun to change this. Households perform housework not only because they enjoy the outcomes directly but also, as I argued above, because they have certain priors on how such services affect other aspects of consumption. For instance, individuals might want to live in cleaner homes, get rid of lice and mosquitoes, breast-feed a baby, and cook better-quality foods because they *enjoy* doing so; or they may spend time cleaning, nursing, and cooking because they believe cleaner homes and more labor-intensive foods are inputs into *other* ultimate objectives such as health or social status.[52] These are analytically distinct objectives, even if they are not always easy to separate in practice. In the last third of the nineteenth century and the first third of the twentieth century the set of propositional techniques expanded dramatically and mapped into techniques that were highly intensive in household labor. Standard economic analysis suggests that if certain household services are produced because households enjoy them directly, any subsequent realization that these services also have a favorable impact on health will normally increase the quantities of them produced and thus increase housework.

The analysis below is by necessity oversimplified. I ignore the obvious difficulty in separating leisure from homework, although the two overlap a great deal. Precisely because of the technological changes in the household, the nature of household labor changed considerably, and, in Ruth Cowan's words, eliminated drudgery, not labor. Yet in this regard, household labor is hardly unique and the blurring at the edges of the boundary between leisure and work is a general issue in post-1945 labor economics. There are also complex issues of changing degrees of sub-

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[51] Humphries (1995, p. 100). Brownlee's estimates of participation rates of married native white women in the U.S. increased from 2.2 percent in 1890 to 6.3 percent in 1920, but he notes that inconsistent definitions make such comparisons hazardous and the actual participation rates of middle class women may have actually lower in 1920. In any event, even the higher rate in 1920 is one-tenth of what it is today (Brownlee, 1979, p. 200). Recent research indicates that female labor force participation rates may have already started to decline by the middle of the nineteenth century. Humphries has reviewed the literature and confirms that female participation rates declined from a plateau of 42–43 percent in 1851–71 to 32–34 percent (1881–1931). This "retreat" cannot entirely be explained away by changes in the definition of the labor force. It also reaffirms that married women's participation rates remained low from their mid-nineteenth-century decline up to World War II (Horrell and Humphries, 1995; Humphries, 1995).

[52] For a recent treatment, see Tomes (1998). There is also a literature emphasizing a cultural dimension in cleanliness. An important early work is Mary Douglas (1966), according to which cleanliness is culturally constructed as a rationalization to create order.

stitutability between home production and market-purchased goods and services.[53] Most perplexing of all, perhaps, is how we generalize from individual decision-making to the household as a unit which makes collective decisions that maximize the composite utility of different individuals with different preferences and perceptions. All the same, it represents a relatively minor extension of standard consumer theory, and much of the work done by Becker and his students applies directly. Although the idea that time is allocated rationally among competing uses conditional on the prior beliefs of the decision-maker seems straightforward, it has eluded some scholars. Schor, for example, suggests that housework has remained so time-consuming because the market places no economic value on work inside the house. This cannot possibly be right: even when women have no outside jobs, the opportunity cost of housework is leisure, and elementary economics suggests than women who set their own schedules will work in their homes until the marginal utility of leisure equals the perceived value of the marginal product of housework.

Of central importance to the question of changes in housework is the effect of knowledge progress on the allocation of time. Let A_D and ϵ_D denote the values of A and ϵ with respect to time allocated to housekeeping labor.[54] Time can be spent in three ways: housework, L_D, leisure, L_E, and work, L_w. Note that the allocation of time could change in two ways. First, if the consumer just changes her appreciation of the impact of consumer good i by raising A_i–ϵ_i, then she would consume more of that good than before. This will increase L_D if i is complementary with household labor.[55] Second, an increase in A_D–ϵ_D—that is, a greater appreciation of the health effects of housework—will lead to a redeployment of time in favor of household work. Note that this could occur through "invention" (that is, improvement in best-practice technique A with constant ϵ) or "diffusion"

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[53] Cowan (1983, pp. 100–101). Laundering, to choose but one example, was an exceedingly hard chore in the nineteenth century, carried out once a week and consisting of endless scrubbing, wringing, drying, ironing, folding, carrying and heating water, disposing of the washwater and so on. Compare this with today's fully automated washing machines in which the labor input consists of some sorting and the pushing of a few buttons up to the point where the clean laundry is folded (without ironing) and put back in place (a process that has eluded mechanization so far). Changes in the substitutability between market goods and domestic production are at the heart of De Vries's (1993, 1994) ideas about the "Industrious Revolution."

[54] Note that L_D can be spent on many different chores, and that the effect of each chore on H may be quite different. We are assuming here that the marginal effect of health work is equalized along the various chores, that is, housework is allocated efficiently.

[55] Thus, if the household decides that it wants to reallocate resources to housing and live under less congested conditions because it has been persuaded of the effect of congestion on its health, it may have to reallocate more time to household work just to keep the increased quantity of housing at a constant level of cleanliness even in the absence of a change in its appreciation of the effect of L_D on health.

or "persuasion" (a decline in ϵ, the lag between actual and best practice).[56] Assume for simplicity that the time worked outside the house, L_w, is fixed. Then the equilibrium allocation of time is given by the equation:

$$\frac{\partial U}{\partial H}\frac{\partial H}{\partial L_D}(A_D - \epsilon_D) + \frac{\partial U}{\partial L_D} = \frac{\partial U}{\partial L_E} \tag{5}$$

The left-hand side of equation 5 is total marginal utility of household labor, and the right-hand side the marginal utility of leisure; for a given level of outside work, an increase in $A_D - \epsilon_D$ will raise the left-hand side of equation 5. To maintain equilibrium, the right-hand side has to rise as well, meaning moving to a position where the marginal utility of leisure is higher, which can only be achieved by consuming less of it.

Other elements also affected the allocation of time to household labor. A decline in the birth rate reduced the number of children the average household had to care for, but the rise in quality standards for child care, nutrition, and education, and a decline in intersibling care may have more than offset this effect. One direct effect of the increase in child quality is the likely increase in the term $\partial U/\partial H$ as far as children are concerned. In other words, when declining birth rates shifted the emphasis from child quantity to quality, mothers naturally became more concerned about the health of their children simply because they had fewer of them. Furthermore, a possible exogenous increase in $\partial U/\partial H$ due to a greater concern for children cannot be ruled out. A "changing concept of childhood" is a notion most often connected with the work of Philippe Ariès, although he sees the turning point in attitude to children at an earlier time.[57] However, the idea that children were worth protecting and nurturing became central

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[56] The term "persuasion" is used here to mean not whether the consumer "believes" that there is an effect of an X or L on his or her health but that she is willing to change her behavior in accordance.

[57] The literature on the emergence of a modern concept of childhood is summarized in Pollock (1983, chs. 1–2). The conclusion of this literature is that an acknowledgment of childhood as a unique phase in human development did occur, but scholars have been unable to agree on exactly when. It seems a consensus view that it occurred later for the working poor than for the educated and better-off urban classes. Subsequent research has pointed toward a fundamental change in the last quarter of the nineteenth century (see, for example, Steedman, 1992 and Hopkins, 1994). As working-class children changed from being workers to being pupils, compulsory education laws and kindergarten movements combined with child labor law reform to enact a basic shift in what childhood was. In addition, Hopkins sees evidence of a broader evolvement in the attitudes of parents toward their children within a decline in the brutality of child punishment (1994, p. 315), a process that has been described as the "sacralization" of children (see especially Zelizer, 1985).

to reformers of the late nineteenth and early twentieth century. Limiting child labor in factory environments, providing them with a proper education, and keeping them healthy was intertwined with the fertility decline. This trend may have been reinforced by ideological forces: eugenicists and social Darwinists in the late nineteenth century propagated the belief that better children would improve their "race" (by and large white, Anglo-Saxon, and middle class). This ideology pressured mothers to protect the health and mental well-being of their children at all costs. Fears of declining "national efficiency" were fueled by the realization that infant and child mortality rates in the closing decades of the nineteenth century were remaining high in the face of declining general mortality.[58]

The impact of such an increase is proportional to $[(A-\epsilon)^* \partial H/\partial L_D]$. That is to say, mothers who become more concerned with the health of their children will work harder at home only to the extent that they believe that such efforts will actually improve their children's health. An increase in the productivity of household labor in producing health ($\partial H/\partial L_D$) is likely to increase the amount of labor allocated to it, as is a decline in the arduous nature of household work (a decline in the absolute value of the negative term $\partial U/\partial L_D$ in equation 5). Furthermore, as already noted, rising incomes and increased consumption do not lead to an unambiguous change in household work. Thus an increase in labor-saving household technologies such as the microwave oven may actually increase housework if it leads to the purchase of microwavable foods rather than take-out food. The same may be true for washing machines and the use of personal computers in teenage education. It is also possible that homemakers increased their appreciation of cleanliness for its own sake, and that as a normal good the demand for it increased with income. But leisure was a normal good as well, and the net change in time allocation depended on the respective income and substitution effects. Moreover, an increase in women's market wages by itself would have negatively affected the

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[58] Indeed the blame intensified with doubts about the military capacity of British males in the Boer War (see Dwork, 1987, ch. 1; Lewis, 1995, p. 3). Lewis (1984, p. 81–85) concentrates on the effects of evolutionary theory in solidifying the role of women in housework in the late 19th century, and the implications of these intellectual trends on female education are tackled by Dyhouse (1976). Reflecting this growing concern about infants and children was George Newman's work, widely read on both sides of the Atlantic. He was a key figure in shifting the blame for infant mortality from physical environment to the socio-economic conditions and the individual. For him, infant mortality as a *national* problem was based on the conditions of motherhood. "This book would have been written in vain if it does not lay the emphasis of this problem upon the vital importance to the nation of its motherhood," he notes, although unlike some of his contemporaries he realized that poverty and the lack of education constrained what individuals could do (Newman, 1907, p. 257; see also Meckel, 1990, pp. 99–101).

demand for both leisure and household work (assuming that substitution effects dominate income effects).

Results from modern cross sections confirm that there is no clear connection between time spent on housework and income; more surprisingly, they do not show any significant correlation between it and the ownership of labor-saving household appliances. The only good predictors were whether there were small children in the family and the employment status of the mother. The conclusion drawn by that literature is that there is a causal relation running from outside employment to the number of hours spent on housework. On the supply side of the labor market, the exogenous variables that may have mattered most were the beliefs and priors of individuals about the effect of housework on their health (and other variables not discussed here, such as the approval of friends and neighbors) that determined the entire allocation of time among leisure, housework, and wage labor.[59]

To bring this about, a new science had to be invented, domestic science, and its lessons taught to the masses. Home economics became committed to the notion of the home as a microbial environment and the need to teach women to control it. Ellen Richards, the pioneer of home economics in the United States, pointed out that "when a pinpoint of dust could yield three thousand living organisms, not all malignant but all enemies of health, cleanliness was a sanitary necessity of the twentieth century whatever it may cost" (Hoy, 1995, p. 153). To be sure, this rhetoric, as Ehrenreich and English point out (1978, p. 66), meant that science acquired a certain moral force. But the transformation was not moral or religious as much as it was about perceptions and understanding how the physical world worked and how and why people got sick. The moral and religious force behind it became part of the persuasion mechanism, although it eventually acquired a life of its own, and intersected with related social movements such as temperance.

How did the breakthroughs in best-practice knowledge affect household recipes and persuade homemakers to change their choices and allocations? In a set of pioneering papers, feminist writers such as Ehrenreich and English (1975), Strasser (1980), and Carol Thomas (1995) explained

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[59] Robinson (1980). Vanek (1974) reports that non-employed women spent fifty-five hours weekly on housework compared to the twenty-six spent by women employed outside the home. It might be added that this model precludes "cleanliness" itself from being in the utility function, which is of course unrealistic. Accounting for it would add another term to the left-hand side of equation 5. It seems difficult, however, to distinguish between a change in preferences favoring cleanliness and one induced by changes in information. The advantage of the latter is that there are good reasons to believe it happened, whereas changes in preferences are always a weak reed for historical changes.

what they saw as the increase in housework (which Thomas regards as an important source of reduced mortality) through the internal dynamics of changes in capitalist production during the second Industrial Revolution. With rising wages and a reduced work week, Thomas argues, women were increasingly relegated to homemaking as the result of an increasingly rigid sexual division of labor. The assumption underlying this interpretation is that following the gradual disappearance of domestic production in the nineteenth century, women lost their economic function.[60]

This argument has been effectively challenged by Bourke (1994), who views the growing economic significance of housework at this time as a way of improving living standards. She insists that the growing specialization in the household was a conscious choice made at a cost, but that the benefits perceived were "cheap at the price." This explanation is correct, but it would be incomplete without noting the rapidly changing notions of disease and health that drove the perceived benefits. Industrialization coincided with a major revolution in the way individuals in the Western world came to think of their health and the interaction of their bodies with their environment. The revolution was not just in the way physicians thought about disease, but in the growing awareness that households could control their destinies by their own actions and prevent disease by avoiding certain well-understood sources of infection. From the beginning, women were to be in charge of family health not so much because there was nothing else for them to do, but because it was inherent in the nature of the concept of gender in Western societies that they would become the protectors of health. In the early 1880s, the president of the British Medical Association said, "It is the women on whom full sanitary light requires to fall. Health in the home is health everywhere; elsewhere it has no abiding place," and while "the men of the house come and go, the women are conversant with every nook of the dwelling...and on their knowledge, wisdom and skill the physician rests his hope."[61] The existing domestic functions of women and the growing perception of the importance of housework on health reinforced each other to produce a growing specialization of the genders within the household.

To sum up: the contribution to the resolution of the Cowan conundrum proposed here is that the health-related demand for L_D rose,

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[60] Strasser (1980) suggests that during the "transition to industrial capitalism" women had no clearly defined role in the new order, and Ehrenreich and English (1975) propose the fanciful concept of a "domestic void" created by commercialization of consumer goods production. Thomas (1995, p. 339) discusses the increased rigidity of the sexual division of labor.

[61] Cited by Plunkett (1885, pp. 10–11). This revolution in the way people thought of health is advanced in Easterlin (1996). The gender-specificity of the burden created within these developments is discussed by Cowan (1983) and by Thomas (1995).

through either a rise in $\partial U/\partial H$ (the marginal utility associated with good health and longevity) or a rise in $A-\epsilon$ in equation 3. The rise in the marginal utility of H was in part an income effect, because health and longevity are more appreciated in richer societies. The primary effect, however, was that large segments of the population acquired more knowledge and understanding about the connection between what they consume and their health. The demand for domestically produced health increased significantly in the past century because of big changes in household knowledge: there can be no demand for a germ-free house or germ-free clothes unless people know and believe that germs cause disease. As a consequence homemakers spent more time cleaning, nursing, laundering, cooking, and looking after their children because they had become convinced that the health of the members of their household was under their control and part of their responsibility. They had been persuaded that wholesome food, clean clothes and bedsheets, and a hygienic environment were critical variables in the determination of good health and longevity.[62]

It would be naive to recount this story in terms of a Whiggish tale of growing enlightenment and rational choice of recipes following the triumphs of science. Equations 3 and 5, which define household behavior, are determined by its priors. Consequently our story has to be about more than just the changes in A, which are recounted in competent histories of medicine and public health. Instead, we need to look at ϵ, that is, focus on the question of how individuals, especially women, were persuaded by outsiders to change their behavior and allocate more time to housework than they otherwise would have. Some of these changes in behavior were simply imitation, either horizontal (looking at neighbors and relatives) or vertical (the emulation of one's social superiors). Some were in response to social pressure to conform to customs and social standards that had taken root. Some resulted from the direct and deliberate brainwashing of the population at large after a small elite of educated, politically powerful, and socially influential people had persuaded themselves they knew the right way or stood to gain from it. Middle-class notions of a culture of respectability were a subtle means by which concepts of proper housekeeping were diffused through the working class (Lewis, 1984, pp. 30–31).

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[62] Changes in household knowledge would also explain an increase in breastfeeding, although the improvements in baby formula and milk quality since the early 1900's tended to offset this. It should be realized that most of the early breast-feeding campaigns emphasized the clean nature of mother's milk and were not aware of its additional immunological and psychological benefits. Dwork maintains that as late as the early twentieth century, while it had been recognized for many decades that breast-feeding was the most effective preventive measure against lethal attacks of childhood diarrhea, "the precise reason for this was absolutely unclear" (1987, p. 36). The statistical evidence seemed irrefutable, but the mechanisms were poorly understood.

Ignorance of good household practices due to deficient education and indoctrination of the working classes was increasingly blamed for poor health conditions and infant mortality, indicating an instinctive sense of a growing ϵ—that is, a growing gap between the best possible and average practices. One consequence of these breakthroughs was a furious debate over the effects on health of working-class mothers being employed outside the home. Books and magazines on the dangers of germs and good housekeeping proliferated, repeating ad nauseam the gospel of cleanliness.[63]

Education systems after 1880 began enforcing stricter cleanliness standards on children while indoctrinating them in the need to avoid germs and infection.[64] School curricula in Britain aimed at girls began to move away from traditional subjects such as needlework and to include home economics, nutrition science, and infant care, with cleanliness and avoidance of infection the highest priorities. Courses in domestic science taught in American schools and YMCAs to working-class girls were an important vehicle by which "middle-class home values" were transmitted to working people. Lectures and meetings provided hygiene education for adults, often clothed in scientific terms such as the *cours de puériculture pratique* taught

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[63] The debate on working mothers is ably summarized by Dyhouse (1978). In addition to the already cited *Popular Science Monthly,* mass circulation magazines such as *Good Housekeeping* and *Ladies Home Journal* soon became effective outlets for the new knowledge, full of advice and recipes on disinfectants, insecticides, food preservation, and so on. A typical example of a domestic science textbook is Campbell's, stressing the dangers of "flourishing colonies of bacteria" and how keeping the house clean was the best way to deal with this "enemy" (see Campbell, 1900, pp. 198–201). Another example is *The Woman's Book* (1911), which filled no fewer than 734 pages with helpful hints on cleaning.

[64] Most of the research confirms a connection between literacy or education on the one hand and "health," however measured, on the other. The best statistical works on the period before 1914, Preston and Haines (1991) for the United States and Woods, Watterson, and Woodward (1988–89) for England and Wales, confirm this finding. These results do not lend themselves, however, to a distinction between alternative interpretations: did schools simply "drill" students in the habits of hygiene, or did they improve their ability to absorb logical and statistical arguments on preventive medicine? Ewbank and Preston suggest that the relative importance of *female* education in the mortality revolution suggests that the mechanism operating worked through the enlightenment of women in charge of hygiene and child care in the home (Ewbank and Preston, 1990, p. 119). Modern research suggests that even the persuasiveness of recommendations based largely on empirical regularities such as abstaining from smoking and eating a full breakfast are strongly correlated with education. For an example, see Evans and Montgomery (1994). Caldwell has argued that the education of women has strong implications for familial balances and power relations. With more schooling, mothers gain control of resources within the family and more will be expended on child care with positive effects for child health (see Caldwell, 1979). Research in labor economics suggests that better-educated people have an advantage in adopting innovation in part because education and schooling improve the ability of individuals to reason statistically and distinguish between systematic and random elements. This relation is complicated by the fact that well-educated people also tend to have lower rates of time preference and are therefore more likely to invest in their health (see e.g., Bartel and Lichtenberg, 1987).

to mothers in France, which was supposed to "persuade mothers by exposing them to the fact."[65]

The idea of maternity and the responsibility of mothers for the health and well-being of their children became one of the most effective tools of persuasion to the new faith. In 1899, the school superintendent of Georgia told the National Education Association that if he were asked to name the great discovery of this century "above and beyond [all inventions] the index finger of the world's progress would point unerringly to the little child as the one great discovery of the century" (Ehrenreich and English, 1978, p. 165). Looking back to a fall of British infant mortality rates by more than two-thirds between 1899 and 1942, Eric Pritchard attributed the achievement to the "discovery of the Mother" (Dwork, 1987, p. 216). What really had been "discovered" was neither "the child" nor "the mother" but that mothers could, by their actions, affect the life and well-being of their offspring. This was the message science had taught, and as mothers became convinced that the physical well-being of children was a function of their actions, they had to rethink their most basic time-allocation decisions.

In the 1920s and 1930s domestic science changed course somewhat. The emphasis on controlling dust and sewer gas was weakened, and nutritional science received a greater emphasis.[66] Rising incomes in the 1920s and the expansion of consumer durables and electrical appliances increased the number of items to keep clean as well as the tools to keep them clean with.[67] Among the latter, running water in the house and hot water boilers were at the top of the list. However, the influenza pandemic of 1920-21 and the appearance of polio once again increased germ awareness (Tomes, 1998, pp. 245–46; Rogers, 1992, pp. 9–29). Homemakers' behavior may not have followed suit right away. Education produced "vintage effects" that delayed the overall decline in ϵ: women

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[65] See Dyhouse (1981, pp. 87–91) and Rosen (1993, p. 392). The effectiveness of the formal schooling system in inculcating the new knowledge among the working class was probably modest, judging from oral history which indicates that the transmission of knowledge occurred largely within families. All the same, the British Education Code of 1882 recognized cooking as a subject of instruction and allocated funds to its teaching. By 1911, when the teaching of domestic science was further expanded, the majority of English schoolgirls were attending domestic education classes (Roberts, 1984, pp. 33–34; Bourke, 1994, p. 183). Domestic science education in the United States is discussed in Ehrenreich and English (1975, p. 159) and Stage and Vincenti (1997, passim). Hygiene education in France is described by Rollet-Echalier (1990, p. 364).

[66] For a good discussion of these changes, see Babbitt, 1997.

[67] As Bourke notes, people not only had more clothes, they also washed them more frequently, and their income and location determined what equipment they could use and whether they had to carry the washing water themselves. An interesting labor-saving response to the bacteriological revolution was the change in home design, replacing the heavy upholsteries of the Victorian home with easier-to-clean surfaces such as tiles and glass in the early twentieth century (Bourke, 1993, p. 225).

may have stuck to the principles they learned from their mothers or as young girls at school. All the same, even adults were open to persuasion and behavior modification.

Advertising also played an important role: "businesses subjected women to a barrage of advertising and social pressure, in order to sell more products...they spread the message that a woman who did not purchase the growing array of consumer products was jeopardizing her family" (Schor, 1991, p. 97). The fundamental message sent to homemakers by advertisers was one of personal responsibility. If her children did not develop properly or became sick, if her husband was unhappy, if she herself grew old and tired before her time, the housewife was to blame. Perhaps she was not cooking the right meals, was not scrubbing the bathroom floors enough, or did not insist that her family members clean their teeth (Cowan, 1983, pp. 187–89). The ironic fact remains that no advertiser stood to gain from an increase in housework in and of itself. But the relentless use of fear and guilt in persuading women to keep their homes cleaner and their diets better in order to sell them a range of goods—always reinforced by other agencies—had precisely that effect.

Perhaps the best example of such unscrupulous marketing can be found in the soap industry, which was always strapped for markets because of the economies of scale in soap production and its highly competitive nature. Aggressive advertising campaigns for such brands as Sapolio and Ivory in the United States and Sunlight Soap in Britain took off in the 1870s and 1880s and relentlessly hammered home soap's role in fighting germs and dirt. The Cleanliness Institute, established by the American Association of Soap and Glycerine products in 1927, embarked on an unprecedented campaign to sell soap at all cost and in the process all but brainwashed Americans that "microbes were everywhere, omnipresent, ever-ready to spread disease, debility, and death" (Vinikas, 1992, p. 85). The institute employed the most effective means of persuasion: selling or giving away hundreds of thousands of storybooks, pamphlets, flyers, teachers' guides, and free samples to schools and children. It also advertised on an unprecedented scale, aiming its resources at women rather than at men, and using fear, guilt, and hope to sell soap. Advertisers pictured germs as "an enemy" that was to be kept outside the home by means of the "armor of cleanliness" (Vinikas, 1992, pp. 79–84; *The Survey*, June 1 and Sept. 1, 1930). In the process of trying to sell soap they may have also, unintentionally, helped to create millions of overworked housewives.

All the same, the net effect of advertising on L_D is not clear. Soap happens to have a low elasticity of substitution with household labor; it does not clean but in conjunction with labor. A large proportion of advertising, however, was aimed at replacing domestic labor. The fast-food industry, for instance, must have saved housewives all over the world trillions of hours of cooking and cleaning. Assertions that industry has had no incentive to come up with labor-saving devices in the household (Schor, 1991, p. 102) are contradicted by endless innovations that did just that: disposable paper products and cellophane, self-cleaning refrigerators and ovens, cake mixes, pressure cookers, and chemical toilet cleaners are just a few examples.

Yet there remained a budget constraint, and some obvious health-enhancing products (such as less crowded housing conditions) remained outside the reach of the working classes for many decades after their effects were realized. Moreover, for households with fewer resources, the substitutability of labor for capital may have been limited: "without running water or sanitary toilets, even superficial cleanliness could be obtained only with backbreaking labor" (Tomes, 1998, p. 204). Wealthier households found it easier to substitute some market-purchased goods for labor, especially hot water, indoor toilets, and easier-to-clean kitchens and bathrooms. At the same time, however, poor families simply had fewer possessions and less space to keep clean. Income and substitution effects run counter to each other, and Tomes's suggestion that increased household labor demand hit the poorer classes hardest is not easy to prove.

The notion that women were naive and credulous victims of a conspiracy run by greedy commercial interests or jealous males ignores the free will of women, conditioned as it was on what they believed was best-practice science (Bourke, 1994). Domestic science of course at times gave erroneous or unproven advice and for decades spurred women to perform more housework than before, possibly more than they should have. But given how high the stakes were in the age before antibiotics, it is not surprising that women, when in doubt, chose to clean too much rather than risk disease. The powerful and often overwhelming propaganda barrage used by the crusaders for cleanliness biased behavior toward overexertion. Risk aversion, as well as biased processing of information, may thus have led to an excessive reallocation of household resources toward housework.

In the notation introduced earlier this scenario implies that the perceived value of A_D–ϵ_D may have exceeded unity and that far more cleaning and cooking were carried out than was necessary, because households had been made to believe that household labor was more health-enhancing than it really was. One result of "overshooting" in the case of housework was for married women to drop out of the labor force altogether (or, more likely, to never join it) in order to "keep house." But because the historian does not know the true value of A either, such a statement is difficult to quantify. Without actually estimating the perceived marginal impact of scrubbing and sweeping on health and comparing it to the true value, we cannot be sure that health production is overusing L_D. However, it is surely false to maintain that just because household labor is not a traded market good, as Schor maintains, it would be oversupplied. Some overshooting is suggested by the fact that today there is a marked difference between the level of L_D in households in which women have outside employment and those in which they do not, without any known costs in terms of health. This fact might suggest at least that the marginal product of housework in terms of H is low—at least in contemporary households. Yet it does not by itself constitute evidence of overshooting in the pre-1945 period.[68]

In terms of our model, overenthusiastic rhetoric and brainwashing by soap commercials may have led to some negative values of ϵ, thus consuming more of some X's than best practice techniques called for, that is, when $A < 1$ if $\epsilon < 0$ and $1+\epsilon < A$. These conditions could lead to "overworked housewives" because of low substitutability between the "overconsumed" X's and L_D, or because they somehow caused overshooting conditions to apply directly to A_D and ϵ_D (e.g., if commercials persuaded guilt-ridden women to sweep floors or scrub sinks more often than necessary).

Moreover, in some instances best-practice medicine of the first decades of the twentieth century itself tended to exaggerate the effects of cleanliness ($A > 1$), so that homemakers following their prescriptions would tend to overexert themselves.[69] This trend was reinforced by the compulsive propaganda of some of the later domestic scientists, such as Christine Frederick who were "so hell-bent on establishing a new 'science' of housework, that their rhetoric became an appalling jumble of exaggeration." The belief that household dust was the carrier of dangerous germs (especially tuberculosis), through dangerous "fomites" (dried contagious matter) stimulated an attack on household dust far beyond anything we would believe necessary today (Horsfield, 1998, p. 101, 120, 183–85; Hardy,1993, p. 14).[70] The popular mechanisms through which science disseminated often

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[68] For a comparison of housework by employed and non-employed women, see Vanek (1974). The concept of oversupply is further complicated by the fact that in the presence of uncertainty, a certain margin of "unnecessary" cleaning may be regarded as an insurance premium against low-probability but high-cost events.

[69] One example of this exaggeration was the notion of "calorific accumulation," which held that immunity was conveyed by an "invisible fire" needed to resist disease required a high degree of cleanliness to operate property, presumably to allow oxygen to penetrate through the pores of the skin into the body. This gave cleanliness, by the end of the nineteenth century, an unsurpassed legitimacy (Vigarello, 1988, pp. 210–11).

[70] The source of this belief was one of the first American bacteriologists, T. Mitchell Prudden whose *Dust and Its Dangers* (1890) became, in Tomes's words, "a foundation of turn of the century domestic hygiene" (Tomes, 1998, p. 97). Tuberculosis can be spread by dust, but only a small percentage of the infected patients become symptomatic, depending largely on interaction with other diseases that weaken immunity.

added to the distortion.[71] Without a more precise notion of how the body defended itself against germs, households fell into the belief that even the smallest traces of microorganisms could be lethal. The fear of germs led homemakers to try to sterilize (rather than just clean) their pots and pans, a laborious and redundant endeavor. Manufacturers of goods from wallpaper to Lysol lent support to science's exaggerations. One conclusion we can draw here (a formal demonstration is provided in the appendix to this chapter) is an affirmation that a "little knowledge can be a dangerous thing," or in the more technical language of economics, that there is no monotonic relationship between the acquisition of knowledge and welfare improvement. After 1945 it was increasingly realized that the perceived marginal benefits of housework may have been, after all, larger than the true level. It is therefore possibly misleading to argue that household labor has declined because women are busier with market activities. Arguably, the causality runs in some part in the other direction: the values of $A_D - \epsilon_D$ today have fallen back to a level closer to unity, after having exceeded unity for many decades, and the decline in the perceived value of household labor has increased the market supply of female labor.

The Cowan paradox has important ramifications. One, of course, is the entire set of problems related to the role of women in the household and in the economy. Given the statistical difficulties with female participation rates, it would be rash to argue that women's newly perceived social role after 1850 or so actually caused a decline in married female participation in the labor market.[72] But it can be safely concluded that by keeping the perceived benefits of housework at high levels, the new knowledge delayed widespread labor force participation of married women by many decades. As Brownlee (1979) has also noted, both market forces (the decline of domestic industry) and demographic forces (the fall in fertility) would have indicated that the increase should have been much faster.

It remains to be seen how much of the low labor force participation rates of married women in the first half of the twentieth century could be accounted for in this way. It is suggestive that when families had a high marginal utility of money, the need to generate cash was reconciled with preserving the married woman's role as the guardian of the gates of health by taking in boarders, laundry, and sewing and similar activities rather than seeking employment outside. It is also suggestive that the preachers of

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[71] Between 1900 and 1904, popular magazines published articles with titles such as "Books Spread Contagion," "Infection through Postage Stamps," and "Menace of the Barber Shop" (Ehrenreich and English, 1978, p. 142). As late as 1932, *Good Housekeeping* provided information on how to disinfect picture frames.

[72] As maintained by Thomas (1995, p. 340); and De Vries (1994, p. 263).

home economics such as Christine Frederick pontificated against "the unnatural craving [of women] for careers" (cited by Horsfield, 1998, p. 117).[73] More specific inferences seem hazardous in view of the poor statistical material available and the difficult definitional issues related to nineteenth-century female labor participation rates. The pertinent question is not whether the growth in knowledge led to a decline in the number of married women working outside the home, but whether it prevented women's labor force participation rates from rising for many decades. It is not until the late twentieth century, when the exaggerated notions of wife- and motherhood could be dispensed with, that housework fell to a level that may be a bit closer to optimal. No doubt there were contributing factors to the recent decline in housework: an ever growing substitution of labor-saving goods and services bought in the market, and antibiotics that weakened the paralyzing fears of infection. Beyond that, the solution to the Cowan conundrum suggested here is consistent with the decline in mortality, and especially infant mortality, in the early decades of the twentieth century. Regardless of its costs, the realization that household work and certain health-enhancing goods could help prevent infectious disease was a major factor in the sharp decline in mortality after 1870 (see Ewbank and Preston, 1990; Preston and Haines, 1991; and Easterlin 1996).

In addition to the material forces that determined the allocation of resources and time in a market economy, autonomous forces altered existing equilibria based on changes in propositional knowledge. This knowledge was then mapped into techniques that were diffused by education, imitation, and persuasion. It is easy to dismiss domestic science as a tool devoid of much scientific content intended to keep women in their proper place. Such a class-and-gender based analysis neglects the crucial role of knowledge and beliefs in the determination of behavior.[74] The radically novel concepts of disease and the concomitant rise of domestic science and home economics in the late nineteenth century, were as dramatic a transformation as the first Industrial Revolution and may have

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[73] Domestic industry had, by the end of the nineteenth century, enjoyed something of a revival in urban Britain, with homeworkers producing such items as matchboxes, artificial flowers, umbrellas, safety pins and tennis balls. Lewis (1984, p. 55). It might be noted that homes with boarders tended all the same to have higher infant mortality rates (see Preston and Haines, 1991, p. 168). The great economist William Stanley Jevons in 1882 railed against "the employment of child-bearing women away from home" and asserted that "the very beasts in the field tend and guard their whelps...only human mothers...systematically neglect to give them nourishment" (quoted in Ball and Swedlund,1996, p. 37).

[74] Such an argument is made in Ehrenreich and English (1975) and Thomas (1995). Ehrenreich and English remark that domestic scientists knew little about the destruction of germs and erroneously believed that they were mostly carried by dust. Oddly, they themselves explain the sharp decline in child mortality with improvements in sanitation and nutrition (cf. Ehrenreich and English, 1975, p. 19, with 1978, p. 167).

had implications that were as profound (Easterlin, 1996). It is, of course, true that notions of dirt and defilement are not an invention of the Enlightenment or nineteenth-century science. Dirt as a notion of "matter out of place" is as old as notions of order and system in society (Douglas, 1966, p. 35). What the past two centuries changed is the understanding of the direct correlation between dirt, nutrition, child care, and other variables controlled by housework on the one hand and the health of members of the household on the other. As Bourke (1993, p. 213) observed, "The purpose of cleaning changed. [It] became less of a ritual...and more of a 'scientific' dirt-control movement."

The errors and exaggerations in this knowledge and the unnecessary and wasteful housework they implied, lamented by today's feminist critics, were real, but probably largely unavoidable. The new knowledge embodied in the three revolutions was so radical that it had to be continuously fine-tuned and its applications to household recipes inevitably followed a long and bumpy learning curve.[75] The fine-tuning has by no means ended in our own time. If we are to make progress on the new and exciting frontier of the economic history of the household and the family, economic historians need to ask again and again, "What did women know, and when did they know it?"

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[75] Douglas herself concedes that "the bacterial transmission of disease was a great nineteenth century discovery. It produced the most radical revolution in the History of Medicine. So much has it transformed our lives that it is difficult to think of dirt except in the context of pathogenicity" (Douglas, 1966, p. 35).

Appendix

The appendix shows the working of a simple static model in which the consumer has "priors" on the effect of goods on her health. The utility function is:

$$U = U(X,Y,Z).$$

Specifically, assume for ease of exposition that the utility function has the simple Cobb-Douglass form

$$U = X^{\alpha} Y^{\beta} H^{\gamma}, \tag{1}$$

Where H is in turn determined only by the quantities of X and Y:

$$H = X^{a} Y^{b}. \tag{2}$$

Now assume that equation (2) is not fully known to the consumer but instead the consumer uses the following equation for his maximization:

$$H = X^{\lambda_1 a} Y^{\lambda_2 b}, \tag{3}$$

Where the λ's are equivalent to the terms of the type $A - \epsilon$ we used in the text. Using the budget constraint

$$P_x X + P_y Y = Z \tag{4}$$

we can easily derive from the first-order conditions the equilibrium level of Y, Y^*:

$$Y^* = \frac{Z}{P_y} \frac{\mu}{1+\mu}, \tag{5}$$

where:

$$\mu = \frac{\beta + b\lambda_2\gamma}{\alpha + a\lambda_1\gamma}. \tag{6}$$

It is easy to see that the demand for Y will rise with increase in λ_2 and fall with an increase in λ_1. A rise in Z and P_y work just as in the standard case. A rise in γ, the marginal utility of H, will usually have an effect on demand for Y, but its sign depends on the four parameters. To see the effect of changes in Z, prices and the λ's on H, the equilibrium solutions for Y^* and X^* can be substituted into H. For values of $\lambda < 1$, it would be expected that H varies positively with either λ. If, for example, $\lambda_1 < 1$ and $\lambda_2 < 1$, an increase in λ_1 will raise the consumption of X, which in and of itself will raise H; but the budget constraint then forces a decline in Y which may offset the effect on H. Depending on the original values of the consumption parameters, H may increase or decrease. Indeed, it can also be shown that consumers for whom the λ's are not unity can still "get it right" (that is, combine X and Y inadvertently in such a way as to maximize H). This would be true if by accident the values of λ_1 and λ_2 were such that:

$$\frac{\beta + b\lambda_2\gamma}{\alpha + a\lambda_1\gamma} = \frac{\beta + b\gamma}{\alpha + a\gamma}, \tag{7}$$

which of course is trivially true for $\lambda_1 = \lambda_2 = 1$ but also for an infinite number of other pairs. If, therefore, condition 7 happened to hold for an arbitrary pair $<\lambda_1, \lambda_2>$ where $\lambda_1, \lambda_2 < 1$, clearly H is maximized and thus any increase in either λ would be health-decreasing. Yet it is not necessary for condition 7 to hold to get that result. Of course that would not be the case in the world of figures 3 and 4, in which only one good has an impact on health.

Chapter 6

The Political Economy of Knowledge: Innovation and Resistance in Economic History

> *Although the inventor often times drunk with the opinion of his own merit, thinks all the world will invade and incroach upon him, yet I have observed that the generality of men will scarce be hired to make use of new practices, which themselves have not been thoroughly tried...for as when a new invention is first propounded, in the beginning every man objects, and the poor inventor runs the gantloop of all petulent wits...not one [inventor] of a hundred outlives this torture...and moreover, this commonly is so long a doing that the poor inventor is either dead or disabled by the debts contracted to pursue his design.*
>
> —William Petty, 1679

Introduction: Selection and Knowledge

Knowledge, much like living beings, is subject to "selection" in the rather immediate sense that more of it is generated than can be absorbed or utilized, and so some forms of knowledge have to be rejected. What is meant by that, however, and how selection on knowledge works is far from simple. Some observations are by now commonplace: in evolutionary epistemology it is widely recognized that selection is carried out by conscious, often identifiable agents, unlike in evolutionary biology where selection is a result of differential survival and reproduction but no conscious selector is operating. The world of propositional and prescriptive knowledge is a world in which agents choose.

In the area of *propositional* knowledge (Ω), selection can mean different things. One is that knowledge is simply retained. A great deal of useful information is discarded or forgotten and eventually becomes irretrievable. Even as storage costs declined historically, with the invention of paper, printing, and eventually electronic storage, the amount of useful knowledge generated increased to the point that most of it had to be junked. In evolutionary epistemology, however, selection of knowledge means that a fact or a theory is believed and becomes part of the consensus and acceptable wisdom (Ziman, 1978). Yet some parts of Ω may remain fairly untight, that is, they may be accepted by most but not all, or the belief in them may be weak. The two definitions do not entirely overlap, of course, since many discarded theories of nature, such as phlogiston physics and the humoral theory of disease, are retained and are still studied by historians of science.

By contrast, it is easy to see why selection is central to any theory of *prescriptive* knowledge (λ). Technology implies choice. There are always more ways to skin a cat than there are cats. There are innumerable ways to cook rice or to drive from Cincinnati to St. Louis or to write operating software. When we produce, we choose. The concept of an isoquant, the most primitive representation of a technical choice set, involves two kinds of choices: first, the obvious choice of selecting a technique that is on the efficiency frontier; and second, selecting the one that is most suitable to the environment in which the selector operates. When a set of instructions is carried out, that technique is "selected."

Historically, a technological choice is made whenever a new technique is proffered, and selectors (firms and households) have to decide whether to adopt it. It might seem that in the vast majority of cases this decision is trivial: if the new technique increases efficiency and profits it will be adopted, otherwise it will not. But few economies have ever left these decisions entirely to the decentralized decision-making processes of competitive firms. There is usually a non-market institution that has to approve, license, or provide some other imprimatur without which firms cannot change their production method. The market test by itself is not always enough. In the past, it almost never was.

It is easy to see why this selection process is difficult. In price theory the selection of an optimal technique is straightforward: in the simplest world, in each environment there is only one technique that maximizes profits and that technique is chosen. Competition ensures that firms that choose wrong will eventually mend their ways or go under. We have seen already that when households do the selecting, such easy mechanisms do not work. But when new inventions are made, particularly those that involve entire technological systems or require considerable social adjustment, the selection process is complex. Similar circumstances can at times lead to very different outcomes. The Netherlands derives 4 percent of its power from nuclear energy, whereas in Belgium the figure is over 56 percent. France and Lithuania derive about three quarters of their energy from nuclear power, the Czech Republic only 18.5 percent (IAEA, press release May 3, 2001, available at *www.iaea.org/worldatom*).

Much as economists might deplore the fact, therefore, the acceptance of innovation is more than an economic phenomenon, and certainly far more than a pure advance in productive knowledge. The concept of competition remains central here, but it is not so much the neoclassical concept of price competition of *firms* in the marketplace as it is Schumpeter's concept of competition between different *techniques* struggling to be adopted by existing firms or between different final products slugging it out over the consumer's preferences. At times individual techniques may be identified with a firm, but often techniques struggle for adoption within a single organization. How are the decisions to adopt a new technique made? Even when a new and superior technology is made available at zero marginal cost, could the society to which it is proposed choose to reject it?

New technologies have failed and opportunities have been missed despite their ostensible economic superiority. The idea that seemingly superior inventions are spurned or rejected is hardly new, as the epigraph to this chapter illustrates. When a radically novel technological idea is first proposed, a normal reaction is that it will not work because otherwise we would have thought of it ourselves. Whether an invention actually works or not can usually be verified through experimentation. Other techniques are *untight*: the full results may take a long time to verify or have many dimensions that are hard to weigh against one another. For many techniques there is a great deal of uncertainty about unintended consequences, whether they be social or environmental in nature. Edward Tenner (1997) has provided many examples in which technology in his term, "bites back—that is, produces outcomes that were unanticipated. Once bitten, twice shy: when technology causes a great deal of social harm, it is not surprising that many intrusive techniques of our time, from genetically modified organisms to nuclear power, are regarded with great suspicion.

Yet throughout history technological progress has run into an even more powerful foe: the purposeful self-interested resistance to new technology. Outright resistance is a widely observed historical phenomenon. Precisely because such resistance must work outside the market and the normal economic process, artificial distinctions between the "economic sphere" and the "political sphere" for this class of problems are doomed. The political battles over technology have profound implications for economic history. One is that technological progress in a society is by and large a temporary and vulnerable process, with many powerful enemies with a vested interest in the status quo or an aversion to change continuously threatening it. The net result is that changes in technology, the mainspring of economic progress, have actually been rare relative to what we now know human creativity is capable of, and that stasis or change at very slow rates has been the rule rather than the exception. It is our own age, and especially the rapid technological change in the Western world, that is the historical aberration. Another implication is that most underdeveloped countries cannot take technology transfer for granted. Even when capital is available and complementary inputs such as skilled labor and infrastructure are present, attempts to transplant technology from one society to another are likely to run into social barriers that economists may find difficult to understand. Without an understanding of the political economy of technological change, then, the historical development of economic growth will remain a mystery.

How should we think of resistance to new knowledge? Knowledge systems are self-organizing systems that in many ways can be thought of in evolutionary terms. The idea of self-organizing decentralized systems, or "catallaxy" as Hayek has called it, is one of the most powerful and influential ideas of the modern age and perhaps the most important element in Adam Smith's thought (Hayek, 1973–76, vol. 1, pp. 35–54; vol. 2, p. 108). The idea of an invisible hand creating order by following well-understood rules lies at the base of Darwinian evolution theory, and although Darwin only acknowledged his debt to Malthus, the philosophical connection to Adam Smith is quite clear.[1] Outside economics, self-organizing systems appear throughout our social system. Language, for instance, is such a system, as are science, technology, the arts, manners, and so on. These systems are all information systems and are organized in a particular fashion. They are, in effect, conventions, and as such self-replicating. Conventions are not chosen; they evolve (Sugden, 1989). Ex ante, an infinite number of ways of organizing the information can be imagined, but once the system settles on a Nash equilibrium, certain rules are observed that give the system its coherence. Ideally we would like it to be an ESS (evolutionary stable strategy) in which no single individual or

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[1] Schweber (1980; 1985). Stephen J. Gould (1980, p. 62) writes that "the theory of natural selection is a creative transfer to biology of Adam Smith's basic argument for a rational economy." See also Hayek (1973–76, Vol. 1, p. 23).

subset of individuals has an incentive to violate the rules, but there is little to suggest that such equilibria are in fact the rule.

In the kind of system analyzed by Adam Smith, an analysis that evolved into modern neoclassical theory, scarcities and desires are translated into prices, which summarize all the necessary information. In language, the information is the meaning of words and the rules of combining them into sentences. In art the information consists of the tools needed to write a symphony or paint a picture. It is obvious that most self-organizing systems have multiple equilibria. It is a convention that we write English, but it is purely accidental that each word means what it means. In science, arts, and literature, there was nothing inexorable about specific historical outcomes. Though clearly not *everything* could have happened, many conceivable outcomes were possible. To demonstrate this, consider the enormously different styles of music, art, and literature that were created by societies that developed more or less independently. Hindu music is an evolved system, but the rules are different from the ones followed by Haydn. Chinese medicine followed a very different path from European medicine.

These systems resist change once they settle down. Novelty and deviations from accepted norms are rejected as much as possible. Violating the rules carries some form of penalty: in economics it is selling or buying at non-equilibrium prices, whereas in language it is not being understood. Children are taught to speak and write correctly, that is, not to deviate from conventions and rules that have been laid down by past generations.[2] In nature the process of elimination is ruthless: mutants and defective babies usually do not survive, and even viable mutants are either sterile or have lower fitness. In science, one of the most typical self-organizing evolutionary systems, resistance to innovation by an established scientific and at times ideological status quo, has always been strong (Barber, 1962). As Ziman puts it, every scientist is raised within the world picture of his day and will not happily accept statements that are at variance with his or her worldview except in the face of strong evidence (1978, p. 8). Resistance to change is one of the selection criteria operating in a Darwinian system. It means that in many cases a favorable innovation has to be more than just marginally better than the status quo; it has to overcome a hump of resistance that eliminates unfavorable innovations and many favorable ones as well. Despite the resistance to change and the strong inertia in these

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[2] Changes imposed from above may run into resistance even in unexpected areas. Thus the latinization of the Turkish alphabet by Ataturk was opposed, and the simplification of the Bulgarian alphabet in 1922 led to the resignation of two ministers (Stern, 1937, p. 48).

knowledge systems, they do change, although it is possible for such systems to lapse eventually into complete stasis.

Given these preliminaries, what can we say about technological systems? To start with, they are not exclusively self-organizing. In the Western world, to be sure, technological development has been largely the responsibility of private enterprise. Individuals choose not only what and for whom to produce but also how to go about it (Rosenberg and Birdzell, 1986). New ideas and inventions are subjected to decentralized survival tests, which in practice means that producers are willing to adopt them because they increase income or reduce efforts. In the West, technological change was rarely imposed from above and did not usually require approval by the authorities. In China, on the other hand, technological changes were often initiated by the government, especially the bureaucracies of the Tang and Sung dynasties.[3] Similarly, the Marxist economies of Eastern Europe developed technologies imposed from above. And although the Trabant and the environmental ravages of southern Poland are testimony to the ultimate failure of government designs, centrally planned economies did have some major technological successes. Their technical backwardness was due to bad incentives and organization rather than inherent technological ineptitude (Hunter, 1991). It is clear that *some* role for a government in the direction of technological progress is warranted. After all, in the West governments played an increasingly active role in technological development in the twentieth century. Not all free-enterprise economies are necessarily technologically creative, and not all command economies are technologically stagnant. All the same, technological progress has a better chance in the long run in free, self-organizing market societies than in command economies. China's technological superiority fizzled out in the centuries of the European Renaissance, and the much-feared Soviet technological advantage of the post-Sputnik years has melted away like the core in the Chernobyl reactor.

Yet even in free-market economies, technological creativity has proved politically vulnerable. The history of technological progress is the history

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[3] The Chinese imperial government generated and diffused new technologies in rice cultivation, including better (drought-resistant) varieties, owned the great foundries that were central to its iron industry, developed and built the great junks with which the Chinese sailed along the African East Coast in the fifteenth century, and encouraged the use of cotton, better implements, and hydraulic techniques. Clockmaking technology was wholly monopolized by the emperor. The authors of the great treatises on agriculture such as Wang Chen and Hsü Kuang Chhi, as well as the inventor of the use of mulberry tree bark in papermaking, were government bureaucrats.

of an endangered and much-resisted species.[4] Such resistance is necessary if a technological system is not to degenerate into anarchy, just as languages have to resist change if communication between individuals is to remain reasonably efficient. If every hare-brained technological idea were tried and implemented, the costs would be tremendous. Like mutations, most technological innovations are duds and deserve to be eliminated.

All the same, overcoming the built-in resistance is the key to technological progress: if no hare-brained idea had ever been ever tried, we would still be living in the stone age. The idea that "if it ain't broke, don't fix it" is one of those half-truths that reflect the ambiguity of the problem. There are cases in which something is not broke, yet by fixing it we can make it better, while in others we are wasting our time and resources. Unfortunately we do not know in advance which of the two situations we are in until we try. For technological progress to occur in a way that we would recognize as desirable, a tenuous midpoint has to be reached between too little resistance and too much resistance. What is needed for technological change is a system in which people are free to experiment and reap the fruits of their success if their experiment works, that is, if it meets the criteria of selection. But this still leaves many issues unsettled: what if individuals disagree about these criteria, or if they agree on the criterion but disagree about interpreting the evidence?

Technological inertia in many societies has often been ascribed to irrationality, technophobia, and a blind adherence to traditional but outmoded values and customs. Yet as Timur Kuran (1988) has shown, conservatism and rationality are not always mutually exclusive. It might be added that not all resistance is purely social. There are instances in which the technological "system" itself resists a novel and improved component because it does not fit the operation of the existing system. Evolutionary systems are often naturally resistant to change. Despite the vast diversity of life forms, actual phenotypical change is quite unusual and runs into many barriers. The understanding that natural selection is inherently a conservative process was first emphasized by Alfred Russel Wallace, who likened natural selection to a governor on a steam engine, essentially a device to correct deviations automatically. The biologist Gregory Bateson notes that the rate of evolution is limited by the barrier between phenotypic

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[4] As Schumpeter wrote, "The reaction of the social environment against one who wishes to do something new...manifests itself first of all in the existence of legal or political impediments....surmounting opposition is always a special task which requires a special kind of conduct. In matters economic, this resistance manifests itself first of all in the groups threatened by the innovation, then in the difficulty of finding the necessary cooperation, and finally in winning over consumers" (Schumpeter, [1934] 1969, pp. 86–87).

and genotypic change, which prevents acquired characteristics from being passed on to future generations; by sexual reproduction, which guarantees that the DNA blueprint of the new does not conflict too much with that of the old; and by the inherent conservatism of the developing embryo, which necessarily involves a convergent process he calls epigenesis (Bateson, 1979, pp. 175–76). Furthermore, the emergence of new species (speciation), analogous to the emergence of radically new techniques, is both rare and poorly understood. Although the resistance to change in natural systems is of a different nature than that in technological systems, it too implies a cohesive force that limits the amount and rate of change. Stability in the systems of living beings is maintained by what biologists term genetic cohesion. This cohesion, as the biologist Ernst Mayr emphasizes (1991, pp. 160–61), while not wholly understood, is essential to the development of the world of living species: the key to success is to strike a compromise between excessive conservatism and excessive malleability. Evolutionary systems, whether biological or other, that are too conservative will end up in stasis; too much receptivity to change will result in chaos.[5]

What economists call system externalities have an equivalent in biology known as "structural constraints." Genetic material is transmitted in "packages" and thus sticks together. The information transmitted from generation to generation does not consist of independent and separately optimizable pieces. A "little-understood principle of correlated development" (as Darwin called it) implies that certain features develop not because they increase fitness but because they are correlated with other developments. We now know why this is so: genetic linkage causes genes that are located in close proximity on the chromosome to be inherited. At the same time, evolution tends to be localized and cannot change too much at once. As François Jacob (1977) put it in a famous paper, evolution does not so much create as tinker: it works with what is available, odds and ends, and much of it therefore involves minor variations on existing structures. Insofar as knowledge behaves like other evolutionary systems such as living beings or cultural structures, it might be expected to follow similar dynamic rules. Yet the two systems are sufficiently different, and evolutionary dynamics are sufficiently complex, to make any obvious inferences-by-analogy hazardous.

In the evolution of useful knowledge, resistance to novelty comes largely from the preconceptions of existing practitioners who have been trained to believe in certain conceptions they regard—perhaps subcon-

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[5] As we have seen, all evolutionary systems have some source of resistance to change or else they might collapse into the indeterminacy Kauffman describes as his "supracritical region." For a detailed argument along these lines, see Kauffman (1995, pp. 73, 194).

sciously—as axiomatic and thus they may miss obvious discoveries that are right before their eyes (Barber, 1962). Among the most famous examples are Tycho Brahe's denial of the Copernican system, Einstein's resistance to quantum theory, Priestley's refusal to give up his belief in phlogiston, Claude Bernard's opposition to any use of statistics in medicine, Kelvin's adherence to the indivisibity of the atom and rejection of Maxwell's electromagnetics, von Liebig's denial of Pasteur's proof that fermentation was a biological and not a chemical process, and James Watt's stubborn resistance to the workability of high-pressure engines. The existing conceptual structures in people's minds provide resistance as much as cohesion. These examples perhaps all point to the futility of resistance, but that is largely because the historical record is written by the winners.

There are a few cases of documented losers, such as the fate of Ignaz Semmelweis, mentioned in chapter 3, whose insight that puerperal fever was transmitted by doctors led to his expulsion from his Viennese hospital position and to the delay, by at least two decades, of a discovery that would have saved the lives of tens of thousands of women. Even after the discovery was made, American physicians fiercely resisted it.[6] On the European continent, which was more receptive to techniques based on the body of useful knowledge we call bacteriology, resistance was weaker.[7] Indeed, the idea went back to a much earlier age. The idea of germ-caused infection was first proposed by Girolamo Fracastoro in his *De Contagione* (1546). In 1687, Giovanni Bonomo explicitly proposed that diseases were transmitted because minute living creatures he had been able to see through a microscope passed from person to another (Reiser, 1978. p. 72). Bonomo's observations, along with the microscopy of pioneers like Leeuwenhoek, ran

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[6] Samuel Gross, the author of the leading textbook in surgery in the U.S., noted in its 1876 edition that the surgeons of his country did not believe in Listerism, and a famous painting by Thomas Eakins depicts him operating without any evidence of antisepsis (Nuland, 1988, p. 372). An enlightening anecdote is provided by Fish (1950): when President Garfield was shot, sixteen years after the introduction of antisepsis, the numerous physicians who saw him did not think twice before poking his wound with their finger. The surgeon general of the Navy introduced his finger to its full extent into the wound, as did Dr. J. J. Woodward and a Dr. Bliss, two physicians present. A homeopathic physician who rushed into the room added a deep finger-poke of his own. It is not surprising that Garfield died not of the shot itself but from infection and complications ten weeks after the incident.

[7] In European hospitals, the decline following Lister's rediscovery of the Holmes-Semmelweiss insight that physicians and other patients infected maternity ward patients was remarkable. French data show that in hospitals the incidence of maternal deaths before 1869 was 9.3 percent; the figure fell to 2.3 percent in the 1870s, to 1 percent in the 1880s and to less than .5 percent after that. Yet these figures are a bit misleading; in the French provinces, for instance, the new knowledge filtered down at a slower pace, and the complete separation of maternity ward patients and those suffering from infectious diseases was not accomplished until the beginning of the twentieth century (Rollet-Echalier, 1990, p. 159).

into skepticism because they were irreconcilable with accepted humoral doctrine. Pasteur and Koch's demonstrations of the culpability of bacteria took many years to be accepted, and the opposition of some of the great figures of public medicine of the time, such as the sanitary reformer Max von Pettenkofer and Rudolf Virchow, the founder of cell pathology, is legendary. In New York, well-known doctors walked out of scientific meetings in protest as soon as the issue of bacteriology was raised (Rothstein, 1972, p. 265). Yet the growing tightness of what in 1860 was still a speculative hypothesis due to improving experimental technology was inexorable. Here, then, the development of the germ theory provides an illustration of the interaction between the selection processes of Ω- and λ-knowledge. At first, physicians were indifferent or hostile to the germ theory, and it had no immediate therapeutic implications; then came the stunning success of the discovery of an antitoxin and vaccination against diphtheria by Emil von Behring in 1886, which led to a sharp fall in diphtheria deaths. The discovery reflected well on the new science and helped to get it widely accepted.

Even more striking is the resistance against anesthesia, at first glance an unambiguously welfare-improving finding: the great English scientist Humphry Davy stumbled upon the idea of anesthesia in 1800 but failed to see its possibilities (Youngson, 1979, p. 45). The use of chloroform in childbirth was resisted because many believed that painless childbirth was unnatural and improper. Was not pain ordained in the scriptures and thus somehow desirable (Youngson, 1979, pp. 95–105; 190–98)? Charles Baudelaire felt that ether and chloroform, like all modern inventions, tend to diminish human liberty and indispensable suffering (cited by Rupreht and Keys, 1985, p. 5).

The resistance to new propositional knowledge is to be expected in any society, but its degree of success depends on the standards by which society judges it and the tightness of the knowledge—that is, how strongly it is confirmed by these standards and becomes part of the "consensus," which is as close as any society can come to "tested" Ω-knowledge. These standards are themselves social conventions and they hardly define an ontological concept such as "truth." It is clear, however, that experimental design, double-blind statistical investigations, mathematical proof, and similar means of verification define some pieces of knowledge as tighter than others. It is difficult to successfully resist a segment of knowledge that is tight by these definitions without sounding like a crackpot. Science is consensual: things are regarded to be true because the majority of people who matter (however defined) accept them (Ziman, 1978). They will be accepted, however reluctantly, if they meet these criteria. Mendel's discovery of the laws of genetics is a good example: when his work was first published in 1865, the use of mathematics (or better put: simple statistics) was not accepted, and his work was dismissed by the eminent botanist Carl von Nägeli for that reason.[8] A generation later the standards had changed enough for the scientific community to accept Mendel's work. It is possible to use the power that established academics have to dismiss new knowledge temporarily or to take the attitude "I would not believe it even if it were true." But if the knowledge is sufficiently tight, such resistance is usually futile in an open, decentralized society where ideas can compete for acceptance in the "marketplace" of knowledge.

The other factor is whether the piece of Ω-knowledge in dispute maps into a technique that works. Knowledge in Ω will become tighter and more difficult to resist if it maps into techniques that actually can be shown to work. To put it crudely, the way we are persuaded that science is true is that its recommendations work visibly (Cohen and Stewart, 1994, p. 54).[9] Chemistry works—it makes nylon tights and polyethylene sheets. Physics works—airplanes fly and pressure cookers cook rice. Every time.[10] Strictly speaking, this is not a correct inference because a functional technique could be mapped from propositional knowledge that turns out to be false. At the same time, techniques may be "selected" because they are implied by a set of knowledge that is gaining acceptance. This is true especially if the efficacy of a technique is hard to observe directly. We do not actually observe the positive effect that daily doses of aspirin have on preventing heart disease, but we trust the scientific insights that suggest this. Because the results are not directly observable, however, such knowledge is usually less tight than knowledge that leads directly to observable results. The idea that knowledge will be accepted simply because it "performs" is even

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[8] Mayr points out that, in addition, von Nägeli was one of the few biologists who subscribed to a "pure" theory of genetic blending, according to which the maternal and paternal idioplasms blend during fertilization. Accepting Mendel would have been a complete refutation of his own views (1982, p. 723).

[9] Ziman recounts the history of Alfred Wegener, who laid out the theory of continental drift in 1912, but whose work, despite convincing evidence, was rejected by the bulk of the geological profession for fifty years. Ziman argues that this was largely because geologists relied on the results of theoretical physics, which showed that the tidal mechanisms he suggested were insufficient (1978, pp. 93–94). The resistance was, however, sustained by the fact that plate tectonics theory did not map into any obvious technique. Just as, say, the claim that a meteorite caused the disappearance of the dinosaurs at the end of the Cretaceous, this kind of useful knowledge is not easily tested by the application of techniques based on it.

[10] Of course, even here some skepticism and resistance has been observed. Camille Flammarion, the French astronomer, recounts that at the first demonstration in France of Edison's phonograph in 1878, when the recorded sentence was replayed, an academician "of ripe age" whose mind was still filled with classical culture threw himself in indignation upon Edison's representative shouting in fury, "Scoundrel, we will not be the dupes of a ventriloquist" (Ziman, 1978, p. 142).

accepted by social constructivists: "It is more the desire for wealth than the desire for knowledge that initially forced upon technology the imperative of performance improvement and product realization," writes Lyotard (1984, p. 45). Legitimization of knowledge is then regarded as a power relation, because technology enhances performance and thus provides wealth. Implicit here is the innocuous assumption that technology can only do that because its very success indicates the likelihood that the knowledge on which it is based provides a good approximation of reality.

Unlike biology, production technology can mold its own selection environment by developing rules of behavior that evolve spontaneously but the purpose of which is presumably to preserve the status quo and protect existing interests. Nelson points out that such action may be central in determining what design or system becomes dominant (1995, p. 77). Technology, too, occurs in "systems," meaning that components that are changed will have effects on other parts with which they interact. Hence a change in technique is likely to change costs subsequent to its adoption through unintended consequences to other components. Many of these occur through externalities or network effects: electrical equipment, trains, software, telephones, farming in open field agriculture, and mechanical devices that use interchangeable parts, all of which share the problem of interrelatedness. In order to work efficiently, they require a uniformity we call standardization, and thus single members cannot change a component without adhering to the standard.[11] Yet here, too, the analogy can be pressed too far: in technology—but not in nature—we can invent "gateway" technologies in which the incompatibilities are overcome, including for instance electrical convertors that allow switching from 115V to 220V or railroad cars with adjustable axles that traveled on different gauges. In open-architecture or modular systems, it is possible to alter one component without affecting the others—within limits. The famous case of the QWERTY keyboard is illustrative. There is no doubt that we use this keyboard (and not another) for historical reasons, but it is also clear that, had such a choice involved substantial efficiency costs, we would have somehow been able to find a solution to make the keyboard more effective.[12] In modern computers, the keyboard is modular: it can be replaced or modified without affecting any of the other components.

Positive feedback traps *can* occur in technological systems but tend to be rare in open economies because of competitive pressures from outside.

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[11] A wide-ranging and informative introduction to some of the issues involved in standardization can be found in Langlois and Savage (2001).

[12] The most famous but also controversial example is the Dvorak keyboard, taught to be superior to the standard QWERTY system (see David , 1986; Liebowitz and Margolis, 1990).

Yet they do occur, especially when there are demonstrable network externalities.[13] Some techniques involving network complementarities such as DAT players and Beta VCR never caught on, with possible losses to consumer welfare, but they must be dwarfed by the billions of hours of TV watching of distorted colors and fuzzy images. Yet the cost of settling on a poor standard must be weighed against the cost of settling on multiple standards: loyal users of WordPerfect, such as this author, find themselves in much the same situation as the Great Western Railroad in Britain, which had settled on a five-foot gauge, which it claimed provided a ride safer and smoother than the 4'8½" gauge that Parliament voted in as the standard in 1846. For half a century, cargo moving from the Midlands to the Southwest had to be trans-shipped at Gloucester from standard to wide-gauge wagon (Kindleberger, 1983, p. 385).

The complementarities involved in network technologies (broadcast-reception in the case of TV; software-hardware in the case of computers) are characteristics of one of the most common sources of technological inertia in history: frequency dependence.[14] Frequency dependence occurs when a new technique succeeds because it has already been adopted by a sufficiently large number of users. This kind of model sounds at first almost discouraging, since in its strictest sense it means that only success succeeds, a blueprint for total stasis. Of course, such hurdles could be and have been overcome: *somebody* bought the first fax machine. It should alert us, however, that in many normal situations new technological ideas that might appear to work well do not catch on and eventually vanish without a trace. IBM's OS/2 operating system, much superior to MS/DOS, was rejected because it was not sufficiently "compatible," much like Beta tapes. Perhaps the most obvious example of a standard with network externalities is a language. Languages are a special case of techniques that requires a great deal of coordination and consequently are resistant to change. The red pencils of language teachers see to that. This resistance is necessary; if there is too much change, there is a serious danger of the loss of uniformity and less effective communication. Yet languages do change: words are

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[13] American color TV has been "stuck" since the 1960s with the NTSC standard, which provides notoriously low-quality screen color and resolution. Noticeably better standards (PAL and SECAM) were developed subsequently in Europe and Japan, but could not be adopted without solving a massive coordination problem, namely the simultaneous change of both the transmission and the reception system. By 1990, a vastly superior system of HDTV had been developed, but Farrell and Shapiro's (1992, p. 5) prediction that we will not see this quality in American homes in "this millennium" has been borne out with time to spare. IBM-based computers for a long time struggled with the often paralyzing constraint of 640K RAM in "conventional memory," the nemesis of computer games and many multimedia applications. For both television and computers, it has turned out to be costly and tricky but not impossible to devise a "gateway" solution.

[14] For a recent survey of this literature, see Arthur (1994). See also David (1992).

added, and spelling and grammatical rules evolve. It is hard to argue, however, that *any* language is as efficient as it could be: arcane grammatical rules and irregular verbs make little sense yet seem to have survived by inertia. Major changes in grammatical rules often have to be coordinated by language academies that impose them on the population. The same is true for weights and measures: the main consideration is the reduction in transactions cost thanks to the ubiquity of the standard. The introduction of the metric system in France was rational first and foremost because it standardized measures over the entire country; its decimal qualities were secondary, and of course rejected by the Anglo-Saxon world. It is telling that the attempt to decimalize time measurement by dividing the year into ten-day weeks was resisted and never caught on.

A special case of frequency dependence is what economists call learning by doing, where average costs decline with cumulative output. It is not possible to know how important these learning effects would have been in products that for some reason never made it to mass production. They are the outcome of an experiment never performed. Would airships have become safe and fast (in addition to being quiet and fuel-efficient) had the world of aviation not switched to fixed-wing aircraft in the interwar period? Would small mass-produced "flivver" personal planes have dominated the civilian air travel market if their production had been pursued vigorously? If Volkswagen and Toyota had tried to implement a steam engine in their mass-produced models, could steamcars have given the four-stroke internal combustion engine the same run for its money that the diesel engine did? Could the same be said for two-stroke engines, Wankel engines, Stirling engines, fuel-cell engines, and similar devices? Frequency dependence can become especially important because useful knowledge often spreads through what is sometimes known as "social learning" in which people save on information costs by imitating what their neighbors do. This phenomenon implies an epidemic model for the diffusion and acceptance of new useful knowledge.

In what follows I set forth two propositions. One is that the development of useful knowledge as a source of economic dynamics is influenced by political economy far more than is often realized. Consequently, economic development and performance were often held back by political processes that arrested the growth of useful knowledge. The second is that technological inertia was usually the outcome of rational behavior by utility-maximizing individuals, and we do not have to fall back on differences in preferences or obtuseness to explain why some societies were more amenable to technological change than others. The conclusion I draw is that economic stagnation and technological inertia may be the result of individually rational and optimizing behavior and are not evidence of irrational behavior.

Institutions and Technology

The rules by which society decides whether to select or reject a given invention are part of its institutional structure. Any change in technology leads almost inevitably to an improvement in the welfare of some and to a deterioration in that of others.[15] To be sure, it is possible to think of changes in production technology that are Pareto-superior, but in practice such occurrences are extremely rare. Unless all individuals accept the "verdict" of the market outcome, the decision whether to adopt an innovation is likely to be resisted by losers through non-market mechanism and political activism.[16] One important distinction should be made between the introduction of a totally new invention in the economy in which it originates, and the transfer of existing technology into new places after it has already been put into effect elsewhere. In both cases resistance may emerge, but its nature may differ substantially between the two. Either way, however, markets judge techniques by profitability and thus, as a first approximation, by economic efficiency. How, then, does conflict occur?

This resistance to progress is one mechanism that provides the theoretical background of Cardwell's Law. The mechanism does not rely on "irrational" behavior of any kind: as Krusell and Ríos-Rull (1996) show, in a simple growth model, rational behavior generates resistance and possibly the suppression of technological change. This insight conforms to our intuition that technological progress is almost never Pareto-superior, and that in the presence of any vintage-specific skills or unmalleable assets there will be losers. The difficulty with persuading economists of this truth is that it is based on a political, not a market process. Yet the significance of the modus operandi of Cardwell's Law is deeper than that. Once again, in evolutionary theory similar problems have come up: Robert Wesson points out that evolutionary change involves moving from one stable attractor to another, and hence the most important competition is not between individuals and their lineages as in the Darwinian view but between new forms and the old: "The old must nearly always win, but the few newcomers that score an upset victory carry away the prize of the

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[15] Two recent books (Bauer, 1995; Sale, 1995) dealing with social response to technology, while totally different in tone and background, implore social scientists to pay more attention to the question of resistance to the seemingly inexorable march of new technology.

[16] As one author (Mazur, 1993, p. 217) has put it, "opposition to a technology is a special case of a broader class of political activities usually referred to as 'special interest' politics, as opposed to the politics of party identification or patronage."

future"(1991, p. 149). This idea carries over to economics in an interesting way: economists have traditionally thought of competition as occurring between similar units ("firms") using comparable technology. Yet there may be an additional, hitherto neglected, level at which competition occurs, namely between "generations" of technology, at which existing knowledge tries to defend its rents against rebellious attempts to overthrow it. Schumpeter (1950, p. 84) was explicit about this matter in a widely cited passage: "In capitalist reality, as distinguished from its textbook picture it is not [price] competition which counts but the competition from the new commodity, the new technology...which strikes not at the margins of the profits of the existing firms but at their...very lives."

To simplify matters, let us define the adoption of a new technique as a binary process: either it is adopted or it is not. Each individual has a set of idiosyncratic exogenous variables (preferences, age, endowments, education, wealth, etc.) that lead him or her to either "support" or "object to" the innovation. To reach this decision, society follows what I will call an aggregation rule, which maps a vector of *n* individual preferences into a <0,1> decision. This aggregation rule may be a market process (as would be the case in a pure private economy), but such a rule is a very special case. The pure market outcome is equivalent to an aggregator that weights preferences by their income. The optimality of the outcome will vary with the income distribution even for the market aggregator.

The argument about a new technique is conducted at two levels. One is an argument about the nature of the aggregators that make the decision if the market is not left as the only aggregator—which it rarely is. Should there be licensing of new techniques? Should there be an agency that regulates food and drugs? How is the patent office to judge novelty? To what extent can production be codified in official rules? A second level of discourse occurs once the institutions exist. Different groups will lobby regulators and politicians to approve or prohibit a new invention. Only in a pure market aggregator is there no room for politics to enter the decision-making process. To start with, different groups in the economy favor different aggregation rules. In the terminology of the new historical institutional analysis, an aggregator is an institution, that is, a non-technologically determined constraint on economic behavior. If the market outcome favors one group, another might find it in its interest to circumvent the market process. If the supporters and opponents of the new technique could form separate societies, the optimal outcome would be to separate them. Because they cannot and one of them has to live with an undesirable outcome, the struggle consists of the attempt of each group to set up an aggregation rule (for example, the market) that is most consistent with its interests. Suppose every invention had to be approved by a referendum. In that case there could be a difference between the market, in which "votes" are weighted by purchasing power, and a democratic process, where each person has one vote. In decisions about technology, at least, there could be a serious inconsistency between democracy and continuous innovation.[17] In other words, unlike the optimism of free market advocates in the tradition of Milton Friedman, it may well be that democratic decision processes do not maximize the long-term economic welfare of economies. This obstacle faced by democratic countries which wish to undergo rapid development has long been recognized.[18] The decision-making about technology in democratic societies is inefficient, but in the twentieth century totalitarian societies by and large did even worse.[19] Insofar as technological decisions are made in the political market, then, there is no reason to believe that decisions will be efficient in any definable sense—we are strictly in worlds of second- and third-best.

We may distinguish between the following decision rules. G_M, the pure market aggregator, means that the new technology will be adopted by profit-maximizing firms following exclusively the dictates of the market. G_D is a decision rule that designates an authorized subset such as representative parliament or a panel of technical experts, a violent mob, a court, or a single dictator, to decide whether to permit and/or support the new technology. G_V is a voting rule, say one-person-one-vote, in which a new technology is voted in or out by referendum. In most realistic situations the decision rule or aggregator that maps individual preferences to the decision space <0,1> is $G = \alpha G_M + \beta G_D + (1-\alpha-\beta)G_V$ where $\alpha + \beta \leq 1$. This mechanical formula underlines the continuous nature of free-market decision-making. The pure market outcome occurs only when $\alpha = 1$ and

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[17] The notion that democracy endangers technological creativity was particularly embraced by nineteenth century reactionary writers opposed to the extension of the franchise, such as Sir Henry Maine who argued that universal suffrage would have prevented most of the major technological breakthroughs of the Industrial Revolution. See Hirschman (1991), pp. 97–100, who adds that the argument was palpably absurd and immediately proven to be so. Yet it is not impossible that democracy could under certain circumstances be *less* hospitable than other political regimes to technological progress.

[18] For an interesting discussion which concludes firmly that "democracy entrenches economic freedoms, and in doing so underpins growth," see "Why Voting Is Good for You," *The Economist* (Aug. 27 1994, pp. 15–17).

[19] Barbara Ward has explained that uncontrolled market decisions will create intolerable gaps in income distribution and thus resistance of new technology, and totalitarian dictatorships would implement technologies regardless of cost. "But in India," she added, "a balance has always to be struck, the dilemma is never absent"(1964, pp. 150–52)." Yet in her view this is precisely India's strength, since whatever modernization is introduced is usually based on a consensus and thus unlikely to ignite political explosions. These words were written many years before the experience of the shah of Iran confirmed her insight.

the pure command economy when $\alpha = 0$. Neither of those are historically realistic.

The social decision process may thus be viewed as consisting of two stages. First, society determines the political rules of the game; that is, it sets α and β. Then, depending on the aggregator chosen, it determines whether the new technique will be adopted or not. An obvious elaboration of the simple model is that one decision-maker may delegate decisions to another: the authorized subset can decide to hand things over to a referendum or leave it up to the market. An election, on the other hand, can appoint a body of people delegated to make the decision or do nothing at all so that the decision whether to adopt is effectively left to the market. The interpretation of α and β as probabilities or proportions of the "cases" that are decided in one arena or another thus lends some intuitive meaning to G.

A great deal of political and social struggle involves not only the implementation of new technology itself, but the decision rules, as it is reasonably believed that some decision rules favor one interest group over another. Economists, in particular, are concerned by the size of α, that is, how much of the decision is left to the market and how much will be decided on by other aggregators. In part, the aggregator will be determined by the nature of the product: technological change in public goods and other areas of perceived market failure will be obviously largely outside the market decision-making process; but there is a huge gray area of private goods where there is room for political action.

Economists on the whole believe that the larger α, the more societies will be creative and technologically successful (Baumol, 2002). This is plausible, but by no means certain. It may well be that the free market, for reasons of its own, forgoes technological opportunities. For instance, the new technology may have insuperable appropriability problems, require unusually large capital spending, or require coordination between existing firms that cannot be materialized without direct intervention. In that case, the government may step in to make up for the market failure. In pre-revolutionary France, especially, the government actively encouraged French inventors, and spurred entrepreneurs to accept British techniques (Hilaire-Pérez, 2000).

When the aggregator has been decided upon, as long as $\alpha < 1$ (so that —as is often the case—some non-market decision is necessary to approve the new technology), opposition occurs within given political structures, such as a courtroom or a parliamentary committee. Of course, many new technologies are too trifling to be the subject of public debate; one hears little public outcry over the switch, say, from spark plugs to fuel injection or from dot-matrix to ink-jet printers. Such decisions are normally delegated to the market. But when major technical choices involve public expenditures, complementary or substitute relations with other technologies, or other types of spillover effects, they will end up being judged by non-market criteria.[20] Similarly, uncertainty of any nature regarding possible externalities, especially when they concern public health and safety, almost invariably lead to a reduction of the market component in the aggregator. In those cases, political lobbying about the new technology is natural. The usual rules of political economy and collective decision-making by interest groups apply, with the additional complications that the introduction of a new technology is by definition a highly uncertain event, involving known and unknown dangers that play no role in, say, political decisions about tariff policy or public works procurement. Moreover, the technical and scientific issues are often highly complex, and even phrasing the questions correctly (let alone the answers) is often beyond the intellectual capability of decision-makers. Precisely for that reason, there is more reliance on the opinion of "experts" but also, paradoxically, a frequent appeal to emotions, fears, and religious and nationalist sentiments. As litigation becomes increasingly important, technological decisions are relegated to courts, and rhetorical imagery and other persuasive tools, from TV ads to neighborhood rallies, become a means by which technological decisions are made. Reliance on technical expertise, a long-standing practice in the West, is weakened by disagreements among experts and even disagreements over who is an expert to begin with.[21]

Why would there be support for removing the market as the sole arbiter of technological decisions and delegate part of the decision-making process to political bodies? Technological progress disrupts the existing allocation of resources and thus involves externalities as soon as we admit that the reallocation involves costs. Yet a mechanism that relies on markets alone effectively truncates preferences over technology at zero. If one supports a new technique, one can vote yes by buying the new product or switching to the new technique. By not buying the product or refusing to switch, one can express indifference or dislike, but individuals have no control over what others do even if they feel it might affect them. In markets it is difficult to express a no vote.

Resistance to technological change thus occurs because there is some "rigidity" in the economic system. In a perfectly competitive economy in

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[20] The adoption of fluoridation of drinking water in the United States, the use of insecticide in mosquito abatement, and all matters pertaining to military technology are prime examples of such public technical choices.

[21] Dorothy Nelkin has pointed out that the very fact that experts disagree —more even than the substance of their disagreement —leads to protests and demands for more public participation (1992, p. xx).

which all capital—including human capital—is fully malleable and people can perfectly distinguish between successful inventions and duds, technological progress may be Pareto-improving. In such an economy, existing producers could license an invention without becoming worse off, with the benefits of the invention accruing to consumers and the inventors. Similarly, in a neoclassical world laborers have no fear of being made redundant by labor-saving innovations, because a worker replaced by a machine can always find an equivalent job somewhere else (and at a higher real wage, because the economy's efficiency has gone up).

In the historical experience, friction made all the difference. The Preston Tuckers of this world threatened the rents generated by existing plant, equipment, engineering skills, and the quiet life that a technologically stagnant world enjoys.[22] Handloom weavers and frame knitters could not find equivalent jobs in factories and had every reason to resent the introduction of the power loom. The more specific a skill or a piece of equipment, the more incentive its owner has to resist anything that will reduce its value through technological obsolescence. It is hard to think of a technological advance that did not reduce the value of somebody's specific assets and skills. In the next section, I deal in some detail with the historical manifestations of resistance to new technology.

Moreover, technological change altered the non-pecuniary characteristics of labor. It created and destroyed labor hierarchies, it changed the physical work environment, and it increased and decreased the advantages of domestic production where workers were in control of their own work schedule. Insofar as such factors mattered and were not entirely reflected in compensating wage differentials, resistance to technological change by labor was to be expected. Moreover, for the producers themselves life in a technologically creative world may be quite different from life in a static economy.[23] It is one thing to resist a once-and-for-all change in technology,

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[22] The Hollywood version of the demise of automotive visionary Preston Tucker is not entirely accurate. Tucker's main problem was raising venture capital. Needless to say, the repeated assurances of the established automobile industry that Tucker's company would fail were less than helpful in raising capital. It is also possible that the Big Three automakers were indirectly responsible for the repeated investigations of Tucker by the Securities and Exchange Commission, although there is no direct evidence for that. The capital market, especially the venture capital market, is clearly a powerful tool for vested interests to keep out innovators. In Tucker's case, however, poor financial management was as responsible for his failure as undermining by competitors (see McLafferty, 1952).

[23] A statement made in 1991 in the context of the new communications technologies by Alfred C. Sikes, then chairman of the Federal Communications Commission, appears equally true today: "In the United States, powerful forces want to preserve the status quo. Political Action Committees have a vested interest in preserving things as they are...they push for the retention of advantageous government subsidies and close government regulation of competitors. In short, no new troublesome competition is wanted" *(Newsweek*, Jan. 14, 1991, p. 8).

quite another to resist living in a hectic and nerve-racking world in which producers have to run to stay in place and constantly spend effort and resources on searching for improvements.[24]

Resistance to technological change is not limited to labor unions and Olsonian lobbies defending their turf and skills against the inexorable obsolescence that new techniques will bring about (Olson, 1982). In a centralized bureaucracy there is a built-in tendency for conservatism. Sometimes the motives of technophobes are purely conservative in the standard sense of the word (Kuran, 1988). This is equally true for corporate and government bureaucracies, and cases in which corporations, presumably trying to maximize profits, resisted innovations are legend. To be sure, well-functioning markets tend to deal summarily with firms that suffer from the "not-invented-here" syndrome and its more malignant relative, "if it were possible we would have done it long ago." Yet in practice firms make these mistakes all the time. It easier to shrug off a new idea when it comes from your own employee. When Henry Ford III was faced with radial tires introduced by Michelin, he contemptuously dismissed them as "frog tires" and then reluctantly had to purchase them despite his distaste for the product (Frey, 1991). Serious pockets of resistance in other parts of the corporation may block the introduction of new techniques. For example, Dupont had committed heavily to nylon-based tire cords. Despite the advantages of polyester-based cords over nylon, Dupont's nylon department outmaneuvered its polyester department with the result that in the late 1960s Dupont lost most of that market to Celanese, which had committed to polyester (Foster, 1986, pp. 121–27). Firms that resist innovation might be clay-footed bureaucratic giants or one-man empires in which a brilliant but erratic entrepreneur makes the decisions himself. For any bureaucracy, routine and standard operating procedures are the essence of its long-run existence, and deviance is persecuted and uprooted if possible (Goldstone, 1987).[25] For that reason, it is critical whether the decision-making body is facing some form of competition; if the Xerox Corporation would not make the computer mouse it developed, somebody else would. If the British established aerospace industries that would not

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[24] This "Red Queen Effect" (after the red queen in *Alice in Wonderland*) has been noted by evolutionary biologists and plays an important role in generating adaptive changes in a world without exogenous environmental changes (see Stenseth, 1985).

[25] Such resistance can even be found in the all-important connections between propositional and prescriptive knowledge. The first professor of engineering science, established by royal decree in 1840 at the University of Glasgow, Lewis D. B. Gordon, was asked by the university senate to abstain from encroaching on or interfering with any existing classes and was refused a classroom to teach by the jealousy and resistance of the established faculty who felt that engineering was not a bona fide discipline (Channell, 1982).

build a jet engine, the Germans would. By the same token, all other things equal, the more centralized and powerful a bureaucracy, the more formidable the obstacles on the road to technological progress.[26] By analogy, weak and ineffectual governments have difficulty enforcing restrictive legislation and thus from this point of view are to be preferred to strong and autocratic ones.[27]

There are important exceptions to this rule. At times, autocratic rulers such as Czar Peter the Great, Napoleon I, and Haile Selassie recognized the political and military importance of technological advances and actually encouraged them. More often than not, however, despotic rulers did all they could to enforce conformity and squelch attempts to make waves. Moreover, by being intolerant in other dimensions, autocrats such as Philip II, Louis XIV, and Hitler lost many of their most innovative citizens even though they were not necessarily opposed to technological progress per se. Both powerful and weak rulers can be intolerant and reactionary, but stronger rulers have more power to inflict stagnation on their economies under the guise of law and order. Could there not be a symmetric argument that the more powerful a ruler, the more technological progress he or she can bring about because by overruling the demands of special interest lobbies? There are such cases on record, but decentralized systems have tended on the whole to be more efficient than centralized ones in engendering technological progress because they did not depend on the personal judgment and survival of single-minded and strong-willed individuals. The ability to pick technological winners is never concentrated in the mind of a single individual and is uncorrelated with political talent.[28]

Economic interest is thus central to the understanding of the political economy of useful knowledge. A different source of resistance comes from purely intellectual sources without a necessary direct economic interest. Much of this resistance derives from a genuine concern for some social

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[26] The anti-modernist thinking among right-wing fringe groups in the early twentieth century manifested itself strongly when the disciples of those schools came to power. The number of students in the *technische Hochschule* fell by half between 1932–33 and 1937–38, and the politicization of science reduced the intellectual standing of science and meant that a generation of scientists had been lost, with far-reaching implications for Germany's mobilization efforts (James, 1990, p. 113).

[27] Yet even relatively unobtrusive governments have to make *some* decisions and often fall victim to sheer conservatism. In 1850 the British government appointed a royal commission to switch the country to a decimal currency, but it happened to have among its members Lord Overstone, who, through a series of ingenious manipulations, managed to put the decimalization off by more than a century— at considerable cost and inconvenience. Kindleberger (1983) explains laconically that his lordship "in general was opposed to change."

[28] The emperor Napoleon I, in many ways a strong supporter of technological progress, totally misjudged the potential of gaslighting, which he deemed "a folly" and its introduction into France was delayed until after 1815.

values. Schumpeter, in fact, predicted that it would be intellectuals that would bring about a growing hostility to what he called the "capitalist order" (which in his thinking was inseparable from technological change). Moreover, anticipating the thinking of Mancur Olson, he thought that for an atmosphere of hostility to develop it was necessary that there be groups who had a vested interest at stake to work up and organize resentment (Schumpeter, 1950 p. 145). Although in some cases technophobic writers have done well,[29] we cannot and should not attribute strictly material motives to these writers. Many of them are expressing sincere and legitimate concerns, even if perhaps their influence is correlated with economic conditions. What, then, are these concerns?

Some resist technological progress because civilian technology is correlated with military technology and advances in one increases the destructive potential of weapons. When World War I and the development and deployment of nuclear weapons in 1945 led to profound disillusionment among many intellectuals with pacifist inclinations and resentment of technological changes in general.[30] Some correlate the technological status quo with a political power structure they object to. Technological choices often involve power relationships, and can thus either threaten or reinforce the existing political structure (Staudenmaier, 1989). Although technological change did not invariably increase the power of the ruling elites over their subjects, *any* change in power relationships is likely to result in complaints by those who are at the losing end of that game.[31]

Some writers believe that the growth of useful knowledge and modern technology, because of increased specialization and professionalization, is responsible for a totalitarianism of experts and thus for a deepening of class divisions and inequality (Dickson, 1974). Moreover, technology often alters the balance of power and control in the workplace itself, shifting it from management to operators or vice versa (Noble, 1984). If the new technology is intensive of highly skilled labor, such workers will experience

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[29] Thomas DeGregori, in his review of Paul and Anne Ehrlich's work, has pointed to the rather lucrative sides of armchair environmentalism. See also Bailey (1993, p. 42).

[30] A classic example of this can be found in the biography of Lewis Mumford, whose conversion from the technological enthusiast of *Technics and Civilization* to the pessimist of *The Pentagon of Power* was brought about by the ravages of World War II (see Hughes ,1989, p. 448).

[31] Such a political power model is at the center of a paper by Acemoglu and Robinson (2000). They argue that a pure rent-seeking model by a lobby powerful enough to block a new technology makes little sense: if a group is sufficiently powerful to stop the new technology, why can it not just tax away all the profits? The answer is that in some cases that is what happened (one thinks of imperial Germany, where the landowning *Junkertum* appropriated a large proportion of the profits of manufacturing by imposing high tariffs on agricultural goods), but it is usually easier to convince others of the possible dangers of a new technique to society at large than to appropriate the rents.

an increase in bargaining power. Labor-saving new technology is particularly effective when it replaces a highly skilled labor-aristocracy that can threaten to strike and paralyze production. But technology also tends to be correlated in some minds with other political objectives. For some, resistance to new technology tends to be associated with radical egalitarianism, and environmentalism seems the best tool in their arsenal to attack corporate capitalism, just as the technological romanticism of the second half of the nineteenth century was the most efficient way of attacking Victorian industrialism. Aaron Wildavsky believes that some of the more bizarre manifestations of the resistance to technology, such as animal rights movement, derive from this egalitarian culture (1991, pp. 70–74).

Anti-technological movements are also often inspired by well-meaning ideologues who feel that technology is somehow "dehumanizing" or, in the traditions of the young Marx, Heidegger, and Marcuse, "alienating." Much of this thinking seems to hark back to naive beliefs in "noble savages" and the liberating effects of a pastoral society: modern society is a technological system in which we have become total slaves of the technology that is supposed to serve us. Jacques Ellul argues that technology has reduced choice rather than increased it because all our choices are constrained to lie within the set of modern technology (Ellul, 1980, pp. 319–25).

Furthermore, technologically backward societies are at times reluctant to import a superior technology. The foreign technology is resented because of fears—often not unfounded—that it will be accompanied by foreign political domination or cultural influence. Both Islam and the Orient displayed a "not-invented-here" attitude, a mixture of arrogance and suspicion. In late nineteenth-century China, the resistance to Western technology represented a mixture of technophobia and xenophobia (Brown, 1979; Brown and Wright, 1981). Imperialism was propelled by technological differences, and Western domination has been resisted as a Trojan horse of alien values and hegemony (Headrick, 1981; 1988, especially pp. 382–83). Western or Western-inspired technology is often bundled with Western culture and much of the resistance to it in nations such as Afghanistan and North Korea has overt political dimensions. Yet the performance of this technology, from machine guns to cell phones to antibiotics to Coca-Cola, is such that it is almost impossible for any government to keep its country sealed to it. Attempts to unbundle components like the "Microchips, not potato chips" 1995 slogan of the Indian Bharatiya Janata Party reflect this attitude.

Another reason that so much technology is subject to political decisions is that so much technology is part of the public sector: transport, public health, education, and the military require political approval of changes in the techniques they employ simply because these are sectors in which some form of *prior* market failure has been observed. In those sectors, of course, G_D may be very large since officials by definition select the new technique. In his classic article "Gunfire at Sea," Elting Morison has described the resistance put up by the U.S. Navy against the introduction of continuous-aim firing in the first decade of the twentieth century (1966, pp. 17–44). In this case the resistance was overcome when the officer in question appealed directly to President Roosevelt, over the heads of his immediate superiors and the officers in charge of the Bureau of Navy Ordnance.

Finally, consumers seem to distrust the free market as an arbiter of new technology just because it is new. Whereas in a technologically static economy there may be no reason to distrust the invisible hand, the informational asymmetries and irreversibilities associated with the generation and adoption of new techniques based on new knowledge seem to demand a cool and unbiased arbiter. New technology introduces uncertainty where none existed before. It is feared that greedy entrepreneurs will sell asbestos-type products to the public and then abscond. Thalidomide-type disasters, however small compared with the benefits of advances in medical technology, produce a constant demand for government assurances that new products and techniques are safe.[32] Perhaps the most salient characteristic of new knowledge is that its impact by definition cannot be anticipated and that it is more likely to have unknown and unintended consequences (Rosenberg, 1996). Any model that economists use to examine how agents predict the future, whether by rational expectations or other means, founders exactly here, where it is needed most.

Particularly when the technological changes are of a discontinuous nature, what I have called macroinventions, the unknowability of the benefits and costs is central to the political economy of new knowledge. Conflicts over whether a new technology should be introduced can occur for three reasons. One is that individuals could disagree about the subjective probability density function of the net benefits of an invention. The attitude toward nuclear power in the West, especially, is strongly correlated with perceptions of danger (Mazur, 1975, p. 66; Jasper, 1992; Nelkin and Pollack, 1981). Moreover, there is a tempting if invalid tenden-

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[32] Not all resistance to technological progress, however, is necessarily conservative and in defense of some technological status quo. Much of the social resistance to a new technique occurs because there are two alternatives to T_0, T_1 and T_2. Left to the market, T_1 will be chosen; if some interest group wishes to use non-market mechanisms to bring about some alternative new technology T_2, it is the *nature* of technological change they wish to influence, not its very existence. This is what sets apart the literature of "alternative" or "soft" technology advocated by Amory Lovins from the shrill and technophobe positions advocated by, say, Ivan Illich and Chellis Glendinning.

cy to draw inferences from one technological outcome to another: the response to the thalidomide affair imposed restrictive brakes on the development of *all* new drugs (Radkau, 1995). There was a serious psychological spillover effect when one poorly executed project such as Chernobyl raised questions about the desirability of nuclear power altogether. There is a tendency to overestimate the costs and underestimate the benefits in such "salient" cases. Inferences from single events about the social costs and risks of entire new technologies are common, but often misleading and mistaken. James Jasper has noted that "the Three Mile Island accident in 1979 and the Chernobyl accident confirmed, interestingly, both the American antinuclear drift and the French pro-nuclear program. And neither accident did much to alleviate Swedish ambivalence about the future of its nuclear program"(Jasper, 1992, p. 108).

Second, even if different agents agree on the likely outcome, they may have different valuations of these outcomes. A new production process may or may not be labor-saving, but if it is, workers and employers would have different valuations of that. The use of DDT or other possibly harmful substances will be valuated differently by a birdwatcher and a malaria patient. A special case of this is different valuation of future costs and benefits. Many persons suspicious of new technology introduced by corporations or governments fear that the decision-making agent has a short horizon and discounts long-term costs at a rate far higher than society as a whole. Big companies are believed to care primarily about their bottom line for the next quarter and the stock market value associated with that. A special case is the concern of many individuals with the *very* long run. Presumably notions that "extinction is forever" and the very long half-life of nuclear waste products should not matter more than "medium" long-run effects, but even a cursory glance at the environmental literature suggests strongly that eternity matters to many people, no matter how emphatically economists tell them it should not. To some extent, this concern is a luxury. The question "What has posterity ever done for us?" is more likely to be asked by the poor in underdeveloped economies than by wealthy consumers in industrialized economies.

Third, individuals can and do differ in their risk aversion. This is not just a matter of differences in the concavity of utility functions (though that matters as well).[33] It is a matter of how optimistic individuals are about society's capability to generate additional new knowledge that will solve

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[33] Differences in the shapes of utility functions can be especially important because so many of the unintended consequences of some techniques range far into the future (e.g., nuclear waste products and greenhouse gas-producing combustion techniques), and individuals could differ greatly in the weight they place on the welfare of posterity as opposed to their own.

whatever unintended consequences a specific new technique will produce. But it should be kept in mind that our ability to deal with technological problems is in a race with the growing scale and range of these problems themselves, and history is of little help in predicting outcomes.

A great deal of resistance comes from those who fear that technological change creates negative externalities that exceed the benefits. Many environmentalists are suspicious of innovations because they believe that new technologies often make extensive use of resources that have poorly defined property rights. Why would new techniques differ from old ones in this regard? It must be that familiar and tried technologies are better understood, and therefore the resources they use are fully paid for. In the standard case of externalities, common resources are not priced at their marginal social cost. In a static economy, arrangements will often emerge that minimize such discrepancies. Constantly changing techniques compound the transaction costs with information problems. Thus, it is felt that it is difficult enough to limit the use of known atmospheric pollutants, but far harder to enforce agreements when the damage is unknown or in dispute. Whether such a bias actually exists is still very much in question. Those new technologies in which there is little question of property rights, such as fuel injection or DVD players, do not get a lot of notice. Yet it appears that unknown effects of new techniques on shared resources thus aggravate disagreement and political resistance to technological progress.

Some new techniques by their very nature, involve certain unknowns and thus may impose unsuspected future hazards that are not reflected in prices when the market chooses between a new and an old technology. In other words, environmental hazards are caused not by property rights failure but by insufficient information due to the novelty of new techniques and the complexity of technological "system" into which they are introduced. When we innovate in one part of the economy, the consequences will show up somewhere else. This sense is reflected in the environmentalist belief that "we can never do only one thing." Chlorofluorocarbons (CFCs) were thought to be a major breakthrough when they were discovered in 1928 by Thomas Midgley at General Motors.[34] Midgley's career is indeed an uncanny parable of the dangers of well-intentioned innovations that misfired.[35] The negative effects of asbestos similarly were

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[34] CFCs, used mainly as a propellant for spray cans, refrigeration and as solvents in the electronics industry have the advantage that they are inert and thus do not react with the materials in the spray cans. Moreover, they are nontoxic and cheap to produce.

[35] In addition to CFCs, Midgley discovered in 1921 the gasoline additive tetraethyl lead, which reduced engine knock. Lead in gasoline has caused environmental damage and is banned in most Western countries. Midgley himself was paralyzed by polio and constructed an ingenious system of harnesses and pulleys to help him out of bed. In 1944 he accidentally strangled himself with his contraption (see Friedlander, 1989, pp. 168–69).

not realized until many years after its introduction in 1868. *The Economist* asked rhetorically, "If the internal combustion engine had, from the start, carried its full environmental costs, would the car have ever become so central to the western economies?"[36] Some inventions have effects that were not and could not have been foreseen, as Tenner (1997) has demonstrated.

Much of the resistance by the environmental movement to superfast railroads, nuclear power, and advanced pesticides, for instance, deals with the non-income effects of technological change. Again, such non-pecuniary effects and the probabilities with which they occur are valued differently by different individuals, and thus the outcome that political aggregators determine will differ from the market outcome. As many authors have pointed out, usually the answer to such concerns is more and different useful knowledge. Some believe that more technology will remedy the negative effects of technology (DeGregori, 1985); others believe that this kind of process diverges into some kind of technological hell. The history of technology and the framework developed here suggests that the widening of the epistemic base of technology makes it more likely that such techniques will in fact emerge: bacteria that eat radioactive waste may be developed, and there could be chemical compounds that restore the ozone layer or substances that make farm-grown fish taste natural (to fix the technologically induced depletion of the world's fish stocks). When it was discovered that burning lignite for home heating or using gasoline with lead compounds is harmful to the environment, market economies—in contrast to command economies—were able to find the means to clean up their acts. The critical point is that these means, by and large, required a more, not less, sophisticated technology.

Some modern environmentalists argue that for twentieth- and twenty-first-century techniques such actions will not work and that therefore the externalities of our time are worse than those imposed by technology in the past (McKibben, 1989 pp. 139–54). There is little evidence for this difference. Whether acid rain, ozone depletion, and the greenhouse effect will produce worse externalities than the burning of coal, lignite, and peat in domestic fireplaces, the pollution of medieval drinking water by alemakers and tanners, and the primitive sanitation and water supply of premodern cities is unclear. To be sure, modern environmental problems tend to differ from earlier ones in that their impact is sometimes global rather than local (Lynn, 1989, p. 184). Modern technology, however, not only produced the CFCs that threaten the ozone layer of the atmosphere, but also provided Molina and Rowland with the tools to detect the danger. The increased

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[36] *The Economist*, Sept. 8, 1990, p. 25.

power of technology to cause damage also means increased power to detect and repair it. All the same, a fear of the power of modern technology seems to have influenced a wide array of modern thinkers, to the point where Barry Commoner's widely cited statement that modern technology is an economic success because it is an ecological failure could be taken seriously (Commoner, 1974, p. 174). Indeed, a reading of such writers as Commoner, Ivan Illich, or E. J. Mishan seems to suggest that all, not just modern, technology is bad, not because it uses resources that are not properly paid for but because it manipulates and alters nature, although that is of course precisely what technology is all about.

Underlying much resistance to new technology is the "slippery slope" argument that implicitly relies on the path-dependence of the history of technology. Useful knowledge, like all evolutionary systems, is characterized by the fact that current choices determine future options because of the tendency of new knowledge to emerge from existing knowledge. This possibility occurs when a new technology is initially adopted, but subsequently some new information emerges or some change in preferences occurs that makes people change their minds. The very nature of new technological information is that it is irreversible; once learned, it is difficult if not impossible for society to "unlearn" a new technique, no matter how socially undesirable. This kind of phenomenon might be called the Pandora Effect. Even if society "regrets" its decision to move to T_1 it may not be able to return to T_0. If this process is anticipated, even in probability, at time 0, it is possible that society may decide not to adopt T_1 "so that we do not regret it later." This is especially the case with technology that can be used for both constructive and military purposes, or which are suspected to lend themselves to some form of political or social manipulation. Certain inventions that misfired badly have led to difficult debates such as the current debates on pesticides, cloning, nuclear power, and genetically modified organisms.

Given the path-dependent nature of technological change, it may therefore make sense for a subset of the population to resist a new technology even if it temporarily increases welfare, if there is an expectation that this technology could eventually lead to the development of further technologies that are deemed undesirable.[37] A generalization of the Pandora Effect would be that all might agree to prefer T_1 to T_0 but if T_1 leads in high probability to $T_2 \ldots T_n$ and T_n is less desirable than T_0. Many today

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[37] An example is the campaign conducted by the Foundation on Economic Trends, a Washington lobby headed by Jeremy Rifkin dedicated to fighting the spread of biotechnology. There is no known case of any serious damage caused by modern biotechnology. Yet the fear persists that if these technologies took off, somehow others would emerge that would be extremely harmful.

may believe that we would be better off without knowing how to release nuclear energy, but this option no longer exists. In other words, technological change involves not just a choice between two techniques, but two different technological "trajectories," such as nuclear versus fossil fuel energy or direct versus alternating current. Political action in this case is aimed to persuade the relevant decision-maker that a certain technological avenue is undesirable even if some initial features appear attractive. Thus there is a sense that medical advances that made transplantations possible will eventually lead to markets in organs, or that the ability to identify the gender of fetuses through amniotic fluid tests may eventually lead to selective abortion to achieve gender selection. "Cyberphobia" is in part based on the futuristic fear that impersonal and inhuman machines could eventually govern society, and that the differences between people and machines would eventually become hazy. In vitro fertilization techniques have resulted in a fear of the mechanization of the human reproductive process and fluoridation of drinking water has raised concerns about socialized medicine but also about the power of a state to affect the health of unsuspecting individuals through the control of a network technology such as water supply.[38] The worldwide resistance to the use of genetically modified organisms in agriculture reflects uncertainty about where this might lead. Precisely because so many new technologies ended up being used in different ways than their developers intended and backfired in unexpected ways, there is a common anxiety that by producing new knowledge we may be unleashing, like the Sorcerer's Apprentice, something powerful that we may not be able to control. The concern is that some forms of technological change are likely to lead to a slide into some vaguely perceived but unacceptable future outcome.[39]

Innovation thus imposes risks and much resistance to it by environmentalists is simply a form of risk aversion, or perhaps an aversion to the

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[38] Fluoridation was first introduced in the United States in 1945, but in 1992 only 62 percent of Americans using public water enjoyed its benefits. In Western states, where the aggregator took the form of referenda rather than an imposition by elected representatives, adoption rates were generally lower (2 percent in Nevada, 16 percent in California). This reflects classical Luddite skepticism about "mass medication" but also mistrust of big government. There is no evidence of any negative side effect of fluoridation except a minor discoloration of teeth when the quantities are higher than optimal (see *Scientific American* 274, no. 2 [Feb. 1996], p. 20).

[39] Arnold Toynbee wrote in 1958 that "if a vote could undo all the technological advances of the last three hundred years, many of us would cast that vote in order to safeguard the survival of the human race while we remain in our present state of social and moral backwardness" (cited by Perrin ,1979, pp. 80–81).

unknown.[40] A conspicuous source of resistance is the Natural Resources Defense Council, which argues that if science cannot be certain that a maximum level of a chemical is safe, this level should be set at zero (H. W. Lewis, 1989). The FDA is indirectly responsible for the endless misery of millions of patients by failing to approve the use of new medications under the theory that the risk of unknown side effects has to be minimized at all cost. The risk function is, however, symmetric. Just as sometimes an innovation disappoints or even turns disastrous, at other times the gains are far larger than originally expected, as in the case of antibiotics, the telephone, and the copying machine.[41] The Dalkon shield intrauterine device may have had some negative side effects for a small minority of users, but even radical technophobes will be hard-put to deny the liberating consequences of birth control technology even if it is not yet entirely risk-free.

Perhaps the most enlightening example of the surprises of technology and the disproportionate response to them, especially when the epistemic base is quite narrow, is the strange history of the drug thalidomide (Stephens and Brynner, 2001). When first introduced in the 1950s, it was believed to be free of side effects, although it was not quite clear what its benefits were. It was introduced as a sedative (because the molecular structure was thought to be similar to that of barbiturates), and it was not until its unexpected effect in the deformation of fetuses was established that it was banned. The resistance to its use by the FDA in the United States meant that American women were saved the fate of thousands of European and Canadian mothers and their handicapped babies. The realized fear that "something could always go wrong" and the gruesome images of the deformed babies meant that thalidomide became a politically poisonous substance and the resistance to it grew to dimensions that were disproportionate. As other beneficial qualities of the drug have become apparent (among others, it helps in the treatment of rare forms of leprosy and some forms of cancer) there is renewed pressure to have it reapproved despite the embittered efforts of some victims. The strikingly visual effect of thalidomide children has biased the perceived dangers upward, as psychologists have pointed out (e.g., Slovic, Fischoff, and Lichtenstein, 1982).

In summary, unexpected and unintended consequences and path dependence are legitimate sources of fear and concern. The real historical question is whether such unintended consequences can be so costly and

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[40] This attitude must be the motivation behind the crusade against genetic engineering Rifkin (1985, 1983), arguably a technology that is more likely to improve than to hurt the physical environment of the planet.

[41] In 1959, when the Xerox Corporation introduced its first copier, a consulting company estimated total demand for copiers in the United States at 5,000 machines (see Herman, Ardekani, and Ausubel, 1989, p. 62).

irreversible that no new and better technology can overcome them, with a series of side effects that eventually converge at some tolerable level. In the cases of asbestos and CFCs, this cost may indeed have been quite high, but in the larger picture such cases are the exception, not the rule, and no single unintended system effect has been large enough to reduce the welfare costs of technological progress in the past century.

Religious beliefs can also be behind resistance to or fear of technology. The relation between religion and technology, although complex, suggests the enormous handicaps that technological progress has to overcome in order to succeed. After all, the game of invention itself is the solution to a physical or chemical puzzle of some sort, and thus a game between a person and nature; what he or she believes about the metaphysics of the physical environment is central for any progress to occur. Religious establishments have often sanctified the environmental status quo or conveyed an aura of infallibility upon previous generations. In the final analysis, the act of invention is an act of rebellion, and religion rarely endorses rebellion. In the acquisition of knowledge, it seems, religion is one of the factors that sets the research agenda. To be sure, religion is itself partly endogenous to economic stimuli and incentives, and any crude notions based on the assumption that culture itself is fixed and a literal interpretation of Weber's thesis are unpersuasive (E. L. Jones, 1995, 2002). Yet organized religion and private religious beliefs bias the search for new knowledge in a direction that may affect the accumulation of useful knowledge capable of serving as the epistemic base of new techniques. Cultural beliefs also affect the attitudes toward the cumulative knowledge of previous generations; religion (or the absence of it) often sets the research agendas of learned and inquisitive scholars. Using mathematical skills to apply numerical methods to the interpretation of key words in religious texts to predict the date of the Apocalypse, as Jewish mystical sages tried to do, does not augment useful knowledge by as much as the study of pumps or crop rotations. As Shapin (1996) points out, many of the advances during the sixteenth and seventeenth centuries in western Europe were motivated by religion. It may be true that in early medieval Europe religious organizations—the monasteries—provided an indispensable bridge between those who worked and those who were educated and as such provided the historical roots of subsequent technological developments in Europe.[42] On the whole, however, religion was at least as much a source of resistance as one of inspiration for inventors and innovators. The idea of humanity as a steward

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[42] By far the most interesting work has been done on medieval Europe (see especially Benz, 1966 and White, 1968, 1978). Paradoxically, many modern critics of technology, such as Jacques Ellul, Ivan Illich, and E. F. Schumacher, are influenced by Catholic doctrine.

of nature, caretaker rather than master, implies the basically conservative position that we leave the planet more or less as we have found it. Such a position is inevitably hostile to the irreversible changes of technological progress. Interestingly, such views are often warmed up by modern critics of technology (Rifkin, 1985, p. 108). Islam has often taken a hostile attitude toward technology (Kuran, 1997), and the failure of European Jews over many centuries to contribute to useful knowledge (as defined here) in anything like a proportional amount in view of their literacy and learning remains something of a puzzle.

Above all, technological change may appear directly in people's utility functions. Such a concept may appear bizarre to economists, but not so to sociologists or psychologists.[43] For economists, moreover, it has been deemed traditionally uninteresting to ascribe differences in behavior to different utility functions. Technology is felt by many people to be something profoundly unnatural, as Freud observed when he compared it to an artificial limb (Winner, 1977).[44] One scholar sighs, "We remain, in part, appalled by the consequences of our ingenuity and...try to find security through the shoring up of ancient and irrelevant conventions" (Morison, 1966, p. 43). Technology is regarded as something uncontrollable and incomprehensible and thus somehow evil (Winner, 1977). The depth of this emotion is attested to by such legends as Prometheus and the Golem of Prague. Jacques Ellul, perhaps the most prominent writer in this tradition, speaks of "the autonomy of technique," in which technology is transformed from servant into master, and "technique's own necessities become determinative...[Technique] has become a reality in itself, self-sufficient with its special laws" (Ellul, 1964, p. 134). Less sophisticated modern writers, influenced by these views, have combined them into a radical technophobia in which a concern about putative externalities and a sense of disappointment that economic progress has not brought utopia are mixed with a subconscious suspicion that "modern technologies exist to impose order and mastery" (e.g., Glendinning, 1990, p. 141).

Religion is part of "culture" and the debate over whether culture is an admissible explanans for divergent economic performances in history

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[43] In the psychological literature there is a great deal of emphasis on seemingly "irrational" phenomena such as fear of new technology. Psychological "diagnosis" of "cyberphobia," "technophobia," and even "neophobia" (fear of new things) is common. For a thoughtful debunking of this literature, see Bauer (1995, pp. 87–122).

[44] The director of the agricultural and biotechnology program at the Union of Concerned Scientists summarizes this attitude about genetically modified crops in saying that from a scientific standpoint, there is no dispute that this technique "is fundamentally different from what has been done before, and that it is *unnatural*" (interview in *Scientific American,* April 2001, p. 65, emphasis added).

continues (Temin, 1997). Between those scholars such as Eric Jones (1995) who argue that culture is largely endogenous and adjusts itself to circumstances and those such as David Landes (1998) for whom culture is destiny, there must be some middle ground where the less doctrinaire can shelter safely. An anti-technological and conservative bias can be built into a culture, so that the decision-making institutions become technologically reactionary. In this fashion, the technological status quo does not have to fight battles against hopeful innovators over and over again. This does not mean that it becomes technologically watertight, and even the most conservative cultures in the end had to accept technology that was clearly superior. But the battle was harder, it took longer, the costs were higher, and the techniques that were adopted were often not up to date. This cultural bias can be introduced through an education system that fosters conformist values in which traditions are held up in respect and deviancy and rebellion are made highly risky.[45] In traditional India there was no organization for the propagation or dissemination of knowledge, and an unbridgeable social barrier existed between theorists and craftsmen (see Morris, 1983, p. 563). Jones has argued that the Indian caste system was a deeply conservative and rigidified institution, in which ascriptiveness is pervasive and personal achievement "is excluded in principle." Jones realizes that a caste system, too, could never be an absolute constraint on economic growth, it "may constitute an infuriating brake, yet it will not be able to switch off a motor located somewhere else in society" (1988, pp. 103–06). The argument made here is exactly about such brakes; societies with such brakes would adopt useful knowledge generated elsewhere and develop much slower than those without. These brakes are what Parente and Prescott (2000) call "barriers," and they explain how the effective deployment of techniques can be retarded and blocked even when access to them is easy. Similar mechanisms hold a fortiori for the generation of new knowledge altogether. Such cultural factors need to be substantial to have much explanatory power; attempts to use them to explain differences *within* the West seem to be doomed to use "explanatory sledgehammers to crack rather modest nuts" (James, 1990, p. 124). Culture can be a brake, but cars with their handbrakes on can move, if at a slower speed, and doing so for a prolonged time does wear the brake down. Perhaps that is as much

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[45] Bernard Lewis has pointed out that in the Islamic tradition the term *bidaa* (innovation) eventually acquired a highly negative connotation, much like "heresy" in the West and that such subtle cultural changes account for much of the technological slowdown of the Islamic Middle East after 1400 (1982, pp. 229–30) . This is not to argue that *any* religion is inherently anti-technological, even in a relative sense. Yet there are many subtle ways—of which religion is surely one—in which an entrenched elite can manipulate institutions and culture in order to make any contemplated challenge to their dominance more difficult.

as we will ever be able to say about the deeper cultural roots of economic growth.

Markets or Politics? The Economic History of Resistance

Although the terminology I use here is different, the concept of heterogeneous aggregators is closest to the concepts enunciated by the late Mancur Olson (1982). When and how will opposition to the market as the arbiter of innovations emerge? When a technology has never been tried before and is genuinely novel, there is a serious fear of the unknown, resulting from risk aversion or deeper fears of "devils we do not know." The disagreement about accepting a new technique has various roots, heterogeneous preferences and heterogeneous expectations. If there is a probability that a technique may malfunction or cause damage, people with high risk aversion will resist it. Moreover, precisely because it is new and there are no exact precedents, people can disagree about the magnitude of the probability of a failure, so that even people with the same rate of risk aversion would have different attitudes. In societies that adopt tried technological changes from other countries such fears of the unknown are secondary, and the resistance is more likely to come simply from having observed the negative effects of a new technology elsewhere. But such "learning" effects are relatively rare.[46] More likely are what could be called "correlation effects," that is, a depiction of technology as "packaged" in a cultural-political deal that is undesirable even if the new technology in and of itself is not. This kind of ambiguity flavors much of the political argument in non-Western nations and is often coupled with a cultural suspicion of foreigners. There is a sense that "the magical identity is development = modernization = Westernization." Especially when new technology takes the form of new products, it is often correlated with undesirable cultural and social side effects. A special case of this occurs when new useful knowledge for one reason or another is associated with a particular group that is disliked.[47] Technological progress is associated with powerful groups or political movements from which individuals feel

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[46] The most obvious example is the prohibition of firearms in Tokugawa Japan, where the government was able to eliminate successfully the production and use of muskets in its attempt to retain a monopoly on violence (Perrin, 1979).

[47] The acceptance of quinine in Britain was impeded by the association of the drug with the Jesuits. Oliver Cromwell, who died of a malarial fever, refused to take it because it was a "Jesuit treatment," and Gideon Harvey's *The Family Physician and the House Apothecary* (1667) likewise denounced it as coming from Jesuits. The full acceptance of the drug—the first truly effective chemical pharmaceutic agent—was delayed by half a century by such resistance. This is reminiscent of Adolf Hitler's resistance to nuclear research, which he associated with "Jewish physics."

alienated. Thus, technological resistance against, say, nuclear power, might be viewed as "a blow to big business or big science." Sociological studies suggest, however, that such resistance is fairly rare (Mazur, 1975, p. 62).

All the same, it seems almost too obvious that technological change was correlated with other changes, which were regarded as harmful by some. Some of the historical suspicion of new technology was related to its association with commercialization. Most technological change affects the proportion of total output that goes through the market. The Green Revolution, with its heavy reliance on purchased inputs (seeds, fertilizers, pesticides), has increased commercialization. Consequently, some have raised serious objections to the alleged disruptions and violence caused by market penetration in self-sufficient small communities, causing the "depeasantization of the peasantry" (Shiva, 1991, pp. 177, 190). In principle, however, technological progress can be either market-enhancing or market-curtailing. On balance, it probably has been favorable to commercialization: market penetration was inhibited first and foremost by the costs of transportation and communication, which fell over time largely because of advances in useful knowledge. On the other hand, many of the household appliances developed during the twentieth century led to home production of cleaning and cooking services that previously were carried out by hired household labor. Another correlation effect is the fear that the new technology will lead to rationalization and secularization, undermining the power of religion and "traditional values." In Europe around 1900, anti-modernist schools of thoughts opposed the stock exchange, vaccination, heavier-than-air flight, the global economy, and positivistic science for causing a "decline of the soul." It is easy, perhaps, to dismiss such thinkers as fringe crackpots, but their writing filtered down, second and third hand, to the young Adolf Hitler and similarly inclined extremists (see, e.g., Fest, 1973, pp. 89–106).

However, self-interest counts too. Economists have used the term "rent-seeking" for the replacement of market decisions by government control or some other form of collective decision-making that benefits a small group or an individual. It is natural to expand the standard definition of rent-seeking to include "loss-avoidance." Technological progress inevitably involves losers, and these losers—as in free trade—tend to be concentrated and usually find it easy to organize. The potential gains, on the other hand, are diffuse and tend to accrue largely to dispersed consumers or lonely inventors, unfamiliar with the political arena. The political economy of technological change thus predicts that it will be resisted by well-organized lobbies, whereas its defenders will usually be a motley group of consumers and inventors and perhaps a few groups with a direct interest in economic growth. The struggle between the two parties will always take the form of a non-market process, because relying on market forces alone would, by definition, lead to the triumph of the new technology. Because non-market conflicts over technology vary enormously in their nature, there is no way to predict their outcome. However, such struggles eventually end in the victory of conservative forces and terminate progress if the winners can then change the decision rule in favor of conservatism to cement the status quo.

Historically, much of the resistance to new technological change had economic reasons: potential losers set up obstacles to obstruct innovation. To start with, assume simply that all utility functions contain only income as an argument, and that the only effect of the transition to the new technique is to increase total income so that the gains of the winners exceed the losses of the losers. This means that the invention is socially preferable, but the potential for conflict is only resolved if the gainers use part of their augmented incomes to compensate the losers. Compensation would seem at first glance a reasonable way to resolve the problem but in fact rarely occurs directly because of the formidable problems of identifying the losers, measuring the dimensions of their loss, and overcoming the problems of moral hazard among losers as well as collective action among gainers. Moreover, it is hard for a potential gainer to make a credible commitment to compensate the losers, because by definition the game of introducing a specific innovation and eliminating the vested interest is played only once.[48] Still, compensation of losers in a wider sense has occurred. The farm support and welfare systems in modern Western economies could be interpreted at least in part as mechanisms designed to compensate and placate groups that ended up at the short end of the stick in rapid industrialization and subsequent de-industrialization. If compensation does not occur, the losers will have an interest in banding together to try to change the social decision rule from G_M to a rule that is more favorable to them. The way for them to do this is to circumvent the market, in our terms by reducing α, and then try to affect the aggregator G_D and/or G_V by political action. The main question is why for some individuals technological change is income- or utility-reducing. Below, I provide a detailed typology of some of the more obvious sources of purely rational resistance to innovation.

Unemployment. One obvious source of resistance to innovation is the belief, widely held since Ricardo's famous chapter 31 "On Machinery" in his *Principles of Political Economy,* that labor-saving technological change

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[48] Paying the losers up-front, before the innovation is introduced is unlikely, because if the adoption of the new technique is associated with a shift in political power as well, any lump-sum compensation can be taxed away in the future (Parente and Prescott 2000, p. 128).

reduces the demand for undifferentiated labor, thus leading to unemployment and a possible decline in wages. As economists have long understood, this statement in and of itself cannot be accepted without working through the general equilibrium properties of an exogenous change in the production function. An invention that replaces workers with machines will have effects on all product and factor markets. An increase in the efficiency of production that reduces the price of one good will increase real income and thus increase demand for other goods; the replaced workers may find employment in other industries, and their real wages may go up or down. In an abstract world, without adjustment costs, in which all workers and productive assets can be costlessly converted from one use to another, there is no a priori expectation that changes in production technology will necessarily reduce labor income and employment. In the real world, of course, temporary disequilibria can cause hardship for large subgroups of the population. Yet in some of the most widely studied instances, the feared patterns of technological unemployment did not materialize. Notwithstanding a long and intricate national debate over the "machinery question" raised by Ricardo, nineteenth-century Britain did not suffer from a secular increase in structural employment feared by Ricardo and the Luddites alike.[49] In a very different environment, it was widely feared that the mechanization of agriculture in Asia in the 1970s would lead to widespread rural unemployment; this did not occur (Campbell, 1990, p. 26). Recent studies by labor economists find that the introduction of new technology is on balance associated with positive job growth. One such study flatly declares that "job growth and the introduction of new technology appear to be complements rather than substitutes. The Luddites were wrong" (Blanchflower and Burgess, 1995, p. 18). The danger here is one of overaggregation: it is likely that compensating fluctuations in labor demand in different sectors will spawn substantial resentment even if total demand for labor is unchanged. The cost of making the transition is often non-negligible, and workers are likely to

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[49] As Berg has noted (1980, p. 67), Ricardo did not imply that technological unemployment was inevitable. It did not occur because machines substituted for labor, but only because they reduced the stock of "circulating capital." It would thus only occur when a country's capital stock was very small and where the construction of machinery demanded a "strong switch to fixed capital" —hardly a description of nineteenth-century Britain (see also Hicks, 1969, pp. 148–54, 168–71). None of the theoretical demonstrations that in certain unlikely configurations some (temporary) unemployment can be caused by the introduction of "machinery" is tantamount to a demonstration that such technological unemployment actually occurred on a large scale. It is telling that working-class leaders resisted the machine because of the economic distress it caused, such as "technological unemployment, long hours of alienated factory labour, and the smoking blight of rapidly expanding industrial towns" (Berg, 1980, p. 17)—the former clearly being contradicted by the latter two.

observe the decline in their own sector before they perceive better opportunities elsewhere.

Capital losses. A different problem occurs when physical capital is of a "putty-clay" variety; once shaped, it is difficult to convert to another use. This can be seen in a simple vintage model in which one product is produced by machines of different efficiency. The lowest-ranked machine earns a rent of zero; all other machines earn a rent that is proportional to the difference between the production cost of the least efficient machine in use and their own. The value of the asset can thus be determined by the standard formulas, in which the value of the asset is a function of this difference and expected future technological depreciation. A rise in the rate of technological change will reduce the market value of existing machines of older vintage, and thus it might be expected that the owners will find a way to avert it if they can.

Yet in practice this happens rarely. The cases in which the owners of physical capital have fought against the introduction of new techniques are comparatively few. The reason must be that while the physical qualities of machines can only rarely be altered, capital goods—including ownership in patents—can be bought and sold.[50] Thus the owner of machines that become obsolete will take a loss on those machines, but he can always buy into the new technology by purchasing new machines that yield higher profits through lower costs. This explains, for instance, the relatively weak resistance to the introduction of steam engines despite the huge locational rents that were being secured by the owners of water mill sites. Industrialists using water power might have been losing when their mills fell into disuse, but they could make up for those losses by buying into steam technology themselves, which is precisely what happened in Lancashire during the British Industrial Revolution. In those cases in which capital markets favored some existing producers over others, however, this principle is violated and resistance is to be expected.[51]

Non-pecuniary losses. Another source of resistance to technological change is that it changes not just the level of average costs, but the overall shape of the cost function. While new technology thus reduces overall costs and increases efficiency, it may also change the minimum efficient size of

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[50] It is critical for this argument that patents do not exclude existing producers from licensing patents or having them assigned. When this happens, it is likely that existing producers will not be able to jump on the new bandwagon. For a survey of how common patent licensing and assignment already was in nineteenth-century America, see Lamoreaux and Sokoloff (1996).

[51] For instance, Norwegian fishermen in the eighteenth century resisted a new technique of multiple lines, which enhanced productivity but whose use was "confined to relatively well-off fishermen who could afford to invest in extra equipment and suitable boats" (Bruland, 1995, p. 131).

the firm and the conditions of entry into the industry. Thus when the minimum efficient size of firms in the textile industry was increased during the first Industrial Revolution, artisans and small domestic producers were effectively driven out of the industry. In a world without transactions- and information costs and hence "perfect" capital markets, the costs of these changes would be mitigated by small producers combining into large firms and exploiting some of the economies of scale. This did occur during the British Industrial Revolution at a larger scale than is usually appreciated.[52] All the same, during the British Industrial Revolution even before the famous Luddite and Captain Swing disturbances, there were some riots by artisans and self-employed producers threatened by factories (Randall, 1991). There was considerable resistance to factory work, with its discipline and rigidity, its physical environment, and its dramatic impact on family and community.

Workers, moreover, care about such non-pecuniary characteristics of the workplace from safety and noise on the shop floor to job satisfaction and decision-making authority. If new technology affects these characteristics negatively, workers will resist unless they can be bought off by employers through fully compensating wage increases or unless they can find new jobs similar to their old ones at zero cost to themselves. During the Industrial Revolution, a particular bone of contention was the attempt by employers to standardize products and reduce the leeway that artisans and domestic workers had in setting the parameters of the product. When the advantages of product standardization led to lower tolerance boundaries on the characteristics of output, from cotton cloth to musket balls, repeated attempts to enforce such standards ran into determined opposition (Alder, 1997, chs. 4–5). Beyond that, technological change affects the regional distribution of production and employment, thus forcing workers to move from one region to another or from a rural to an urban area. New technology is often felt to destroy traditional communities. For some members of those communities that counts for little, whereas others care about it a great deal; thus any kind of aggregator will lead almost inevitably to some subset of the population being dissatisfied.

Human capital. The opportunities for conflict are much wider when we consider human capital.[53] Skills and experience are acquired over a

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[52] In other societies, too, such workshops occurred early on in the industrialization process. In India, in industries such as cotton ginning, rice polishing, and flour milling, entrepreneurs often just provided the machines and their maintenance and charged a fee for processing from the workers (see Morris, 1983, p. 675).

[53] In a formal analysis of the emergence of resistance among skilled workers, Krusell and Ríos-Rull ingeniously capture an example of this kind of problem. They model an economy in which all capital is technology-specific human capital and show that older workers who have

lifetime, but the ability to learn new skills declines over the life cycle.[54] Workers beyond the student or apprentice stage can be expected to resist new techniques insofar as innovation makes their skills obsolete and thus irreversibly reduces their expected lifetime earnings. The new technology may be inaccessible to them for more reason than one; factories require a willingness to submit to discipline and hierarchy that independent artisans were too proud to submit to. It is of little consolation to an older generation that their children may have no difficulty adjusting to the new regime, mastering the new technique, and thus improving their material standard of living. The truth that Max Planck discovered for science holds just as much for radical new techniques: "A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it"(1949, pp. 33–34).[55] Again, the example of the British Industrial Revolution illustrates this point vividly. As the old domestic industries came increasingly under pressure from the more efficient factories, the older artisans by and large refrained from seeking employment in them; the reliance of factories on child and teenage labor was motivated by the ability of youths to learn the skills and adopt the docility required for the factory environment.[56] Some new technology was in fact deliberately designed to exclude males and favor women and children, as was the case in the early factories of the Industrial Revolution (Berg, 1994b; Tuttle, 1999).

Other rents. The protection of skills and specific human capital is often combined with other forms of rent-seeking through the creation of barriers to entry and the control of output. This is clearly a widespread interpretation of the European craft guild system which ruled urban

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invested in a skill that is specific to a technology threatened by obsolescence can be modeled as a "vested interest" for whom it is optimal to try to block the new technology (see Krusell and Ríos-Rull, 1996). For an analysis along similar lines and the important constraint on the effectiveness of such resistance by the openness of the economy, see Holmes and Schmitz (1995).

[54] As *The Economist* put it, "What grown-up who spent years of childhood learning to tie shoes, to count to ten, to parse Greek or to find triple integrals does not now sigh at having to lipread the baffling instructions for a video recorder or for Windows 95? Almost every generation gets overtaken in some department of knowledge as new discoveries and unfamiliar technologies replace yesterday's learning" (see "Cranks and Proud of It," *The Economist*, Jan. 20, 1996, pp. 86–87).

[55] Lavoisier, more than a century earlier, wrote in his *Reflections on Phlogiston,* "I do not expect my ideas to be adopted all at once. The human mind gets creased into a way of doing things...it is the passage of time, therefore, which must confirm or destroy the opinions I have presented. Meanwhile I observe with great satisfaction that the young people are beginning to study the science without prejudice" (cited by Gillispie, 1960, p. 232).

[56] The best discussion of this issue is still Pollard (1965, pp. 213–25). See also Redford ([1926] 1976); for a restatement see Lyons (1989).

artisans in many areas for many centuries. In pre-modern urban Europe these guilds enforced and eventually froze the technological status quo.[57] Similar phenomena, mutatis mutandis, occurred in China.[58] It is important to stress that many of those guilds were originally set up to fulfill different functions, acting as clearing houses for information, organizational devices to coordinate training and quality control, mutual insurance support organizations, and sincere attempts to prevent opportunism and free riding on others' reputations. Yet over time many of them degenerated into technologically conservative bodies.[59]

In most of Europe, then, craft guilds eventually became responsible for a level of regulation that stifled competition and innovation. They did this by laying down meticulous rules about three elements of production that we might term "the three p's": prices, procedures, and participation. As guilds gained in political power, their efforts to weaken market forces as aggregators tended increasingly to freeze technology in its tracks. The regulation of prices was inimical to technological progress because process innovation by definition reduces costs, and the way the inventor makes his profits is by underselling his competitors. Regulating prices might still have allowed some technological progress because innovators could have realized increased profits if their costs were lower even if they could not undersell their competitors. To prevent this, procedures stipulated precisely how a product was supposed to be made, and such technical codes, while originally designed to deal with legitimate concerns such as quality,

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[57] Herman Kellenbenz, for example, states that "guilds defended the interests of their members against outsiders, and these included the inventors who, with their new equipment and techniques, threatened to disturb their members' economic status. They were just against progress" (1974, p. 243). Much earlier Pirenne pointed out that "the essential aim [of the craft guild] was to protect the artisan, not only from external competition, but also from the competition of his fellow-members." The consequence was "the destruction of all initiative. No one was permitted to harm others by methods which enabled him to produce more quickly and more cheaply than they. Technical progress took on the appearance of disloyalty" (1936, pp. 185–86). For a similar description of the Italian guilds, see Cipolla (1968). An eighteenth-century guild in Prussia went so far as to issue an ordinance laying down that no artisan "shall conceive, invent, or use anything new" (Behrens, 1977, p. 596).

[58] See Olson (1982, p. 150), and Mokyr (1990, pp. 232–33).

[59] S. R. Epstein (1998) has defended the technological role of craft guilds, pointing out that they fulfilled an important role in the dissemination and intergenerational transmission of technical information. There is no contradiction between such a role and the inherently conservative role played by craft guilds. More controversial is his claim that guilds provided a cloak of secrecy that worked as a protection of the property rights for inventors. Even if such a system could be demonstrated to have existed, most authorities agree that eventually much of the guild system was overtaken by technologically reactionary forces which, instead of protecting innovators, threatened them. An extreme example is the printers' guild, one of the most powerful and conservative guilds in Europe, which steadfastly resisted any innovation and as late as 1772 legally restrained one of its members from building an improved press (cf. Audin, 1979, p. 658).

eventually caused production methods to ossify. Enforcing these procedures, however, was far more difficult than enforcing preset prices. In the long run perhaps the most effective brake on innovation was participation: by limiting and controlling the number of entrants into crafts, and by forcing them to spend many years in apprenticeship and journeymanship, guild members infused them with the conventions of the technological status quo and essentially cut off the flow of fresh ideas and the cross-fertilization between branches of knowledge that so often is the taproot of technological change.[60] One especially pernicious custom was the rigid division of labor between craft guilds so that each guild was confined to its designated occupation, a practice that required from time to time royal intervention to prevent egregious abuses.[61] Exclusion of innovators by guilds did not end with the Middle Ages or even the Industrial Revolution. In 1855 the Viennese guild of cabinetmakers filed a suit against Michael Thonet, who had invented a revolutionary process for making bentwood furniture. The *Tischlermeister* claimed that the inventor was not a registered cabinetmaker. The suit was dismissed when the court made his workshop an "Imperial privileged factory" (Lang, 1987).[62]

The weak position of the guilds in Britain in the eighteenth century can go some way in explaining the series of technological successes we usually refer to as the British Industrial Revolution and why it occurred in Britain rather than on the European continent, although clearly this was only one of many variables at work. In the century before the Industrial Revolution, inventions perceived to be labor-saving were almost guaranteed to run into opposition. The question is whether the opposition would succeed. In Britain, on the whole, it did not. William Lee, the inventor of the stocking frame, left for France, but after the death of King Henry IV the frame industry spread gradually but inexorably in Britain. The ribbon loom (invented in 1604) was restricted by the Dutch Estates General and was introduced in England in 1616. Resistance flared up there as well, but received no support from the authorities and remained ineffective. Wadsworth and Mann concluded in their classic study that "there is a striking contrast between the unhampered progress of the invention in

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[60] The custom of confining the intergenerational transmission of skills to kinship was also restrictive. In some industries, particularly in ironmaking, skills were the traditional realm of dynasties in which technological knowledge was kept as much as possible within the family (see Evans and Rydén, 1998).

[61] Thus in the 1560s, three Parisian coppersmiths invented improved *morions* (military helmets), but were prevented from producing them because the armorers held the exclusive rights to defensive weapons. In this case they were overruled by King Charles IX (cf. Heller, 1996, pp. 95–96).

[62] I am indebted to Professor Martin Pesendorfer for this information.

Lancashire and the resistance it was encountering in the older urban communities of the Continent in which the influence of the gilds and the decrees of responsive...authorities were powerful enough to prevent, as they were not in England, the adoption of labour-saving machinery" (1931, p. 104). The differences were differences of degree: not all prohibitions on the continent were effective, and in Britain the picture was far from homogeneous. The one industry in Britain that fell behind technologically even during its era of industrial triumph in the first half of the nineteenth century was watchmaking, where both labor and entrepreneurs resisted innovation (Landes, 1983, pp. 300–301). Resistance was not confined to manufacturing; when large department stores were introduced into Germany following the French model of retailing technology in the later nineteenth century, small shopkeepers banded together and were able to convince the major states in Germany to pass a special tax on large stores to protect the small merchants from the threat of modernization (Lohmeier, 1995, ch. 2). In Japan, as late as the 1990s, physicians with remunerative abortion practices resisted the introduction of oral contraceptives (Perutz, 1992).

Perhaps the arena in which the largest number of technological battles have been fought since the Industrial Revolution is in free trade. Tariff protection for domestic industries often was motivated by the need for the defense of obsolete technology. While the battles against free trade and technological progress by no means coincide, they overlap considerably, and free trade and an open economy are by far the best guarantees that an economy will be induced to employ best-practice techniques, just as protection is the best way of keeping out threatening foreign techniques. However, free trade was hardly a necessary condition for technological progress: Britain remained a protectionist country until the 1840s, and the United States followed highly protectionist policies in the last third of the nineteenth century, yet both were highly open to innovation.[63]

In the past century, resistance to new production technology has come in part from labor unions. There is no compelling reason why labor unions must always resist technological change: after all, as "encompassing organizations" they ought also to be aware of the undeniable benefits that new technology brings to their members qua consumers (Booth, Melling and Dartmann, 1997). The growth of the labor movement's power in Britain is often held responsible for the declining technological dynamism of post-Victorian Britain. Resistance by organized labor slowed down techno-

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[63] The strong connection between openness and economic growth was demonstrated by Sachs and Warner (1995). Oddly they neglected the *technological* implications of the open economy in their list of links between openness and more rapid economic growth.

logical progress in mining, shipbuilding and cotton weaving.[64] Such resistance was not a hundred percent effective, but Industrial Revolution may have "reinforced the increasingly apathetic attitude of employers toward technological change" (Coleman and MacLeod. 1986, p. 606). In printing, London's notorious Fleet Street earned a reputation for stormy industrial relations, where management's major preoccupation was with avoiding disruptions to production, even at the expense of high unit labor costs and restrictions on technological innovation (Martin, 1995, p. 194). The crisis in the Bombay cotton industry in the 1920s and 1930s, when Bombay lost much of its market share to other areas, is attributed to the militancy with which Bombay trade unions fought against a technical and administrative rationalization of cotton mill practices (Morris, 1983, pp. 622–23). Susan Wolcott (1994) has documented in detail how Indian workers were able to successfully block the implementation of larger spindles in the cotton spinning industry, not only in Bombay but in Ahmedabad and Sholapur as well. Her argument that Indian workers had a bigger stake in blocking labor-saving machinery because they tended to be male breadwinners whereas Japanese textile workers were young women who only worked for a few years before leaving the labor force again is interesting, but does not wholly explain why the Indian workers' demands succeeded.

In our own time, labor unions have been held responsible for impeding technological progress in many industries. In the European and American auto industry, for instance, they have resisted the closing of outdated plants and the introduction of the flexible work practices that have increased the efficiency of Japanese car manufacturers (Holmes and Schmitz, 1995; Kenney and Florida, 1993, p. 315).[65] Needless to say, not all unions have taken a consistently conservative stance against new technology: in post-1945 Sweden and Germany, for example, unions were induced to join coalitions aimed at increasing productivity. These unions were large and encompassing groups, and their membership benefited enough from technological progress for the benefits to outweigh the costs.

To summarize, then, resistance to technological change derives from two sources that aid and abet each other, though they can exist independently. One is the economic and political interest of the technological status

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[64] On the cotton industry, see especially Lazonick (1990, pp. 78–114).

[65] When the distinction between management and labor becomes fuzzy with worker participation in management, technological breakthroughs may encounter less resistance. When United Airlines became employee-owned in the 1990s, workers devised a simple way to use electricity to power idling planes instead of jet fuel, saving the company a reported $20 million a year. The executive in charge of the matter remarked, "In the past we would just have sent out an edict and nothing would have happened" ("United We Own," *Business Week*, March 18, 1996, pp. 96–100).

quo. The other is the resistance of intellectuals, who, for one reason or another, are genuinely and sincerely fearful of technology. Though at times the intellectuals' sincerity may be in doubt, it is reasonable to distinguish between these selfish and selfless currents in technophobic responses. Whatever its motives, the resistance to technological change has to rely on non-market forces, above all the control of political power. Its precise form and the arena in which the battles between progress and reaction are fought vary a lot: some of them are within the law, such as tariff legislation, institutions designed ostensibly to protect consumers (e.g., the FDA or the EPA), exclusive professional associations and guilds, restrictive union contracts, and outright prohibitions on certain technologies. Others exploit social norms and cultural taboos, such as "not invented here" and "if God had meant us to fly he would have given us wings" mentalities. At times resistance has had an extralegal nature: machine-breaking riots, animal-rights demonstrations, and personal violence against innovators.

Political Economy and the Industrial Revolution

The Industrial Revolution was a western European phenomenon, not a purely British one (see ch. 2). The knowledge base on which the techniques rested was to a considerable part imported, and many of the putative advantages that Britain enjoyed over its rivals seem to have melted away over the course of the nineteenth century as its continental competitors caught up. The unusual success of the Industrial Revolution in Britain between 1760 and 1830 was a function of its political structure. This argument is not new. The typical story focuses on credible commitments to mutually beneficial compromises and cautious fiscal policies, property rights enforcement, and the rise of a powerful monied elite with a materialist outlook on life (North and Weingast, 1989; Perkin, 1969). Parliament's mostly mercantilist legislation after 1660 has been argued to have had favorable spillover effects on the cotton industry, especially in its support of the fustian industry (O'Brien, Griffiths, and Hunt, 1991).

What needs emphasis is that in addition Britain was unusually unreceptive to the conservative political forces that tried to oppose new knowledge and technological progress. The British government was by and large unsupportive of the attempts to slow the Industrial Revolution down. When technologically reactionary forces then resorted to extralegal means, the government brought all its power to bear on them. Moreover, the geographic decentralization of power in Britain meant that even if there were regions within Britain where resistance to technological change was effective locally, innovative entrepreneurs would simply migrate to places where they were more welcome. In the decades after 1850, when technologically conservative forces realized that they could not control the government directly, they found roundabout but eventually equally effective ways in which novel technologies could be slowed down if not blocked. Their ultimate success, though never absolute, nonetheless contributed to the loss—in the long run—of British technological leadership.

The evidence about the resistance to technological progress tends to suffer from a classic identification problem. There were violent responses to technological innovations during the Industrial Revolution in Britain. Yet riots and political agitation against new machines were rampant precisely because they were in the final analysis impotent. The technological innovations could not be stopped. Conversely, when resistance is truly effective, it may be not be observed directly, because would-be innovators anticipate it in advance and either choose another activity or try out their new techniques in a more tolerant environment.

More specifically, a "high" level of rioting is in and of itself not sufficient evidence that Luddites were effective in preventing technological progress. On the one hand, the level of rioting is positively related to the level of innovation, all other things equal, simply because social disruption is a function of change. On the other hand, a high level of rioting itself prevents further technological progress by intimidating would-be innovators. The interplay of these factors is sketched in figure 5. The curve *LL* is the Luddism effect and simply relates the level of resistance associated with each level of innovation. The curve *DD* is the discouragement effect and is downward sloping. At the intersection of the two, E_0, an equilibrium of sorts occurs in that the levels of resistance and innovation are mutually consistent.

In a correct analysis of the interplay of resistance and innovation, the outcome is determined by the exogenous variables that underlie the location of the curves *L* and *D*. For example, if potential innovators have increased confidence in the support of the authorities and their ability to maintain law and order, the curve *D* will shift to the right to *D'*, at which both technological change and rioting are higher (E_2). Or, if the existing organization of production becomes more vulnerable to changes or lends itself well to resistance, the *LL* curve would be higher and we would observe a point like E_3 with low innovation.

Resistance to the new machines came primarily from entrenched vested interests threatened by new technologies. These included artisans, skilled domestic workers and outworkers, and to some extent rural laborers. Calhoun argues that in the early stages of the Industrial Revolution "workers were not fighting for control of the industrial revolution as much as against that revolution itself" (1982, p. 55).

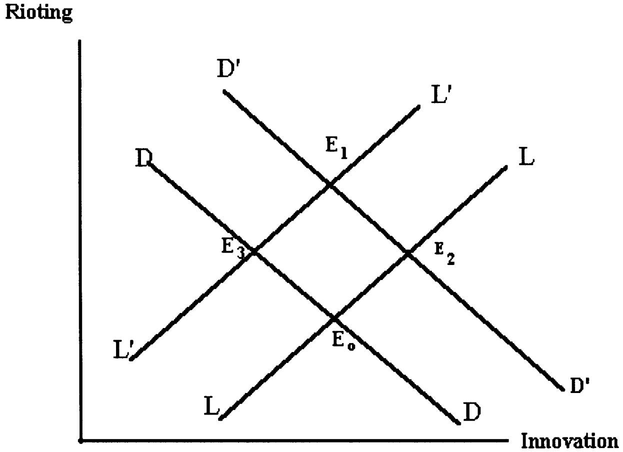

Figure 5: Luddism and Innovation

Calhoun's list of grievances of these workers includes some unlikely items such as a "complete subjugation of consumers and producers to market forces" and "distance between the worker and the market." Artisans who could not or would not join the factories and could not beat them in the marketplace resorted to radical political activity. The remarkable thing is not that the resistance occurred but that it was by and large ineffective in halting the Industrial Revolution.

In the textile industries, by far the most resistance occurred in the woollen industries. Cotton was still a relatively small industry on the eve of the Industrial Revolution and had weakly entrenched power groups. There were some riots in Lancashire in 1779 and 1792, and a Manchester firm that pioneered a power loom was burned down. Yet cotton was unstoppable and it must have seemed that way to contemporaries. Wool, however, was initially far larger and had an ancient tradition of professional organization and regulation. Laborers in the wool trades tried to use the political establishment for the purpose of stopping the new machines. In 1776 workers petitioned the House of Commons to suppress the jennies that threatened the livelihood of the industrious poor, as they put it. Time and again, groups and lobbies asked Parliament to enforce old regulations or to introduce new legislation that would hinder the machinery. Parliament refused. The old laws regulating the employment practices in the woollen industry were repealed in 1809, and the 250-year-old Statute of Artificers was repealed in 1814. Lacking political support in London, the woolworkers tried extralegal means. In the west of England the new machines were met in most places by violent crowds protesting against jennies, flying shuttles, gig mills, and scribbling machines (Randall, 1986; 1989). Moreover, in these areas magistrates were persuaded by fear or propaganda that the machine breakers were in the right. The tradition of violence in the west of England deterred all but the most determined innovators. Worker resistance was responsible for the slow growth and depression of the industry rather than the reverse (Randall, 1989). As a result, the region lost its supremacy to Yorkshire. Resistance in Yorkshire was not negligible either, but that is to be expected in a region that finds itself on a point like E_2.

Resistance appeared in other industries too, sometimes from unexpected corners. When Samuel Clegg and Frederick Windsor proposed a central gas distribution plan for London, they were attacked by a coalition that included the eminent scientist Humphry Davy, the novelist Walter Scott, the cartoonist George Cruickshank, insurance companies, and the aging James Watt (Stern, 1937).[66] The steam engine was resisted in urban areas for fear of "smoky nuisances," and resistance to railroads was rampant in their first years. Mechanical sawmills, widely used on the continent, were virtually absent from Britain until the nineteenth century.[67] Even in medical technology, where the social benefits were most widely diffused, the status quo tried to resist. When Edward Jenner applied to the Royal Society to present his findings, he was told "not to risk his reputation by presenting to this learned body anything which appeared so much at variance with established knowledge and withal so incredible" (Keele, 1961, p. 94).[68] In medical technology, in general, resistance tended to be particularly fierce because many of the breakthroughs after 1800 were inconsistent with accepted doctrine and rendered everything that medical professionals had

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[66] In 1819, an article in the *New Times* listed no fewer than seven reasons why street lighting was objectionable, and concluded, "Let us be careful to preserve the empire of darkness." Compare this with modern objections to light pollution, such as can be found on the various websites linked to http://astronomylinks.com/light_pollution/.

[67] The resistance to sawmills is a good example of attempts to use both legal and illegal means. It was widely believed in the eighteenth century that sawmills, like gigmills, were illegal, although there is no evidence to demonstrate this. When a wind-powered sawmill was constructed at Limehouse (on the Thames, near London) in 1768, it was damaged by a mob of sawyers "on the pretence that it deprived many workmen of employment" (Cooney, 1991).

[68] Jenner's discovery of the smallpox vaccine ran into the opposition of inoculators concerned about losing their lucrative trade (Hopkins, 1983, p. 83). The source of the vaccine, infected animals, was a novelty and led to resistance in and of itself: Clergy objected to the technique because of the "iniquity of transferring disease from the beasts of the field to Man" (Cartwright, 1977, p. 86). Cartoonists depicted people acquiring bovine traits, and one woman complained that after her daughter was vaccinated she coughed like a cow and grew hairy (Hopkins, 1983, p. 84). Despite all this, of course, the smallpox vaccine was one of the most successful macroinventions of the time, and its inventor became an international celebrity.

laboriously learned null and void. Even such a seemingly enormously beneficial and harmless invention as anesthesia was objected to on a host of philosophical grounds (Youngson, 1979, pp. 95–105; 190–98). Many of these innovations, moreover, were founded on narrow epistemic bases, and it was not clear how and why they did what they did. This made objecting to them all the more tempting and persuasive.

The two most famous cases of technology-related rioting in Britain are the Luddite riots between 1811 and 1816, and the Captain Swing riots of 1830–32. In both cases the riots were partially caused by technological innovation. To be sure, in Nottingham, where the Luddite troubles started, there had been no technological change in the stocking frames, and the anger of workmen was directed against low wages, work practices, and similar issues. When the riots spread to Yorkshire, however, the finishers ("croppers") in the wool trade were directly motivated by the introduction of gig mills, shearing machines, and other machinery used in the finishing trades. The Yorkshire croppers were well organized, and their main organization, "the Institution," was small and highly effective (Thomis, 1972 pp. 48–57). Their abortive attack on an advanced and mechanized mill at Rawfolds has become famous in the literature through its depiction in Charlotte Brontë's *Shirley* (Thomis, 1972; Thompson, 1963, pp. 559–65). In Lancashire, on the other hand, machine-breaking during the Luddite riots occurred largely because they were a convenient target, not because of any deeply felt anti-technological feeling.

The Captain Swing riots were aimed against the steam threshers. They bore some resemblance to the Luddite riots a decade and a half earlier in that the resentment against machinery was aggravated by short-run fluctuations in the economy, and that the anger against new machinery was compounded by other grievances. The Swing riots were aimed in part against Irish migrant workers (Stevenson, 1979, p. 243). Yet they stand out because they were the only antitechnological movement in Britain, legal or extralegal, that was successful in slowing down the adoption of the technology. The steam thresher against which they were aimed vanished from southern England until the 1850s. The resistance to the machines was shared by some farmers and gentry. It was the first successful act of Luddism in Britain, and it is perhaps symbolic that it occurred in the year typically (and arbitrarily) designated as the last year of the period known as the Industrial Revolution (Hobsbawm and Rudé, 1973, pp. 256–59, 317–23). The history of machine breaking and violence against innovators is of course a complex story, and not all cases of rioting were necessarily a response to technological change (Bohstedt, 1983, pp. 210–21). Moreover, machine breaking and rioting was just one of the ways in which resistance to technological change could manifest itself.

Despite the resistance, in the crucial years of the British Industrial Revolution the new technologies won, and won easily, primarily because the government took a firm position in their support. Without the support of the central and local authorities, the forces of technological reaction were deprived of the most effective means of resistance against new technologies: prohibitive legislation. When violence was resorted to, the government sent soldiers, who smothered the rebellions in a wave of executions and deportations and did all they could to prevent the organization of groups that could be hostile to the emerging industrial class. Earlier British governments had not been so accommodating, but the power structure that emerged in the decades before the Industrial Revolution was increasingly friendly to the new technologies. Combination Acts made attempts of workers to band together against the new technology illegal. In the fateful year of 1769, the same in which Watt and Arkwright took out their great patents, Parliament made the tampering with the bridges and engines employed in mines a capital offense. As Mantoux ([1905] 1961, p. 464) put it, laissez-faire proved irresistible because it was supported by theory and practice walking hand in hand. The famous story about the inventor of the flying shuttle, John Kay, having to flee to France to escape the wrath of workers fearing for their livelihood, is apocryphal.[69] A resolution passed by the justices of the peace in Preston in 1779 fully summarizes the position of the British authorities:

> Resolved that the sole cause of great riots was the new machines employed in the cotton manufacture; that the country notwithstanding has greatly benefited by their erection; that destroying them in this country would only be the means of transferring them to another country, and that, if a total stop were put by the legislature to their erection in Britain, it would only tend to their establishment in foreign countries, to the detriment of the trade of Britain. (Cited in Mantoux, [1905] 1961, p. 403).

The true motivation of the British elite probably had a more selfish cause. The Industrial Revolution in its first stages benefited the landlords as much as the industrialists, without making them assume many risks. At least until

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[69] There was some mob action when the first shuttles were introduced, and a few houses that used them were burned down. Yet notwithstanding these threats, the weavers, "being sensible of the Benefit which would arise to them if they could manufacture their goods upon easier terms than their neighbours," adopted them rapidly (Wadsworth and Mann, 1931, p. 457). Kay's subsequent exile to France was caused by financial difficulties.

the election reform of 1867 it represented no serious threat to their grip on power. The technological changes led to a sharp rise in real estate values throughout the industrializing regions and mining areas, and with the exception of the debate over the Corn Laws (which the landed interests won, if only temporarily in 1815) there was little conflict between landed interests and the economic interests created by the Industrial Revolution.

A second reason for the failure of the resistance to technological change was its lack of unity. The activities of radical technophobic groups were largely localized and community-based. Moreover, although the Industrial Revolution destroyed the economic basis of artisans and domestic workers, it did so piecemeal. Indeed, at different stages, mechanization favored some traditional workers. The factories increased demand for some domestic industries, as was the case during the "golden age" of the handloom weavers before 1815. The assault on traditional technology was thus staggered, and consequently the defense was divided and ineffective.

Was resistance more successful on the continent? If it was, we would have another entry in the catalog of explanations of "why was Britain first." Conclusive evidence on this point is hard to produce, especially because of the many political upheavals the continent experienced before and during the Industrial Revolution. It is often difficult to attribute worker unrest to antimachinery feelings as opposed to other grievances. What is clear is that the guild structure, albeit on the decline everywhere in the late eighteenth century, was still quite powerful on the continent.[70] In papermaking, wool, shipbuilding, and printing, resistance was strong.[71] Artisans and domestic workers were well organized and rioted for many reasons, new machinery being one of the more prominent.

There is dispute among scholars over how much damage these riots really caused in France.[72] In the early stages of the Revolution, a crowd of furious artisans destroyed the factory of a St. Etienne hardware manufacturer, Jacques Sauvade, who had shown an interest in mechanized and

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[70] In pre-revolutionary France the network of craft guilds and small producers, often supported by local authorities, was adamantly opposed to all technical innovation (Deyon and Guignet, 1980). The Crown did its best to circumvent this conservative force by awarding privileges, pensions, and monopolies to successful innovators and inventors. The French government defaulted on these commitments after the Revolution, which clearly did not increase the confidence of inventors in their ability to collect a financial return for their efforts. See also MacLeod (1991).

[71] In a recent study, Rosenband (2000) has documented the extent to which journeymen in the French paper industry, in the words of Etienne Montgolfier, had as their principal goal "to suffer no change nor ameliorations n the mills where they work and to maintain in them the ancient customs" (p. 60).

[72] See for example Manuel (1938), who minimizes the effects of resistance as opposed to McCloy (1952).

flexible mass production (Alder, 1997, ch. 4). In Rouen and other places, the Revolution provided Luddite elements with an opportunity to destroy some textile machinery that had come over from England in the previous decades. Perhaps the most serious damage to French technology was inflicted by the tenacious resistance to the armories employing interchangeable parts under the leadership of Honoré Blanc. Whether France really could have taken off in that direction and based an Industrial Revolution on precision machine tools and interchangeable parts is something we will never know. Alder shows convincingly that resistance by worried artisans, provincial merchants, and conservative officers, and the lack of firm government backing, ruined Blanc's enterprise. During the Empire, order was restored, and the attitude of the government toward machinery changed after 1789 in favor of novel technology (Reddy, 1984, pp. 65–67). The concern with resistance remained on the mind of would-be innovators, however, as the weavers of Lyons launched an abortive attempt to thwart the Jacquard loom after 1802 (Ballot, [1923] 1978, p. 379). After the Restoration, workers and small craftsmen became stronger and in a number of cases a new invention that threatened the livelihood of an existing group was nipped in the bud.[73] East and north of France, resistance varied quite a bit from country to country.[74] In southern Europe, as far as can be ascertained, matters were substantially worse.[75]

In Britain, too, the undisputed triumphs of the new technology ran into trouble after the successes of the first Industrial Revolution were secure. As far as intellectual resistance to technological change is concerned, the romantic reaction to industrialization of poets such as Blake and Wordsworth is well known (Williams, 1958). As the changes in British industry became more visible and invasive, the voices of dissent and protest grew louder and acquired more influence. William Cobbett, perhaps the most influential of the early critics, regarded the new industrial system as the taproot of social inequality and poverty, the source of the growing polarization of the relation between employer and employee, and as some-

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[73] For example, the inventor of the sewing machine using a chain-stitch mechanism, Barthélemy Thimonnier, saw his factory raided twice and his machines destroyed.

[74] For an example of resistance to power looms in Switzerland, see Henderson (1954, p. 206 and note 42). The spinning jennies, too, were subject to "blind, uncomprehending hate," and there were times when there was an acute danger that the spinning machinery in the Zurich Oberland would be attacked (Braun, 1990, p. 179). In the Netherlands there were sporadic incidents during the nineteenth century, but they seem to have had little effect (Bakker and Berkers, 1995, p. 143).

[75] The decline of the Italian manufacturing city in the seventeenth century was to a large extent attributed to the ability of the guilds to arrest innovations and frustrate the natural forces of competition (Sella, 1979, p. 103; Cipolla, 1968, p. 137). A campaign by the Spanish government in the middle of the eighteenth century to introduce spinning wheels into the countryside ran into such violent opposition that it had to be abandoned (Gille, 1978, p. 1258).

thing profoundly unnatural and inhuman. Like Cobbett, subsequent radical critics of the new order such as Thomas Carlyle, John Ruskin, and William Morris idealized the Middle Ages, a characteristic attitude of romantic Victorian intellectuals. Carlyle's criticism preceded the young Marx's and Matthew Arnold's writings on the alienating influence of machinery (Williams, 1958). Arnold's writing, together with John Ruskin's and William Morris's, formed the core of a growing technophobic movement after the middle of the nineteenth century. Ruskin, for instance, rejected the railroad as "nonsensical" and insisted on using mailcoaches to underscore his point. Morris, deeply influenced by Carlyle and Ruskin, sponsored an arts-and-crafts movement not unlike the appropriate technology movement of the 1970s inspired by E. F. Schumacher and Amory Lovins, and lived in a house designed to look like a medieval building.

Underlying the Victorian criticism of technology were different currents, some protesting the condition of the labor class, others based on a naive nostalgia for an earlier and greener Britain, others again representing an anti-materialist critique of economic growth (Carlyle, 1977, pp. 9–11; Morris, 1973, p. 93). Within the larger set of social critics, there was a subset of highly influential educators, essayists, poets, and artists who expressed a social as well as an aesthetic aversion to the new technology of the Industrial Revolution. It is hard to assess what impact these intellectuals had. Their influence on public opinion has been described by Martin Wiener as "a counterrevolution of values" (Wiener, 1981). Wiener directly attributes the decline of Britain as a technological leader to the cultural changes that occurred within the British economic elite in the post-1850 period. By this time, "change...had gone far enough, and further change afforded prospects more disquieting than cheering." Resistance to subsequent change was a direct result of the establishment of a new elite "which threw earlier enthusiasms for technology into disrepute" (Wiener, 1981, p. 158). Economists and economic historians have dealt harshly with Wiener's reinterpretation of British history, in part because his treatment of economic history was neither charitable nor informed (Wiener, 1981, pp. 167–70; Collins and Robbins, 1990). The most severe and influential critics of the British economy that emerged from the Industrial Revolution, however, such as Marx and Engels, were not hostile to technology per se. Like the authors of industrial novels, they were not so much opposed to the new technology itself as they were to the industrial capitalists who were believed to profit from it.

It would be misleading to argue that the decline of Britain's leadership in the closing decades of the nineteenth century was simply attributable to its social structure being more resistant to technological progress than that of its competitors. Harold James has argued cogently that attitudes toward "business" in Germany were no less critical and disdainful than in Britain. If Britain in the late nineteenth century returned to its aristocratic gentlemanly values, as Wiener has maintained, one might equally argue that Germany returned to its feudal militaristic codes (James, 1990). As already noted, a powerful anti-modernist movement developed in Germany, especially among artisans and shopkeepers, who looked anxiously at the rapidly growing factories and department stores around them and cultivated a nostalgia for medieval guilds. These master craftsmen, "instead of attempting to adjust to the emerging modern world...developed an ideology designed to protect them against [it]" (Volkov, 1978, p. 325). For all of Germany's achievements in the fields of science and technology, James notes that "modern German culture is widely recognized as being largely anti-modern, pessimistic, and specifically anti-industrial" (1990, p. 96).[76]

An interesting example of resistance to innovation can be discerned in the years following the invention of the automobile by Karl Benz and Gottlieb Daimler. Especially in Germany, resistance was fierce, with blacksmiths, horsebreeders, and railroad investors forming an unholy coalition to stop the invention. In some places the rural population erected barricades to prevent automobiles from advancing. The one country in which automobiles became popular right away was France, with its wide open roads. On the eve of the first World War, France had 2.3 cars per thousand, the United Kingdom 2.6 per thousand, but Germany only .9 cars per thousand, and at that time France produced almost three times as many motorcars as Germany although Germany's population was more than 50 percent larger (Mitchell, 1975, passim). The difference between the two countries was thus one of degree, and not a very large one at that. Yet in a number of key industries—chemical, electrical, precision engineering, optical, food processing—resistance to change in imperial Germany was less effective, in part because of the pro-technology bias of its government (which realized how indispensable modern industrial technology could be to its military objectives) and in part because of the stronger technical background of its business leadership.

The success of technological innovation in its struggle against those who would try to frustrate it depended to a great extent on the openness of the economy. As Mancur Olson has pointed out, international competition was a safeguard against restrictive policy measures of lobbies trying to

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[76] Symptomatic of the ambivalence of the Germans to technology and modernity was the phenomenal success of a confused book by Julius Langbehn, *Rembrandt as an Educator*, published in 1890, which went through thirty-nine editions in the first two years and launched a square attack on science and everything it was associated with: technology, mechanistic materialism, urbanism, and specialization (Stern, 1961, pp. 116–36).

protect special interests (Olson, 1982, pp. 137–40). In that regard, the triumph of economic liberalism in Britain after 1850 provided a partial safeguard against technological conservatism. In machine tools and shoemaking, especially, the American invasion stimulated technological change (Church, 1968). Moreover, hard evidence that business attitudes toward new technology changed significantly after 1850 or 1870 is lacking. Conservatism, not change, was at the heart of Britain's problem. In this case, conservatism was found in the mechanism of technological change itself.

The Industrial Revolution marked an era of ever-widening epistemic bases, but many new production techniques were still based on frail and weak knowledge of why and how things worked. In many cases such knowledge may not even have been necessary; most of the textile machinery may have been mechanically complex, but it did not require a deeper knowledge of the natural processes at work. The ways of solving technical problems in the first Industrial Revolution, which had served Britain so well, were upheld. British innovators continued to be mostly products of an informal on-the-job-training system who saw little need to combine theory and practice (Coleman and MacLeod, 1986). Their knowledge of mathematics was in most cases limited, and although there were some instances of scientists and engineers cooperating in a mutually beneficial way, they were fairly rare. Wiener's argument is that the stubborn adherence to this trusted and proven approach that had been at the basis of British innovation during the Industrial Revolution, led to the gradual erosion of Britain's head start in the second half of the nineteenth century. More systematic scientific bases for techniques in chemistry, metallurgy, food processing, mechanical engineering, and other areas were increasingly appropriated by French and German inventors.

Dismissing Wiener-type arguments with the same sneers he reserves for Cliometricians seems to me unwise. As I have stressed, the resistance to technological change operates through non-market processes. Schumpeter warned us not to take such processes too lightly:

> The social atmosphere...explains why public policy grows more and more hostile to capitalist interests, eventually so much so as to refuse on principle to take account of the requirements of the capitalist engine and to become a serious impediment to its functioning. The intellectual group's activities have however a relation to anti-capitalist policies that is more direct... Intellectuals rarely enter professional politics and still more rarely conquer responsible office. But they staff political bureaus, write party pamphlets and speeches...which few men can afford to neglect. In doing these things they can to some extent

> impress their mentality on almost everything that is being done. (Schumpeter, 1950 p. 154)

Schumpeter did not mention education, but clearly it belongs in there with other intellectual professions. Indeed, the inability of British technical education to keep up with the requirements of the second Industrial Revolution has been repeatedly singled out as a central factor (Ashby, 1958; Landes, 1969 pp. 339–47; Cardwell, 1972 p. 192; Wrigley, 1986).[77] Economic and social historians have so far not explained very well why educational systems differ, both over time and in cross section. The importance of this factor may have been overstated: education systems in the Western industrialized countries has shown more convergence than divergence over the twentieth century, and the useful knowledge that drove innovation was increasingly accessible as the scientific and engineering communities became more integrated. Yet the application of this knowledge to new techniques was not universally acceptable, and the continuing resistance to a host of new techniques demonstrates the importance of political economy to technological selection. It is in this realm that Schumpeter's intellectuals and their Wienerian values and culture had the most pernicious influence.[78]

All of this is not to suggest that the decline of Britain's technological leadership could be entirely blamed on a number of influential intellectuals, whose abhorrence of industrial technologies and aesthetic concerns doomed Britain to lose its position as the workshop of the world. Olsonian coalitions of various kinds started to become more powerful after the Captain Swing rebellions. After 1850, complaints multiplied about British artisans and workers actually preventing new technologies from penetrating.[79] In the shoe and boot industry, fears of the "dilution" of labor led to the hostility of union leaders toward machinery (Church, 1968, p. 234). The most detailed work on the subject has been carried out by Lazonick on the cotton industry. His conclusion is worth repeating: "Vest-

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[77] Recent work has questioned some of the details of this argument. Fox and Guagnini state that by the early twentieth century all European countries suffered from an excess rather than a lack of graduates of technical schools (1999, p. 175).

[78] Consider, for instance, what Matthew Arnold wrote of Cornell University: "The university, a really noble monument to his [Ezra Cornell's] munificence, yet seems to rest on a misconception of what culture really is, and to be calculated to produce miners, engineers, or architects, not sweetness and light" (Arnold, 1883, p. xxvii).

[79] The British engineer Joseph Whitworth, in a well-known 1854 report on the differences between American and British manufacturing, emphasized the difference in attitudes and explained that British workers were more successful in keeping out new technologies because they were better organized, more skilled, and less mobile, thus neatly capturing variables on both the demand and the supply side of the resistance to technological progress (see Rosenberg, 1969).

ed interests—in particular the stake that British workers had in job control and the historic underdevelopment of British management—stood in the way of...promoting the diffusion of advanced production methods" (Lazonick, 1987, p. 303). Labor viewed the adoption of new machines with "acute suspicion." Rather than block the new machinery altogether, however, their resistance was often veiled in new demands. To secure labor's acceptance, management had to make concessions that reduced the profitability of new machinery (Payne, 1990, pp. 38–41). The resistance of organized labor slowed down technological progress in mining, shipbuilding and cotton weaving.[80] Labor was not alone in its resistance: British local and municipal authorities, with a vested interest in the gas supply, deliberately slowed-down the development of mass-consumption of electrical power in the thirty years before 1914 (Michie, 1988). "Red-flag" legislation, which made horseless carriages all but impossible, remained on the books until 1896 and impeded the automobile industry in Britain in its early days.

It is perhaps surprising that in spite of the narrow self-interest of special lobbies and coalitions, and the influence of anti-technological ideologies on the left and the right, technological progress in the West and in societies that followed the West accelerated in the twentieth century. To be sure, some areas, especially those that concern the human body and the physical habitat, continue to encounter problems. Between the outrages of eco-terrorists and the caution of the FDA, progress has been slower than it could have been. The introduction of new products, from toys to birth-control devices, is encumbered and often aborted by fears of product liability lawsuits. Activists, bureaucrats, and lawyers are hampering promising research and making it more costly. But the achievements made possible by new useful knowledge in terms of economic well-being and human capabilities have been unlike anything experienced before by the human race. The question remains, can this advance be sustained?

Cardwell's Law Revisited

To summarize, the economic history of useful knowledge must come to grips with the political economy of technological progress. Those who write the history of techniques in terms of market processes have to realize that in the past the market has not always been the arbiter in choosing between techniques. Technological advances were influenced by the deci-

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[80] In shipbuilding, for example, the boilermaker union limited the ability of employers to introduce pneumatic machinery after 1900 (see Lorenz, 1991b).

sion of societies to leave the technical choices up to the free market, limiting the role of the government to the protection of innovators from their enemies and making up for the worst failures of the market through institutions such as patent systems and government support for scientists and inventors. Few governments have actually followed this kind of policy in a pure form, and Britain's success during the Industrial Revolution may be due to the uniqueness of its governing elite to take this "just right" attitude.

More generally, the theory of self-regulating systems suggests that they have a built-in tendency toward stability, and that technological progress is therefore fundamentally a deviation from the norm. This underlines what I have called "Cardwell's Law" (Mokyr, 1990, pp. 207, 261–69; 1994b). In his classic book on the evolution of modern technology, D.S.L. Cardwell stated that most societies that have been technologically creative have been so for relatively short periods.[81] This observation holds for individual European societies, of course, but precisely because Europe was fragmented it does not hold for the continent as a whole. It is as if technological creativity was like a torch too hot to hold for long; each individual society carried it for a short time. So long as there was another nation or economy to hand the torch to, however, some light source illuminating the landscape has been glowing in Europe more or less continuously since the eleventh century. As Cardwell put it "the diversity inside a wider unity has made possible the continued growth of technology over the last seven hundred years" (1972, p. 210). Led first by northern Italy and southern Germany, technological leadership passed briefly to Spain and Portugal in the Age of Discoveries and to the Low Countries in the age of Reformation. Much of Holland's spectacular success in the Golden Age was a result of that nation's technological innovativeness, which complemented its commercial achievements. From there technological leadership passed to Britain during the first Industrial Revolution, then to the United States and Germany. No society, then, was able to hold on long to leadership, but competition among independent political entities (known as the "states system") ensured that as long that there was at least one nation that was truly creative, the others would have to follow suit (Maddison, 1982, ch. 2; Kindleberger, 1996). Even regions in eastern and southern Europe, remote from the sources of innovation, were inevitably affected by technological advances elsewhere on the continent.

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[81] The idea that in the long term nothing fails like success is an old notion. David Hume wrote in 1742 that "when the arts and sciences come to perfection in any state, from that moment they naturally, or rather necessarily decline, and seldom or never revive in that nation, where they formerly flourished" (Hume, [1742] 1985, p. 135). For a similar statement, see Carr (1961, p. 154).

Why, then, does Cardwell's Law hold? Cardwell himself provided no explanation for his observation, which as it stands now is little more than an empirical regularity. Various mechanisms could account for it. After all, economists have been trained to conceive of economies as equilibrium systems, in which bodies in motion gradually lose their momentum and come to a standstill. Does this hold for technology as well? One possibility depends on the relationship between market structures and innovation (Mokyr, 1990a, p. 269). At times monopolistic structures are more conducive to innovation, while under different circumstances competitive and decentralized markets are preferable. Technological innovation may of course change market structure by changing optimal plant size and other barriers to entry. Assume for simplicity that there is an "appropriate" market structure under which innovation continues and an "inappropriate" one under which it terminates. For some forms of innovation a monopolistic structure may be better suited, whereas for others oligopolistic or even perfectly competitive structures may be more suitable. Innovation may change both the existing market structure and the appropriate market structure for continued technological change. Thus there are two possible ways in which technological change may come to an end: either it changes the existing market structure to one that is inappropriate for continued innovation, or it leaves the market structure intact but changes the technological parameters so that the existing structure is no longer appropriate. If we assign finite probabilities to these transitions the economy will inexorably end up in what is known in probability theory as an absorbing barrier, and technological progress will cease.

A similar dialectical approach, in which technological change brings about the conditions of its own demise and which may thus end economic growth, would postulate that the degree of risk aversion or of time preference is affected by income, so that people's willingness to take risks and to wait for the long-delayed fruits of research declines as technological creativity yields more and more fruits. In other words, when economies become sufficiently rich, they may lose some of the "animal spirits" and ambition that drive the innovation process. However, because only a small number of strategic individuals drive the process of innovation, the likelihood that these sources will dry up just because the economy becoming profligate and lazy seems remote.

An alternative interpretation of the dialectic of growth comes from the political economy of new knowledge and is essentially a variation on a theme first proposed by Mancur Olson (1982). The mechanism through which this operates is the emergence of social resistance to further innovation. In every society there are powerful forces that tend to resist change because they have a vested interest in the status quo. New knowledge displaces existing skills and threatens rents: technological change leads to substantial losses sustained by those who own specific assets dedicated to the existing technology. These assets could be formal skills, tacit knowledge, reputation, specialized equipment, ownership of natural resources, barriers to entry that secured monopoly positions, and community-based non-pecuniary assets (Krusell and Ríos-Rull 1996). Suppose that new technologies arrive at a constant rate, and would invariably be adopted if free-market competition were allowed to be the sole arbiter of the choice of technology. There would still be diffusion lags of various types, but in the long run the new techniques would drive out the old ones.

Sooner or later in any society the progress of technology will grind to a halt because the forces that used to support innovation become vested interests. In a purely dialectical fashion, technological progress creates the forces that eventually destroy it. This result holds for a single closed economy. For a set of fragmented and open economies that compete with one another, this result does not hold. The argument reflects the well-known hypothesis that maintains that western Europe's advantage over large empires such as China, the Ottoman Empire, and Russia was its pluralism, its diversity, and its fragmentation. This view goes back at least as far as David Hume, who pointed out in 1742 that "nothing is more favorable to the rise of politeness and learning than a number of neighboring and independent states, connected together by commerce and policy. The emulation which naturally arises among those neighbouring states is an obvious source of improvement. But what I would chiefly insist on is the stop [i.e., constraint] which such limited territories give both to power and authority" (Hume, [1742] 1985, p. 119). In our time it was most cogently stated by E. L. Jones (1981; 2002).[82]

How important was this pluralism or genetic variety in the rise of modern technology? The competitive model of standard economics underscores the advantage of any competitive system over one in which power is concentrated. No single arbitrary ruler can turn off the lights for the entire system. Moreover, because technology affects economic performance as well as military capability, even arbitrary rulers will discover that much as they may dislike the disrupting effects of technological change, they cannot really afford to fall behind. The history of czarist Russia, from Peter the Great to Count Witte, demonstrates this

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[82] The modern formulation of the analogy with a competitive model is due to Douglass C. North who pointed out correctly that because the number of states was small, there were opportunities for colluding and cooperating between the participants as well as incentives to cheat on the arrangement; thus dynamic instability is a possible outcome of this system (1981, pp. 138–142).

salient conflict. The notion of the states system as the bulwark against technological reactionaries is by no means a theoretical structure dreamed-up by economists enamored with their competitive model. In the 1680's a member of the English Parliament pointed out "If Engin Looms be supprest it will force the Weavers to goe to remote Citties and Nations to the great prejudice of the Trade of the Kingdom...and the English cannot goe to any forraine Market by reason the Dutch and French useing them will much undersell us" (cited by Wadsworth and Mann, 1931, p. 103).

To the idea of competition in the states system we can add the equally intuitive argument of geneticists that diversity in any gene pool is more likely to produce creativity. Thus a multitude of diverse cultural traditions is more likely to result in successful combinations.[83] In the history of the West, an underrated source of creativity has been the complementarity between the pragmatic Anglo-Saxon mechanics with limited mathematical knowledge and the more theoretically minded French and Germans. Such generalizations are of course at most central tendencies, but they illustrate the importance of building up and widening an epistemic base for new techniques that are developed by the engineers. Furthermore, the diversity of Europe lent itself admirably to the free experimental method that led curious scientists and engineers to many of the most pathbreaking discoveries before 1800 (Rosenberg and Birdzell, 1986). Original and creative minds who found, for one reason or another, the environment in their native land inhospitable to their ideas, could and often did flee to another country. The European historical record thus illustrates the difference between the local behavior of a single economy and the behavior of a set of economies in a global interactive system. The interaction can be competitive in nature, or it can be purely symbiotic (imitative), or a combination of the two, but it has to be part of any dynamic argument about the advantage of open economic systems. To be sure, quantitative evaluations in this area are unlikely to emerge, but the emergence of technological creativity in Europe in feudal and feuding societies is too widespread to be accidental. All the same, the argument should be qualified.

The first point to be made is that although there is a correlation between political pluralism and technological creativity, it is quite clear that pluralism is neither a sufficient nor a necessary condition for technological creativity. The stunning technological successes of Imperial China during the Sung dynasty were taking place in an imperial context. Although for much of this period China was struggling with Mongol and Manchurian tribes, the Southern Sung, where most of the population remained intact,

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[83] This principle is shared with other evolutionary systems and has been particularly emphasized by Dobzhansky (1974).

destroyed the Jurchen Chin dynasty. When the Sung itself was overthrown by the Mongols, they established a Chinese-type empire that ruled as the Sung had. Throughout these upheavals, Imperial China and the Mandarin bureaucracy remained intact, yet the progress of Chinese technological creativity proceeded until at least a century into the Ming dynasty (1368–1644). Large empires *can* generate technological change, and their bureaucracies have played at times important roles in its emergence.

Second, political fragmentation is no guarantee that technological creativity will persist. From classical Greece to Moslem Spain to pre-Mogul India, cases of severe political fragmentation and Balkanization have been experienced without having any visible effect on the advance of technology. As in evolutionary biology, genetic diversity does not *guarantee* natural innovation, any more than in economics the existence of competition between firms can guarantee economic progress.

Third and most serious, both Jones and North fail to fully acknowledge the enormous costs and hazards of political fragmentation.[84] The burden that internecine wars imposed on Europe for centuries is easily underestimated. Political fragmentation and interstate competition did far more damage than was tolerably affordable in exchange for the putative technological benefits they may have conferred. The destruction of prospering commercial and industrial regions is well known: Italy after 1490, the Spanish Netherlands after 1580, Germany and central Europe after 1620, Ireland after 1650, and Sweden after 1700 are just a few examples of societies whose prosperity was severely damaged by the *direct* impact of armed conflict. No such effects exist in economic models of competition, where the game rarely if ever turns seriously negative-sum.

The misleading nature of the application of the economic model of competition to the "states system" is illustrated by the problem of the optimal size of the state. Much of the history of Europe (as well as the Middle East) demonstrates that for many purposes the city-state may be the optimally sized unit of organization.[85] Independent or autonomous city-states were well structured for contract enforcement and the information-processing needed for trade. They also played, from the later Middle Ages on, an increasingly pivotal role in the generation of new useful knowledge

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[84] Jones stresses the costs of invasion and conquest on the Asian empires, but fails to note that the corresponding costs of the smaller-scale wars in Europe were equally devastating (1988, pp. 116–19).

[85] City States are discussed briefly by Rosenberg and Birdzell (1986, pp. 59–60) and Hicks (1969, pp. 42–59). Neither attempts to provide a coherent explanation of the advantages of this form of political organization. Clearly, however, the persistent economic success of city states, from Tyre to Hong Kong, suggests that there was something efficient about this mode of organization.

and innovations. Yet the competition and conflicts between city-states and larger political units resulted in military victories of the larger units, leading to the economic demise of prosperous city-states. The fates of Carthage, Antwerp, Nuremberg, and Venice all testify to the political non-viability of an economically successful form. Only when city-states were able to organize into a cooperative arrangement to share their defensive resources (as the Lombard League and the Hanseatic League, for example, were able to do), or when they could take advantage of unusual geographic conditions, such as the use of rivers as a protective barrier by the Dutch city-states, could such entities withstand the pressure of larger units for extended periods. Even then, however, their viability was often eroded by the high cost of defending them (Mokyr, 1995).

A dramatic illustration of these costs and benefits can be drawn from the period between 1870 and 1914. The competition between five or six large national economies produced an undeniable stimulus to technological progress. German, French, and British engineers worked hard to outdo each other in steel, chemicals, transportation, and electrical engineering and felt they were short-changing their nations if the competition pulled ahead.[86] Moreover, after 1850 it was becoming increasingly clear to most European nations (Britain being an exception) that technological progress required direct government aid (much of it of course motivated by "national security" considerations). In some nations, such as Italy, Japan, the Habsburg Empire, and Russia, political competition implied the need to emulate and keep up with best-practice technology. These nations soon discovered that military and political power were inseparable from industrial and infrastructural development. Yet in 1914 the European system fell off the knife's edge of continual progress and plunged into an abyss that eliminated many of the material benefits that pre-1914 technology had brought. Similarly, the Cold War has had ambiguous effects. The launching of the Russian *Sputnik* in 1957 led to a re-energizing of the American

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[86] An example of the interaction of the European states system and technological change is the development of chemicals in Germany. In 1795, Gaspard Monge, the French mathematician, recommended that French national education should be directed toward matters "which demand exactness...to accustom the hands of our artificers to the handling of tools of all kinds" in order "to raise the French nation from that position of dependence on foreign industry" (Booker, 1963, p. 104). In 1815, the German chemist Karl Kastner wrote that "chemistry should serve the German nation just as conversely it is the mission of the nation to promote chemistry" (James, 1990, p. 109). His most famous student, Justus von Liebig, believed that, by increasing agricultural productivity, chemistry could reduce rural unrest and enhance political stability. Many decades later, the Haber nitrogen-fixing process in the early 1900s was strongly motivated by Fritz Haber's fervent German patriotism. The uses made of the nitrogen-fixing process and Haber's own subsequent fate as the chief promulgator of German chemical warfare in the War of 1914–18 serve as a reminder of the ambiguities of this kind of ideologically spurred invention.

R&D program (Mowery and Rosenberg, 1998, p. 128), and while the Cold War did not plunge the world into a 1914-type disaster (or worse), the ex ante chances of that event were certainly not negligible. It is thus far from a priori obvious that political fragmentation is on balance beneficial.

All the same, some measure of decentralization is probably desirable. History provides little guidance to what will happen if globalization becomes a political reality, and weighing the costs and benefits on the basis of historical precedents in economies that were in so many ways vastly different from ours seems unwise. Yet in terms of the generation and utilization of useful knowledge, it seems that too much coordination can be unhealthy. The need to retain some political diversity, coupled with openness and freedom of both ideas and the people in which they are embedded, seems to be undiminished even as knowledge itself has become more mobile than ever before. It does not appear as if the world is about to lose this diversity anytime soon, all the talk about homogenization and globalization notwithstanding.[87]

Concluding Remarks

One of the main rediscoveries of the new growth theory and recent thinking about economic development is the importance of institutions and politics. This conclusion comes from scholars who come straight from neoclassical economics (e.g., Parente and Prescott, 2000), as well as from scholars in a historical tradition (e.g., E. L. Jones, 2002). These scholars conclude that policies that would encourage competition and remove obstacles, brakes, and barriers, would increase incomes in the poorest economies for whom the useful knowledge generated elsewhere in the world is there for the grasping. The introduction of politics into formal economics is important because it diverts attention away from factors that are relatively unimportant (such as differences in savings rates) and toward explanations that resonate with other social sciences and history.

The political economy of knowledge suggests the possibility of the existence of poverty traps or multiple equilibria. It is possible for an economy to be "stuck" at a low level of income because its institutions are somehow inappropriate for the adoption of new techniques. Because technological progress, both homemade and imported, is still regarded as one of the main engines of productivity growth, the suitability of institutions to the successful adoption of new ideas is an important issue. Institu-

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[87] Because ethical qualms about cutting-edge biomedical research seem to be strong in the United States, American scientists working on cloning and stem cell research are moving to more liberal countries (*The Economist*, Aug. 4–11, 2001, p. 14).

tional reform in countries such as the Philippines, Haiti, Moldova, and Nigeria would indeed go a long way toward helping these countries adopt the techniques that made Korea and Singapore rich. Yet the problem is that these institutions are there for a reason; they were not imposed on poor countries by an evil spirit. They represent some kind of equilibrium that may be as sustainable as it is undesirable. Poverty and backwardness may sustain the ability of corrupt institutions and regulations to survive, keeping the country poor and backward. One type of such institutions is the one that protects a technological status quo from would-be innovators. Yet these institutions differ in some important aspects from other sources of institutional failure such as corruption, repression, and violence. Industrialized and developed countries are not immune to their threat.

The deeper question is whether sustained economic growth is the exception and stagnation the default, or whether, as argued especially by E. L. Jones (1988), economic growth is a natural condition for most economies, but that more often than not political and cultural impediments drag an inherently dynamic economy into stagnation and poverty. This debate may seem to some a bit like whether a zebra is black with white stripes or the other way around. What is certainly not guaranteed is the continuing expansion of useful knowledge in either its Ω or λ forms. The generation of new Ω-knowledge is the fuel that keeps the engine of growth running. A great deal of growth can be generated in the world today by diffusing existing knowledge and by eliminating the barriers to riches, but eventually growth can only be sustained by generating new useful knowledge. In either case, the political economy of technological progress must occupy its rightful place at center stage.

Chapter 7

Institutions, Knowledge, and Economic Growth

There is no subject in which we must proceed with more caution that in tracing the history of arts and sciences; lest we assign causes which never existed and reduce what is merely contingent to stable and universal principles. Those who cultivate the sciences in any state are always few in numbers: The passion which governs them limited: Their taste and judgment delicate and easily perverted: And their application disturbed with the smallest accident. Chance, therefore, or secret and unknown causes, must have a great influence on the rise and progress of all the refined arts....But I am persuaded that in many cases good reasons might be given, why a nation is more polite and learned than any of its neighbours. At least, this is so curious a subject that it were a pity to abandon it entirely.

—David Hume, 1742

Useful knowledge, as I employ the term in this book, describes the equipment we use in our game against nature. Most of it is quite mundane: we know that it is cold in Chicago in January and that heavy layers of clothing protect the human body from losing the heat it generates, so this knowledge maps into the obvious technique of wearing sweaters. In principle, such knowledge could be entirely private. Yet the evolution of technology is something in which the interaction between different individuals is as important as what each of them knows. Although at base, then, technology is a "game against nature," for it to make sense as a historical factor we need to consider it as part of the social game of people against and with one another.

What needs to be explained is the past two and a half centuries. For all the clamor against Whiggishness and mindless "modernization theory," economists have relentlessly reminded other social scientists and historians cringing at "triumphalist Eurocentric teleologies" that the rise of the western economies based on economic growth and technological progress is the central event of modern history. Nothing else even comes close. But how to explain it? If revisionist historians such as Pomeranz (2000) are even remotely correct in arguing that the great divergence between Western Europe and the "Orient" really occurred after 1750, the onus placed on the events we refer to as the Industrial Revolution is all the more weighty.

What, exactly, was the role of useful knowledge? It is simply incorrect that *all* modern economic growth is due to technological change. Economies can grow as a result of continuous reallocation of resources or the establishment of law and order and concomitant commercialization. They can grow because people become more conscientious and cooperative, more thrifty, diligent, and prudent, and more trusting of one another. Some scholars (e.g., Landes, 1998) have pointed to *culture* as the primary cause of the rise of the West: traditions of honesty, hard work, frugality, and education for one's offspring are transmitted from generation to generation and can differ a great deal among different societies. Hard work, trust, and frugality can indeed help an economy do better; but if the useful knowledge base does not expand, such laudable efforts will run into diminishing returns. Only an increase in useful knowledge can permanently remove the ceiling on prosperity growth.

Others feel that *institutions*—formal and informal—matter more: the trustworthiness of government, the functionality of the family as the basic unit, security and the rule of law, a reliable system of contract enforcement, and the attitudes of the elite in power toward individual initiative and innovation. Some societies are simply better organized and their incentive systems work better. In this view, best expressed by North (1990) and Eric Jones (2002), hard work, initiative, and frugality will bring about growth if they are properly rewarded, and such rewards are determined by the institutional structure. The economic differences between the Koreas and the two parts of Germany serve as a stark reminder of how important the social rules are by which the economic game is played. David Landes's (1998) approach to economic performance is cast in more cultural terms, but the distinction between "culture" and "institutions" in this literature is often hard to delineate.

The juxtaposition of "institutions" and "useful knowledge" as alternative explanations of economic growth is, to a large extent, artificial. Two statements seem, however, a rough characterization of the economic history of growth. One is that differences in institutions are better at explaining differences in income *levels* in cross section at a given moment. Knowledge can and does flow across national boundaries, if not always with the frictionless ease that some economists imagine. If the only reason why Germany is richer than Zimbabwe today were that Germany possesses more useful knowledge, the difference might be eliminated in a relatively short time. If we were to ask, however, why Germany is richer today than it was in 1815, the importance of technology becomes unassailable—though better institutions might still be of importance as well. The second statement is that before 1750 technology was of secondary importance in pre-modern growth, such as it was. This was true even in China and Europe, where episodes of significant technological progress can be discerned. In the blooming of certain economies, such as medieval Flanders and Renaissance Italy, institutional change such as the development of markets and the growth of trade and specialization loomed large. Some inventions, such as premodern improvements in shipping and textiles, affected these economies, but they tended to be one-off improvements, without the sustainability and persistence of technological progress that marks the modern age. It is this change in the relative weight of the driving force that marks the true significance of the Industrial Revolution.

Institutional factors mattered first and foremost because they determined the efficiency of the economy by affecting the exchange relations among people, resource allocation, and savings and investment behavior. Useful knowledge is different. The fundamental nature of production is an attempt to tease out of the environment something that is desirable by humans but that nature is not willing to give up voluntarily. By abandoning hunting and gathering and by exploiting the regularities they detected in nature, people invented farming and created what we might call a production society. By formalizing these regularities into something that eventually became "science" and allowing them to interact with the techniques they implied, the Baconian program reached a critical mass in late eighteenth-century western Europe. There was nothing inevitable about this, and it is far from obvious that, had western Europe never existed, or had it been wiped out by Ghenghis Khan, that some other society would have eventually developed X rays, freeze-dried coffee, and solar-powered desk calculators (Mokyr, 2002, forthcoming). An evolutionary approach to the history of knowledge implies that we cannot "explain" *why* modern economic growth happened after 1800 much better than we can explain why homo sapiens emerged when it did, and not, say, 30 million years earlier in the middle of the Oligocene. We can show, however, *how* it evolved from earlier intellectual developments, such as the Renaissance, the scientific revolution, and the Enlightenment.

The tale, however, is more complex. Institutions play a central role in the rate and direction of the growth of useful knowledge itself. Science and technology, as the constructivist school insists, are social processes. This approach is not as remote from the thinking of economists as they believe: everyone agrees that incentives matter. It is also understood that the supply of talent in the economy is finite, and that it should be regarded as another scarce resource (Murphy, Shleifer, and Vishny, 1991). Institutions help determine on which margins the efforts and time of the most resourceful and ambitious men and women will be applied. Entrepreneurs, innovators, and inventors will try to make their fortune and fame wherever they perceive the rewards to be most promising. There are many potential avenues where this can be done: commerce, innovation, and finance—or plunder, extortion, and corruption. The institutions of society determine where these efforts will be most rewarding and remunerative. From the point of view of the economic agent a dollar made in any activity is the same. From the point of view of the economy, however, entrepreneurial activity is enriching, rent-seeking is impoverishing (Baumol, 1993). The search for new knowledge can take many different avenues, some of which are more useful than others. Such distinctions are complex: some activities regarded by some as rent-seeking (e.g., litigation) are regarded by others as an essential part of property-rights enforcement. Knowledge that may have seemed initially as rather abstract, such as pure mathematical knowledge, can find eventually unexpected uses.

And yet, the accumulation of useful knowledge is not like other entrepreneurial activities. The drive for the understanding of nature and the recognition of one's peers for having done so successfully transcends purely material motives. In all human societies, curiosity and the thirst for knowledge for its own sake have been a driving motive in the accumulation of propositional knowledge. One way of describing the modern age is that the relative importance of knowledge for its own sake has declined relative to knowledge that may be mapped into better techniques. Whereas some part of the growth of Ω in a society of market-driven capitalist institutions may still be motivated by such epistemic motives, economic interests, no matter how remote, have become increasingly important in the past century and a half. The Baconian dream is increasingly becoming a reality. Of course, much of the mapping of Ω onto λ comes from discoveries whose significance as an epistemic base was realized only much later. It would be absurd to think that Niels Bohr and Erwin Schrödinger were thinking of

MRIs and lasers when they helped develop quantum physics.[1] Yet such detachment cannot be said to describe much of "pure" science today. Somewhere in the back of the minds of most pure scientists are funding considerations. Funding agencies, somewhere in the back of their minds, think of legislators. And legislators, one hopes, in a remote corner of the back of their minds, have society's needs at heart. Much research into propositional knowledge, moreover, is directly inspired and motivated by the perceived needs of industry. Curiosity and other "internal" mechanisms have not disappeared, but they have to share the dominant motivation for research into propositional knowledge with pragmatic needs. In that sense, modern economies represent the ultimate triumph of the Industrial Enlightenment.

The existence of organizations in which such knowledge is preserved, diffused, and augmented (such as academies, universities, and research institutes) and the rules by which they play (such as open science, credit by priority, reproducibility of experiment, and rhetorical rules of acceptance) help determine its historical path. The rate of technological development has been deeply affected by the fact that the people who studied nature and those who were active in economic production have been, through most of history, by and large disjoint social groups. The flows of knowledge between them and the ease of access to social stores of knowledge were of central importance in explaining progress over past centuries. Access was important because useful knowledge could only become economically significant if it was shared, and access was shaped by institutions, attitudes, and communications technology. Today, far more than in the past, those who create new techniques and products have the training and the technology to give them easy access to the propositional knowledge that serves as the epistemic base for the new prescriptive knowledge. The miracle of modern economic growth cannot be understood without a clear understanding that the modern age is different in this respect.

To be sure, different institutional structures produced somewhat different outcomes. Some nations were more attracted to the formal study of nature, while others were more inclined to look for applications. In the industrialized West as it emerged in the nineteenth century, a rough division of labor on the matter emerged.[2] Yet the free flow of information

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[1] An anecdote has it that Joseph J. Thomson, the discoverer of the existence of subatomic particles in cathode rays, proposed a toast at an event celebrating his Nobel prize in physics: "Here's to the electron, may no one ever find a use for it."

[2] De Tocqueville famously observed in the 1830s that Americans were not much interested in theory and the abstract parts of human knowledge. Rosenberg observes that this attitude was to characterize American culture for many decades to come (1998b, p. 196). In a classic paper, Kranakis (1989) has analyzed the differences in the types of contributions to engineering made by France and the U.S., noting that French engineers generated theoretical knowledge of a universal nature, heavy with mathematics and abstractions, while American knowledge was pragmatic, often

across national boundaries meant that American engineers could and did access French physics when they needed it and British manufacturers could rely on German and Belgian chemistry.[3] This openness was enhanced both by institutions and technology: western science maintained its open structure, and with declining communication and transport costs, access costs kept falling. Between 1902 and 1914, 61 percent of the students studying electrical engineering in Darmstadt were foreign (König, 1996, p. 76). Even economies that themselves contributed little to best-practice useful knowledge could, if they wanted, take advantage of the new opportunities that the increased useful knowledge created.[4]

In the West, then, useful knowledge flowed across boundaries to blend these difference sufficiently to create a more-or-less coherent "Western useful knowledge." Discussions of different national styles and of "success vs. failure" or "leaders and laggards" *within* the West obscure the fundamental unity of the Western world, transcending the superficial differences in national style (Fox and Guagnini, 1999). Not just useful knowledge was shared: the different institutions that supported it were constantly influencing one another. The British idea of a patent system was influential in other Western countries, and in its turn, Britain learned from other nations in the late nineteenth century that it had to reform its institutions of higher learning if it wanted to participate in the games on the different playing fields of the second Industrial Revolution.

There are four channels through which the institutional framework determines the effectiveness of societies in generating new technology. The first is the ability of society to generate new propositional knowledge. What is the research agenda regarding natural regularities, what is motivating it,

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cast in terms of tables and graphs.

[3] For instance, Frederick Crace Calvert, one of the most successful British industrial chemists of his time and a pioneer in the study of carbolic acid (the first useful disinfectant) in the late 1850s, was trained in France by Chevreul; another leading British chemist, Lyon Playfair, studied in Giessen with von Liebig himself; William Perkin, the inventor of aniline mauve, as well as most other British industrial chemists of his generation were trained by August von Hofmann, a German brought to England to head the Royal College of Chemistry; Heinrich Caro, who eventually became one of the pivotal figures of the German synthetic dye industry, worked in Manchester from 1859 to 1866; Ira Remsen, the director of the first American graduate program in chemistry at Johns Hopkins and the co-inventor of saccharin, was also German-trained. Because of Germany's obvious superiority in training chemists, other nations (including Britain) relied increasingly on Germans for key positions and foreign students went to Germany for advanced training in organic chemistry.

[4] A simple example: the venerable Dutch sugar refining industry after 1815 had fallen behind best-practice technology and was at first not capable of keeping up. By 1880, however, the Amsterdam Wester refinery management had access to professional periodicals and, if necessary, the greatest experts of Europe could be brought in by fast train for a consultation (Bakker, 1995, p. 71).

and which areas is a society most interested in? Many societies in antiquity spent a great deal of time studying the movements of heavenly bodies, which did little to butter the turnips (though it helped work out the calendar). For many generations Jewish sages spent their lives on the exegesis of the scriptures, adding much to wisdom and legal scholarship but little to useful knowledge as defined here. Beyond the question of the agenda, there is the question of allocation: How many and what kinds of resources are spent on generating this new knowledge? How many people are engaged in the study of natural regularities and how are they recruited and compensated? What tools and instruments are employed?

The second channel is the diffusion and tightness of the propositional knowledge generated. Who shares in the knowledge, and how many do? What is the culture of access: is knowledge kept secret or inaccessible through impenetrable codes and jargon, or is it publicized as fast and as widely as possible and further disseminated to wider audiences through popularizing books, magazines, and TV programs? How is knowledge tested and "selected"—that is, accepted by the consensus of the people who matter? What criteria exist to determine that a proposition is "true," and what kinds of languages and symbols exist for practitioners to communicate with one another?

The third channel is the application or "mapping" of propositional knowledge onto the set of prescriptive knowledge or "techniques." Institutions set up the payoffs and penalties of innovation, and the likelihood of successful resistance to the innovation to suppress it and discourage others. How will the person who makes the invention be compensated and what other incentives are there to carry out the often dreary and frustrating work of actually making techniques work? Beyond that, the people who are engaged in production need to communicate with those who study nature. The institutions that matter most here, as I noted above, are the ones that determine the communications and trust between those who know things in Ω and those who make them using instructions in λ. Do philosophers, alchemists, and modern scientists receive signals about what society might need, and are they inclined to respond to them? Conversely, do artisans, peasants, navigators, and physicians have access to the Ω set, and if not, can they approach or hire people who do?

Finally, the fourth channel is the diffusion of innovation: even assuming that a "mapping" from Ω to λ occurs and an invention is made, will it be adopted? Here the institution on which I focused in chapter 6 is the widely observed social and political resistance of groups within society who might end up being the losers from the new technique or who dislike it for some other reason. Institutions determine whether these groups will be successful, and whether society will put up with the risks and turmoil of creative destruction. But other factors matter as well, and they have been widely debated in economic history over the years. For instance, will there always be enough entrepreneurs who will take the initiative and accept the risks of adopting a new technique? If there are, can they control the resources needed to make the technique work properly? Do capital markets provide venture capital and labor markets the necessary complementary skills?

The rise of Western technology in the past three centuries suggests at least some tentative answers. Historians can track the social and physical connections between people who studied natural phenomena and those who actually applied these techniques and made them work. Knowledge has to flow from those who know things to those who make things. There are many forms these flows can take, from the lecturers, philosophical societies, and encyclopedias of the eighteenth century to the community colleges and internet of the twenty-first. But the institutions that facilitate these flows have to exist.

For better or for worse, the history of the growth of useful knowledge is the history of an elite: the number of people who augmented the sets of propositional and prescriptive knowledge is small, even if we take into account the majority of experimenters, philosophers, would-be inventors, and thoughtful mechanics whom history has not recorded because they contributed small sentences to the book of λ-knowledge. The bulk of productivity gains came from the small incremental improvements by anonymous technicians and mechanics who find a way to tweak the instructions on the margin to make things work just a little better. The conquest of nature, noted Robert Hooke in (see the epigraph to this book), would be carried out by a Cortesian army (such as the band led by Hernando Cortes in 1519 to conquer Mexico): organized and disciplined but not necessarily very large (repr. in Hunter, 1989, p. 223, document C). Human capital matters a great deal for technological progress, but just counting aggregate education and technical training may be meaningless. What counts is what the few who mattered knew, how they knew it, and what they did with this knowledge.

The new growth theory has explicitly drawn the connection between technological change and investment in knowledge production through human capital and R&D. This approach can now be re-examined for its ability to explain the past. The idea of a Cortesian army means that only the human capital invested in a relatively small elite matters for purposes of developing the knowledge base of technological progress. In other words, technological advances are determined not so much by the stock of human capital as by its distribution and by the tendency of the education system to teach not only technical skills but also the ability to access and absorb knowledge subsequently and then employ it in creative ways.

Where average human capital was more important is in the application and deployment of the new techniques, what I have called "competence." A considerable literature has evolved about whether technological change is "skill-biased" or not. Even here, however, it is far from obvious whether it matters what the *average* worker knows. After all, the unit that applies the technique, be it an artisan, a large industrial plant, or a household, does not need to know the epistemic base of the technique in question. Instead what it needs is the wherewithal to carry out the rules and instructions that prescriptive knowledge consists of. This competence is normally much less encompassing than the epistemic base. As the equipment in which the new technique was embodied became more sophisticated, it became increasingly possible to front-load the competence into the production-goods and materials end, and to simplify the competence needed to carry out the instructions. Furthermore, in larger plants, what I have called factories, there was a division of labor: the knowledge involved in this competence could be concentrated in a few experts and managers, with a larger group of foremen and mechanics possessing some measure of technical literacy and skill; the bulk of the employees who carried out simple operations needed to know very little except whom to ask if something went wrong. The nature of the factory system ensured easy access to knowledge.

Production in the nineteenth century using new techniques involved above all coordination, disciplining, and controlling the mass of workers rather than instructing them much beyond basic literacy and numeracy. This seems at first glance consistent with the history of human capital formation in the past. The most literate countries in Europe in the first part of the nineteenth century were not the first to industrialize: the experience of the Scandinavian countries, the Netherlands, and Prussia demonstrate this amply. To be technically literate beyond the basics was equivalent to holding a ticket in a lottery, the prizes in which were promotion to foreman, mechanic, engineer, accountant, or some other expert position. All this, of course is not to suggest that human capital was not important in economic growth. However, its role in pushing out the envelope of useful knowledge is perhaps more complex than suggested by those economists who simply approximate it by counting the total number of school years.

To what extent was technological progress "induced," that is, responsive to signals about scarcity and preferences emitted by the economy? In a monumental work, Vernon Ruttan (2001) has made the case as well as it could be made. In some well-established sectors such as agriculture, engineering, and metallurgy, there can be little doubt that differences in endowments and costs imparted a "direction" on technological change. But inducement is at most a steering wheel, not an engine. The growth of knowledge itself seems to be subject to more intractable forces. Ruttan describes in detail the rise of the computer and semiconductor industries in recent decades, but it is hard to see how technology in this industry was in any sense induced. All the same, using the framework proposed in chapter 1, three different "inducement" mechanisms can be distinguished. First, the growth of Ω itself can be influenced by agenda-setting signals. If a society is deeply concerned about rabies or atmospheric pollution, it will find ways to steer pure research into related areas rather than solid-state physics. Curiosity alone might not account for that; there are rewards, monetary and others, that create this bias. This kind of activity takes place in "Pasteur's quadrant" (Stokes, 1997). Of course, if the people who expand Ω-knowledge are themselves involved in the mapping of their insights onto λ, this bias is almost automatic.

Second, given a certain Ω, prices and similar signals will send inventors, engineers and technicians to scour the existing bodies of propositional knowledge for guidance on how to create new combinations and mappings in order to solve high-priority items and create new techniques. This is what Stokes calls "Edison's quadrant," which seeks to apply existing knowledge, not to expand the epistemic base itself (1997, p. 74). The activation of dormant knowledge in Ω seems to be primarily what "induced innovation" means, though it is rarely fully distinguished from the induced growth of Ω.

Third, relative costs and prices determine which elements of λ will be selected, that is, which technique will be in use (in other words, what is actually produced and how). Whereas at first glance this choice is little more than standard substitution, this selection process too could impart a direction on technological change. Given that experience and learning-by-using tend to generate "local" improvements in given techniques, at least up to a point, this kind of mechanism could explain a great deal of what appears to be "induced" innovation (David, 1975).

The growth of useful knowledge, like the growth of living forms, has, however, a great deal of autonomy to it, which cannot be explained in terms of demand or factor endowments. David Hume, insightful as ever, noted in *Of the Rise and Progress of the Arts and Sciences* that the progress of "learning," precisely because it depended on the actions of a small number of people, was more attributable to chance than to a systematic cause. It is easier to account for the rise of commerce than that of arts and sciences because "the love of knowledge" is spread very thinly. In a memorable phrase he added that you will never want booksellers while there are buyers of books, but there may frequently be readers where there are no authors (Hume, [1742] 1985, p. 113). Useful knowledge, more often than not, emerges before people know what it will be used for. Much of it emerges serially, as the next logical step that follows an early discovery, or as a combination of earlier pieces of knowledge. It is then subject to selection mechanisms, which impart the inducement. But picking items from a menu is a different-order problem than asking how the menu was written in the first place and what is on it. Much of the growth of propositional knowledge is a function of the tools and instruments of observation and analysis available at any given moment. A detailed evolutionary model of useful knowledge and technology cannot be attempted here but has been repeatedly proposed elsewhere (Saviotti, 1996; Mokyr, 1998a, 2000d).

Another question that comes up is whether the resources that society allocates to R&D translate somehow directly into "more useful knowledge" as the new growth theory seems to suggest. New useful knowledge is expensive and requires a considerable investment—far more, indeed, than can be readily measured just by looking at the cost of invention. The nature of all evolutionary change is that it is inevitably *wasteful* because of the inherently uncertain nature of the process (Rosenberg, 1996). But not all R&D is equally uncertain. Insofar as it concentrates on relatively minor alterations in and permutations of existing knowledge, what I have called *microinventions*, the likelihood of hitting on something successful is fairly good, and much of the inherent risk can be diversified away. However, the epistemic base is finite, and such work ultimately runs into diminishing returns. It is at that stage that the returns to R&D become highly uncertain and progress unpredictable. It is one thing to scour the *existing* base of propositional knowledge for new technological ideas, quite another to construct such a base *de novo* by adding previously unknown material to the set of Ω knowledge.

The technologies that shaped the major advances in the nineteenth and twentieth centuries have been in many case the result of patient and costly searches—but because of the great deal of noise in the system it is hard to know whether there was a clear-cut or even monotone relationship between how much a society spent on R&D and any measure of technological advance. Much depends on the agenda and interests of the researchers, the prior beliefs and degree of risk aversion of those who control their budgets, and the willingness of society at large to accept radical changes in what is produced by the innovators. In any case, much of the research that augments Ω is determined by political agendas. Heavy spending on military hardware, civil engineering, or space exploration will generate different kinds of knowledge than spending on research in entomology or geology.

Designing institutions that advance invention is not an easy task. Economists typically believe that agents respond to economic incentives.

Some of the best recent work in the economic history of technological change focuses on the working of the patent system as a way of preserving property rights for inventors. In a series of ingenious papers, Kenneth Sokoloff and Zorina Khan have shown how the American patent system exhibited many of the characteristics of a market system: inventors responded to demand conditions, did all they could to secure the gains from their invention and bought and sold licenses in what appears to be a rational fashion. It was accessible, open, and cheap to use and attracted ordinary artisans and farmer as much as it did professional inventors and eccentrics (Khan and Sokoloff, 1993, 1998, 2001; Khan, 2002).

Whether this difference demonstrates that a well-functioning system of intellectual property rights is truly essential to the growth of useful knowledge remains an open question. For one thing, the American system was far more user-friendly than the British patent system prior to its reform in 1852. Yet despite the obvious superiority of the U.S. system and the consequent higher propensity of Americans to patent, there can be little doubt that the period between 1791 and 1850 coincides roughly with the apex of British superiority in invention. The period of growing American technological leadership, after 1900, witnessed a stagnation and then a decline in the American per capita patenting rate. Other means of appropriating the returns on R&D became relatively more attractive. In Britain, MacLeod (1988) has shown that the patent system provided only weak and erratic protection to inventors and that large areas of innovation were not patentable. Patenting was associated with commercialization and the rise of a profit-oriented spirit, but its exact relation to technological progress is still obscure.[5] What is sometimes overlooked is that patents placed technical information in the public realm and thus reduced access costs. Inventors, by observing what had been done, saw what was possible and were inspired to apply the knowledge thus acquired to other areas not covered by the patent.[6] In the United States, *Scientific American* published lists of new patents from 1845, and these lists were widely consulted. Despite the limi-

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[5] In fact, economists have argued that for countries that are technologically relatively backward, strict patent systems may be on balance detrimental to economic welfare (for a summary, see Lerner, 2000). In a different context, Hilaire-Pérez (2000) has shown how different systems of invention encouragement in eighteenth-century Europe were consistent with inventive activity: whereas in France the state played an active role of awarding "privileges" and pensions to inventors deemed worthy by the French Academy, in Britain the state was more passive and allowed the market to determine the rewards of a successful inventor. These systems were not consistently enforced (some British inventors whose patents for one reason or another failed to pay off were compensated by special dispensation) and, as Hilaire-Pérez shows, influenced one another.

[6] The informational role of the patent system is the subject of ongoing research by Ross Thomson; I am indebted to Professor Thomson for enlightening discussions on the matter.

tations that patents imposed on applications, they reduced access costs to the knowledge embodied in them. This function of the patent system apparently was fully realized in the 1770s. The full specification of patents was meant to inform the public. In Britain this was laid out in a decision by chief justice Lord Mansfield, who decreed in 1778 that the specifications should be sufficiently precise and detailed so as to fully explain it to a technically educated person. In the Netherlands, where patenting had existed from the 1780s, the practice of specification was abandoned in the mid-1630s but revived in the 1770s (Davids, 2000, p. 267).

In at least two countries, the Netherlands and Switzerland, the complete absence of a patent system in the second half of the nineteenth century does not seem to have affected the rate of technological advance (Schiff, 1971). Of course, being small, such countries could and did free-ride on technological advances made elsewhere, and it would be a fallacy to infer from the Dutch and Swiss experience that patents did not matter. It also seems plausible that reverse causation explains part of what association there was between the propensity to patent and the generation of new techniques: countries in which there were strong and accessible bridges between the *savants* and the *fabricants* would feel relatively more need to protect the offspring of these contacts. Lerner (2000) has shown that rich and democratic economies, on the whole, provided more extensive patent protection. The causal chain could thus run from technological success to income and from there to institutional change rather than from the institutions to technological success, as Khan and Sokoloff believe. It may well be true, as Abraham Lincoln said, that what the patent system did was "to add the fuel of interest to the fire of genius" (cited by Khan and Sokoloff, 2001, p. 12), but that reinforces the idea that we need to be able to say something about how the fire got started in the first place.

Other institutions have been widely recognized as aiding in the generation of new techniques. Among those are relatively easy entry and exit from industries, the availability of venture capital in some form, the reduction of uncertainty by a large source of assured demand for a new product or technique (such as military procurement), the existence of agencies that coordinate and standardize the evolution of new techniques, and revolving doors between industry and organizations that specialize in the generation of Ω-knowledge such as universities and research institutes. Behind these institutions and the inventions they stimulate, however, is the propositional knowledge on which they rest. Augmenting this knowledge opens the door that economic incentives and markets push societies through. If the doors are closed, however, any incentives for innovation will be useless. Commercial, entrepreneurial, and even capitalist societies have existed that made few important technical advances, simply because the techniques they employed rested on narrow epistemic base and the propositional knowledge from which these bases were drawn was not expanding. Given that increasing this knowledge was costly and often socially disruptive, the political will by agents who controlled resources to actually do so, whether they were rich aristocratic patrons or middle-class taxpayers, was not invariably there. The amounts of resources expended on R&D, however, are not more important than how they are spent, on what, and what kind of access potential users have to this knowledge.

The argument in this book is that useful knowledge mattered. It is neither Whiggish nor naive to suggest that its accelerating growth since 1750 has affected the world more than all other social and political changes taken together. The roots of twentieth-century prosperity were in the industrial revolutions of the nineteenth, but those were precipitated by the intellectual changes of the Enlightenment that preceded them. To create a world in which "useful" knowledge was indeed *used* with an aggressiveness and a single-mindedness that no other society had experienced before was the unique Western way that created the modern material world. It is this useful knowledge that first unlocked the doors of prosperity and threw them wide open, as Kuznets noted. Nations began to walk in, first hesitantly, slowly, almost half-heartedly. But once Britain had made the first steps to its immense gain, others learned and followed. Those that did became rich and comfortable beyond any measure. Eventually it became a rush, if not for all. Even today resistance to and concerns about technology are still rampant, but the institutional setup of the world is such that holdouts that reject modern technology or cannot adopt it will eventually have to change their minds and somehow limp through the doorway.

All this is not to suggest that the growth in useful knowledge is leading us to a world of bliss. Athena's gifts were many: she gave King Cecrops the olive tree, but she also gave the city of Troy the wooden horse that led to its destruction. Technology makes people more powerful in exploiting nature, but how and for what purpose they do so remains indeterminate. If the twentieth century has shown us anything, it is that the capacity of humans for intolerance, stupidity, and selfishness has not declined as their technological power has increased. As Freud said with masterly understatement in his *The Future of an Illusion*, "While mankind has made continual advances in its control over nature and may be expected to make still greater ones, it is not possible to establish with certainty that a similar advance has been made in the management of human affairs."

References

Acemoglu, Daron, and James Robinson. 2000. "Political Losers as a Barrier to Economic Development." *American Economic Review* 90, no. 2 (May), pp. 126–30.

Acemoglu, Daron, and Fabrizio Zilibotti. 1997. "Was Prometheus Unbound by Chance? Risk, Diversification and Growth." *Journal of Political Economy* 105, no. 4 (Aug.), pp. 709–51.

Aghion, Philippe, and Peter W. Howitt. 1997. *Endogenous Growth Theory.* Cambridge, Mass.: MIT Press.

Alchian, Armen, and Harold Demsetz, 1972. "Production, Information Costs, and Economic Organization. *American Economic Review* 62, no. 5 (Dec.), pp. 777–95.

Alder, Kenneth. 1995. "A Revolution to Measure: The Political Economy of the Metric System in France." In M. Norton Wise, ed., *The Values of Precision.* Princeton, N.J.: Princeton University Press.

———. 1997. *Engineering the Revolution: Arms, Enlightenment, and the Making of Modern France.* Princeton, N.J.: Princeton University Press.

———. 1998. "Making Things the Same: Representation, Tolerance and the End of the Ancien Régime in France." *Social Studies of Science* 28, no. 4 (Aug.), pp. 499–545.

Alexander, W. O. 1978. "The Utilization of Metals." In *A History of Technology,* Vol. 6: *The Twentieth Century,* edited by Trevor I Williams, pp. 427–61. Oxford: Oxford University Press.

Allen, Robert C., and Cormac Ó Gráda. 1988. "On the Road Again with Arthur Young: English, Irish, and French Agriculture during the Industrial Revolution." *Journal of Economic History* 48, no. 1 (March), pp. 93–116.

Antonelli, Cristiano. 1999. "The Evolution of the Industrial Organization of the Production of Knowledge." *Cambridge Journal of Economics* 23, no. 2 (March), pp. 243–60.

Apple, Rima D. 1987. *Mothers and Medicine: A Social History of Infant Feeding, 1890–1950.* Madison: University of Wisconsin Press.

Arnold, Matthew. 1883. *Culture and Anarchy.* New York: Macmillan.

Arora, Ashish, and Alfonso Gambardella. 1994. "The Changing Technology of Technological Change: General and Abstract Knowledge and the Division of Innovative Labor." *Research Policy* 23, no. 5 (Sept.), pp. 523–32.

Arora, Ashish, Ralph Landau, and Nathan Rosenberg, eds., 1998. *Chemicals and Long-Term Economic Growth.* New York: John Wiley.

Arrow, Kenneth J. 1969. "Classificatory Notes on the Production and Transmission of Technological Knowledge." *American Economic Review* 59, no. 2 (May), pp. 29–35.

Arthur, W. Brian. 1994. *Increasing Returns and Path Dependence in the Economy.* Ann Arbor: University of Michigan Press.

Ashby, Eric. 1958. "Education for an Age of Technology." In Charles Singer et al., eds., *A History of Technology* vol. 5, *The Late Nineteenth Century*, pp. 776–98. New York and London: Oxford University Press.

Audin, Maurice. 1979. "Printing." In Maurice Daumas, ed., *A History of Technology and Invention.* Vol. 3: *The Expansion of Mechanization, 1725–1860.* New York: Crown.

Babbage, Charles. 1835. *On the Economy of Machinery and Manufactures.* Repr. ed. Fairfield, N.J., Kelley.

Babbitt, Kathleen R. 1997. "Legitimizing Nutrition Education: The Impact of the Great Depression." In Sarah Stage and Virginia Vincenti, eds., *Home Economics: Women and the History of a Profession.* Ithaca, N. Y.: Cornell University Press.

Bagley, J. A. 1990. "Aeronautics." In Ian MacNeil, ed., *An Encyclopedia of the History of Technology.* London: Routledge.

Bailey, Ronald. 1993. *Ecoscam: The False Prophets of Ecological Apocalypse.* New York: St. Martin's Press.

Bakker, M.S.C. 1995. "Beheerst Innoveren." In Harry Lintsen ed., *Geschiedenis van de Techniek in Nederland.* Vol. 6, pp. 69–89. Zutphen, the Netherlands: Walburg Press.

Bakker, M.S.C., and E.A.M. Berkers, 1995. "Techniek ter Discussie." In Harry Lintsen, ed., *Geschiedenis van de Techniek in Nederland,* vol. 6, pp. 139–90. Zutphen, the Netherlands: Walburg Press.

Ball, Helen H., and Alan Swedlund. 1996. "Poor Women and Bad Mothers: Placing the Blame for Turn-of-the-Century Infant Mortality." *Northeast Anthropology* no. 52 (Fall), pp. 31–52.

Ballot, Charles. [1923] 1978. *L'Introduction du machinisme dans l'industrie française.* Geneva: Slatkine.

Barber, Bernard. 1962. "Resistance by Scientists to Scientific Discovery." In Bernard Barber and Walter Hirsch, eds., *The Sociology of Science,* pp. 539–56. New York: Macmillan.

Bartel, Ann P., and Frank R. Lichtenberg, 1987. "The Comparative Advantage of Educated Workers in Implementing New Technology." *Review of Economics and Statistics* 69, no. 1 (Feb.), pp. 1-11.

Bateson, Gregory. 1979. *Mind and Nature: A Necessary Unity.* New York: Dutton.

Bauer, Martin, ed. 1995. *Resistance to New Technology.* Cambridge: Cambridge University Press.

Baumol, William J. 1993. *Entrepreneurship. Management, and the Structure of Payoffs.* Cambridge, Mass.: MIT Press.

———. 2002. *The Free-Market Innovation Machine: Analyzing the Growth Miracle of Capitalism.* Princeton, N.J.: Princeton University Press.

Becker, Gary. 1981. *A Treatise on the Family.* Cambridge: Harvard University Press.

Becker, Gary S., and Kevin M. Murphy. 1992. "The Division of Labor, Coordination Costs, and Knowledge." *Quarterly Journal of Economics* 107, no. 4 (Nov.), pp. 1137–60.

Belofsky, Harold. 1991. "Engineering Drawing—A Universal Language in Two Dialects." *Technology and Culture* 32, no. 1 (Jan.), pp. 23–46.

Benz, Ernst. 1966. *Evolution and Christian Hope: Man's Concept of the Future from the Early Fathers to Teilhard de Chardin.* Garden City, N.J.: Doubleday.

Berg, Maxine. 1980. *The Machinery Question and the Making of Political Economy, 1815–1848.* Cambridge: Cambridge University Press.

———. 1994a. "Factories, Workshops, and Industrial Organization" In Roderick Floud and D. N. McCloskey, eds., *The Economic History of Britain since 1700.* 2d ed. Vol. I, pp. 123–50. Cambridge: Cambridge University Press.

———. 1994b. *The Age of Manufactures.* 2d rev. ed. London: Routledge.

Berthollet, Claude. 1791. *Elements of the Art of Dyeing.* Translated by William Hamilton. London: Stephen Couchman.

Bijker, Wiebe. 1995. *Of Bicycles, Bakelite and Bulbs: Toward a Theory of Sociotechnical change.* Cambridge, Mass.: MIT Press.

Black, Jeremy. 1994. "Continuity and Change in the British Press, 1750–1833." *Publishing History* 36, pp. 39–85.

Blanchflower, David G., and Simon M. Burgess, 1995. "New Technology and Jobs: Comparative Evidence from a Two-Country Study." Presented to the National Academy of Sciences Conference on Technology, Firm Performance and Employment, Washington, D.C., May (version cited dated Dec. 1995).

Bodde, Derk. 1991. *Chinese Thought, Society, and Science.* Honolulu: University of Hawaii Press.

Bohstedt, John. 1983. *Riots and Community Politics in England and Wales, 1790–1810.* Cambridge, Mass.: Harvard University Press.

Booker, Peter Jeffrey. 1963. *A History of Engineering Drawing.* London: Northgate.

Booth, Alan, Joseph Melling, and Christoph Dartmann. 1997 "Institutions and Economic Growth: The Politics of Productivity in West Germany, Sweden, and the United Kingdom, 1945–1955. *Journal of Economic History* 57, no. 3 (June), pp. 416–44.

Bourke, Joanna. 1993. *Husbandry to Housewifery: Women, Economic Change and Housework in Ireland, 1890–1914.* Oxford: Clarendon Press.

———. 1994. "Housewifery in Working Class England, 1860–1914." *Past and Present*, no. 143 (May), pp. 167–197.

Braudel, Fernand. 1981. *Civilization and Capitalism, 15th-18th Century: Vol. 1: The Structures of Everyday Life.* New York: Harper and Row.

Braun, Rudolf. 1990. *Industrialization and Everyday Life.* Cambridge: Cambridge University Press.

Bresnahan, Timothy F., and Manuel Trajtenberg. 1995. "General Purpose Technologies: 'Engines of Growth'?," *Journal of Econometrics* 65, no. 1 (Jan.), pp. 83–108.

Bresnahan, Timothy F., Erik Brynjolfsson, and Lorin M. Hitt. forthcoming 2002. "Information Technology, Workplace Organization, and the Demand for Skilled Labor: Firm Level Evidence." *Quarterly Journal of Economics.*

Brock, William H. 1992. *The Norton History of Chemistry.* New York: W. W. Norton.

Brown, G. I. 1999. *Scientist, Soldier, Statesman, Spy: Count Rumford.* Gloucestershire, Eng.: Sutton Publishing.

Brown, John C. 1988. "Coping with Crisis? The Diffusion of Waterworks in Late Nineteenth Century German Towns." *Journal of Economic History* 48, no. 2 (June), pp. 307–18.

———. 1990. "The Condition of England and the Standard of Living: Cotton Textiles in the Northwest, 1806–1850." *Journal of Economic History* 50, no. 3 (Sept.), pp. 591–614.

Brown, Shannon R. 1979. "The Ewo Filature: A Study in the Transfer of Technology to China." *Technology and Culture* 20, no. 3 (July), pp. 550–68.

Brown, Shannon R., and Tim Wright,. 1981. "Technology, Economics, and Politics in the Modernization of China's Coal-Mining Industry, 1850–1895." *Exploration in Economic History* 18, no. 1 (Jan.), pp. 60–83.

Brownlee, W. Elliot. 1979. "Household Values, Women's Work, and Economic Growth, 1800–1930," *Journal of Economic History* 39, no. 1 (March), pp. 199–209.

Bruland, Kristine. 1995. "Patterns of Resistance to New Technologies in Scandinavia: An Historical Perspective." In Martin Bauer, ed., *Resistance to New Technology.* Cambridge: Cambridge University Press.

Bryant, W. Keith. 1996. "A Comparison of the Household Work of Married Females: The Mid-1920s and the Late 1960s." *Family and Consumer Sciences Research Journal* 24, no. 4 (June), pp. 358–84.

Bryant, Lynwood. 1967. "The Beginnings of the Internal Combustion Engine."In Melvin Kranzberg and Carroll W. Pursell, Jr., eds., *Technology in*

Western Civilization, Vol. 1, pp. 648–63. New York: Oxford University Press.

Buchanan, R. A. 1985. "The Rise of Scientific Engineering in Britain." *British Journal for the History of Science* 18, no. 59 (July), pp. 218–33.

Buchheim, Gisela, and Rolf Sonnemann. 1990. *Geschichte der Technikwissenschaft.* Basel: Birkhäuser.

Cain, Louis, and Elyce Rotella. 2001. "Death and Spending: Did Urban Mortality Shocks Lead to Municipal Expenditure Increases?" *Annales de Démographie Historique* 1, pp. 139-54.

Cairncross, Frances. 1997. *The Death of Distance: How the Communications Revolution Will Change Our Lives.* Boston: Harvard Business School Press.

Caldwell, John C. 1979. "Education as a Factor in Mortality Decline: An Examination of Nigerian Data." *Population Studies* 33, no. 3 (Nov.), pp. 395–413.

Calhoun, Craig. 1982. *The Question of Class Struggle: Social Foundations of Popular Radicalism during the Industrial Revolution.* Chicago: University of Chicago Press.

Campbell, Donald T. [1960] 1987. "Blind Variation and Selective Retention in Creative Thought as in Other Knowledge Processes." In Gerard Radnitzky and W. W. Bartley III, eds., *Evolutionary Epistemology, Rationality, and the Sociology of Knowledge,* pp. 91–114. La Salle, Ill.: Open Court.

Campbell, Helen. 1900. *Household Economics.* New York: G. P. Putnam.

Campbell, M. J. 1990. "Technology and Rural Development: The Social Impact." In M. J. Campbell, ed., *New Technology and Rural Development: The Social Impact.* London: Routledge,.

Campbell-Kelly, Martin, and William Aspray. 1996. *Computer: A History of the Information Machine.* New York: Basic Books.

Cardwell, Donald S. L. 1971. *From Watt to Clausius: The Rise of Thermodynamics in the Early Industrial Age.* Ithaca, N.Y.: Cornell University Press.

———. 1972. *Turning Points in Western Technology.* New York: Neale Watson, Science History Publications.

———. 1994. *The Fontana History of Technology.* London: Fontana Press.

Carlyle, Thomas. [1843] 1977. *Past and Present.* New York: New York University Press.

Carnot, Sadi. [1824] 1986. *Reflections on the Motive Power of Fire.* Translated and edited by Robert Fox. Manchester: Manchester University Press.

Carpenter, Kenneth J. 1986. *The History of Scurvy and Vitamin C.* Cambridge: Cambridge University Press.

Carpenter, Kenneth. 1993. "Nutritional Diseases." In W. F. Bynum and Roy Porter, eds., *Companion Encyclopedia of the History of Medicine,* vol. I, pp. 464–83. London: Routledge.

Carr, Edward Hallett. 1961. *What is History?* New York: Vintage Books.

Carr, J. C., and W. Taplin, 1962. *A History of the British Steel Industry.* Oxford: Basil Blackwell.

Carroll-Burke, Patrick. 2001. "Tools, Instruments and Engines: Getting a Handle on the Specificity of Engine Science." *Social Studies of Science* 31, no. 4, pp. 593–625.

Cartwright, F. F. 1977. *A Social History of Medicine.* London: Longman.

Casti, John. 1990. *Searching for Certainty: What Scientists Can Know about the Future.* New York: William Morrow.

Chadwick, Edwin. [1843] 1965. *Report on The Sanitary Condition of the Labouring Population of Great Britain. London: Her Majesty's Stationery Office.* Edited by M. W. Flinn. Edinburgh: Edinburgh University Press.

Channell, David F. 1982. "The Harmony of Theory and Practice: The Engineering Science of W. J. M. Rankine." *Technology and Culture* 23, no. 1 (January), pp. 39–52.

Chapman, Stanley D. 1967. *The Early Factory Masters.* Newton Abbot, Eng.: David and Charles.

———. 1974. "The Textile Factory before Arkwright: A Typology of Factory Development." *Business History Review* 48, no. 4 (Winter), pp. 451–78.

Church, R. A. 1968. "The Effect of the American Export Invasion on the British Boot and Shoe Industry, 1885–1914." *Journal of Economic History* 28, no. 2 (June), pp. 223–54.

Cigno, Allesandro. 1993. *Economics of the Family.* Oxford: Oxford University Press.

Cipolla, Carlo. 1968. "The Economic Decline of Italy." In Brian Pullan, ed., *Crisis and Change in the Venetian Economy in the Sixteenth and Seventeenth Centuries.* London: Methuen.

Clark, Gregory. 1994. "Factory Discipline." *Journal of Economic History* 54, no. 1 (March), pp. 128–63.

Clow, Archibald, and Nan L. Clow. 1952. *The Chemical Revolution: A Contribution to Social Technology.* London: Batchworth. Repr. 1992. New York: Gordon and Breach.

Cohen, H. Floris. 1994. *The Scientific Revolution: a Historiographical Inquiry.* Chicago: University of Chicago Press.

Cohen, Jack, and Ian Stewart. 1994. *The Collapse of Chaos: Discovering Simplicity in a Complex World.* Harmondsworth, Eng.: Penguin.

Cohen, Jon S. 1981. "Managers and Machinery: An Analysis of the Rise of Factory Production." *Australian Economic Papers* 20 no. 36 (June), pp. 24–41.

Cole, Arthur H., and George B. Watts, 1952. *The Handicrafts of France as Recorded in the Descriptions des Arts et Métiers 1761–1788.* Boston: Baker Library.

Coleman, Donald, and Christine MacLeod. 1986. "Attitudes to New Techniques: British Businessmen, 1800–1950." *Economic History Review* 39, no. 4 (Nov.), pp. 588–611.

Coleman, William. 1982. *Death Is a Social Disease: Public Health and Political Economy in Early Industrial France.* Madison: University of Wisconsin Press.

Collins, Bruce, and Keith Robbins, eds. 1990. *British Culture and Economic Decline.* New York: St. Martin's Press.

Commoner, Barry. 1974. *The Closing Circle.* New York: Bantam.

Constant, Edward W. 1980. *The Origins of the Turbojet Revolution.* Baltimore: Johns Hopkins Press.

Cooney, E. W. 1991. "Eighteenth Century Britain's Missing Sawmills: A Blessing in Disguise?" *Construction History* 7, pp. 29–46.

Cooper, Carolyn. 1984. "The Portsmouth System of Manufacture." *Technology and Culture* 25, no. 2 (April), pp. 182–225.

———. 1991. *Shaping Invention: Thomas Blanchard's Machinery and Patent Management in Nineteenth-Century America.* New York: Columbia University Press.

Cosmides, Leda, and John Tooby. 1992. "Cognitive Adaptations for Social Exchange." In Jerome H. Barkow, Leda Cosmides, and John Tooby, eds., *The Adapted Mind: Evolutionary Psychology and the Generation of Culture,* pp. 163–228. New York: Oxford University Press.

———. 1994. "Better Than Rational: Evolutionary Psychology and the Invisible Hand." *American Economic Review* 84, no. 2 (May), pp. 327–32.

Couclelis, Helen. 2000. "From Sustainable Transportation to Sustainable Accessibility: Can We Avoid a New 'Tragedy of the Commons'?" In Donald Janelle and David Hodge, eds., *Information, Place, and Cyberspace: Issues in Accessibility.* Berlin: Springer Verlag.

Cowan, Robin. 1990. "Nuclear Power Reactors: A Case of Technological Lock-in." *Journal of Economic History,* 50, no. 3 (Sept.), pp. 541–68.

Cowan, Robin, Paul A. David, and Dominique Foray. 1999. "The Explicit Economics of Knowledge Codification and Tacitness." Unpublished, presented at the 3rd TIPIK Workshop, Strasbourg, April.

Cowan, Robin, and Dominique Foray. 1997. "The Economics of Codification and the Diffusion of Knowledge." *Industrial and Corporate Change* 6, no. 3 (Sept.), pp. 595–622.

Cowan, Ruth Schwartz. 1983. *More Work for Mother.* New York: Basic Books.

Cox, W. Michael, and Richard Alm. 1998. "The Right Stuff: America's Move to Mass-customization." *Federal Reserve Bank of Dallas, Annual Report.*

Crosby, Alfred B. 1997. *The Measure of Reality: Quantification and Western Society, 1250–1600.* Cambridge: Cambridge University Press.

Crouch, Tom. 1989. *The Bishop's Boys: A Life of Wilbur and Orville Wright.* New York: W. W. Norton.

Crouzet, François. 1985. *The First Industrialists: The Problems of Origins.* Cambridge: Cambridge University Press.

Cullen, M. J. 1975. *The Statistical Movement in Early Victorian Britain.* New York: Barnes and Noble.

d'Alembert, Jean Le Rond. [1751] 1995. *Preliminary Discourse to the Encyclopedia of Diderot.* Translated by Richard N. Schwab. Chicago: University of Chicago Press.

Daumas, Maurice, and André Garanger. 1969. "Industrial Mechanization." In Maurice Daumas, ed., *A History of Technology and Invention,* vol. II. New York: Crown.

Daunton, M. J. 1983. *House and Home in the Victorian City.* London: Edward Arnold.

David, Paul A. 1975. *Technical Choice, Innovation, and Economic Growth.* Cambridge: Cambridge University Press.

———. 1986. "Understanding the Economics of QWERTY: The Necessity of History." In William N. Parker, ed., *Economic History and the Modern Economist,* pp. 30–49. Oxford: Basil Blackwell.

———. 1992. "Path-Dependence in Economic Processes: Implications for Policy Analysis in Dynamical System Contexts." Unpublished working paper, CEPR, Stanford University.

———. 1997. "Reputation and Agency in the Historical Emergence of the Institutions of 'Open' Science." Unpublished ms., Oxford University.

———.1998."The Collective Cognitive Performance of 'Invisible Colleges'." Presented to the Santa Fe Institute Workshop "The Evolution of Science."

Davids, Karel. 2000. "Patents and Patentees in the Dutch Republic between c. 1580 and 1720." *History and Technology* 16, pp. 263–83.

———. 2001. "Windmills and the Openness of Knowledge: Technological Innovation in a Dutch Industrial District, the Zaanstreek, c. 1600–1800." Unpublished paper, presented to the Annual Meeting of the Society for the History of Technology, San Jose, Calif.

Davis, Arthur G. 1942–43. "William Smith, Civil Engineer, Geologist (1769–1839)." *Transactions of the Newcomen Society* 23, pp. 93–98.

Dear, Peter. 2001. *Revolutionizing the Sciences.* Princeton, N.J.: Princeton University Press.

DeGregori, Thomas R. 1985. *A Theory of Technology.* Ames: Iowa State University Press.

DeLong, J. Bradford. 2000. "Cornucopia: The Pace of Economic Growth in the Twentieth Century." Working Papers, 7602, Cambridge: National Bureau of Economic Research.

Demsetz, Harold. 1988. "The Theory of the Firm Revisited." *Journal of Law, Economics, and Organization* 4, no. 1 (Spring), pp. 141–61.

De Vries, Jan. 1993. "Between Purchasing Power and the World of Goods: Understanding the Household Economy in Early Modern Europe." In John Brewer and Roy Porter, eds., *Consumption and the World of Goods.* London: Routledge.

———. 1994. "The Industrial Revolution and the Industrious Revolution." *Journal of Economic History* 54, no. 2 (June), pp. 249–70.

Deyon, Pierre, and Philippe Guignet. 1980. "The Royal Manufactures and Economic and Technological Progress in France before the Industrial Revolution." *Journal of European Economic History* 9, no. 3 (Winter), pp. 611–32.

Dickson, David. 1974. *The Politics of Alternative Technology.* NewYork: Universe Books.

Dobbs, B.J.T. 1990. "From the Secrecy of Alchemy to the Openness of Chemistry." In Tore Frängsmyr, ed., *Solomon's House Revisited: The Organization and Institutionalization of Science,* pp. 75–94. Canton, Mass.: Science History Publishing.

Dobzhansky, Theodosius. 1974. "Chance and Creativity in Evolution." In Francisco J. Ayala and Theodosius Dobzhansky eds., *Studies in the Philosophy of Biology,* pp. 307–38. Berkeley: University of California Press.

Donald, Merlin. 1991. *Origins of the Modern Mind.* Cambridge, Mass.: Harvard University Press.

Donovan, A. L. 1975. *Philosophical Chemistry in the Scottish Enlightenment.* Edinburgh: at the University Press.

Douglas, Mary. 1966. *Purity and Danger.* London: Routledge and Kegan Paul.

DuBrin, Andrew J., and Janet C. Barnard. 1993. "What Telecommuters Like and Dislike about Their Jobs." *Business Forum* 18, no. 3 (Summer), pp. 13–17.

Dupré, John, ed. 1987. *The Latest on the Best: Essays on Evolution and Optimality.* Cambridge, Mass.: MIT Press.

Dwork, Deborah. 1987. *War Is Good for Babies and Other Young Children.* London: Tavistock Publications.

Dyhouse, Carol. 1976. "Social Darwinistic Ideas and the Development of Women's Education in England, 1880–1920." *History of Education* 5, no. 1, pp. 41–58.

Dyhouse, Carol. 1978. "Working-Class Mothers and Infant Mortality in England, 1895–1914." *Journal of Social History* 12, no. 2 (Winter), pp. 248–67.

———.1981. *Girls Growing Up in Late Victorian and Edwardian England.* London: Routledge and Kegan Paul.

Dyson, Freeman. 1997. *Imagined Worlds.* Cambridge: Harvard University Press.

Eamon, William. 1990. "From the Secrets of Nature to Public Knowledge" in David C. Lindberg and Robert S. Westman, eds., *Reappraisals of the Scientific Revolution,* pp. 333–65. Cambridge: Cambridge University Press.

———. 1994. *Science and the Secrets of Nature.* Princeton, N.J.: Princeton University Press.

Easterlin, Richard. 1995. "Industrial Revolution and Mortality Revolution." *Journal of Evolutionary Economics* 5 (December), pp. 393–408.

———. 1996. *Growth Triumphant.* Ann Arbor: University of Michigan Press.

Ehrenreich, Barbara, and Deirdre English. 1975. "The Manufacture of Housework." *Socialist Revolution* 26 (Oct.–Dec.), pp. 5–41.

———. 1978. *For Her Own Good: 150 Years of the Experts' Advice to Women.* Garden City, N.Y.: Anchor Press/Doubleday.

Eisenstein, Elizabeth. 1979. *The Printing Press as an Agent of Change.* Cambridge: Cambridge University Press.

Ellul, Jacques. 1964. *The Technological Society.* New York: Alfred Knopf.

———. 1980. *The Technological System.* New York: Continuum Publishing Corp.

Epstein, S. R. 1998. "Craft Guilds, Apprenticeships, and Technological Change in Pre-industrial Europe." *Journal of Economic History* 58, no. 3 (Sept.) pp. 684–713.

Evans, Chris, and Göran Rydén. 1998. "Kinship, and the Transmission of Skills: Bar Iron Production in Britain and Sweden, 1500–1860." In Maxine Berg and Kristin Bruland, eds., *Technological Revolutions in Europe*, pp. 188–206. Cheltenham, Eng.: Edward Elgar Publishers.

Evans, William N., and Edward Montgomery. 1994. "Education and Health." Working paper No. 4949, National Bureau of Economic Research.

Ewbank, Douglas C., and Samuel H. Preston.1990. "Personal Health Behavior and the Decline of Infant and Child Mortality: the United States, 1900–1930." In John Caldwell et al., eds., *What We Know About Health Transition* pp. 116–48. Health Transition Series. Canberra: Australian National University.

Eyler, John M. 1979. *Victorian Social Medicine: The Ideas and Methods of William Farr.* Baltimore: Johns Hopkins University Press.

Farrell, Joseph, and Carl Shapiro. 1992. "Standard Setting in High-Definition Television." *Brookings Papers on Economic Activity*(Microeconomics), pp. 1–77.

Feinstein, Charles. 1998. "Pessimism Perpetuated: Real Wages and the Standard of Living in Britain during and after the Industrial Revolution." *Journal of Economic History* 58, no. 4 (Dec.), pp. 625–58.

Ferguson, Eugene S. 1971. "The Measurement of the 'Man-Day'," *Scientific American* 225, pp. 96–103.

———. 1992. *Engineering and the Mind's Eye.* Cambridge, Mass.: MIT Press.

Ferrant, Natalie. 2001. "Books and Reading." In Michel Delon, ed., *Encyclopedia of the Enlightenment,* pp. 186–91. Chicago: Fitzroy Dearborn.

Fest, Joachim. 1973. *Hitler.* New York: Harcourt Brace Jovanovich.

Field, Alexander J. 1994. "French optical telegraphy, 1793-1855: Hardware, Software, Administration." *Technology and Culture* 35, pp. 315-48

Fish, Stewart A. 1950. "The Death of President Garfield." *Bulletin of the History of Medicine* 24, no. 4, pp. 378–92.

Fleming, Donald. 1952. "Latent Heat and the Invention of the Steam Engine." *Isis* 43, no. 131, pp. 3–5.

Flinn, Michael W. 1962. *Men of Iron: The Crowleys in the Early Iron Industry.* Edinburgh: Edinburgh University Press.

———.1965. "Introduction" to Edwin Chadwick's *The Sanitary Condition of the Labouring Population of Great Britain.* Edinburgh: Edinburgh University Press.

———. 1984. *The History of the British Coal Industry, 1700–1830.* Oxford: Oxford University Press.

Folbre, Nancy. 1986. "Cleaning House: New Perspectives on Households and Economic Development," *Journal of Development Economics* 22, no. 1 (June), pp. 5–40.

Foster, Richard, 1986. *Innovation: The Attacker's Advantage.* New York: Summit Books.

Fox, Robert. 1998. "Science, Practice and Innovation in the Age of Natural Dyes, 1750–1860." In Maxine Berg and Kristin Bruland, eds., *Technological Revolutions in Europe,* pp. 86–95. Cheltenham, Eng.: Edward Elgar,

Fox, Robert, and Anna Guagnini. 1999. *Laboratories, Workshops, and Sites: Concepts and Practices of Research in Industrial Europe, 1800–1914.* University of California, Berkeley, Office for History of Science and Technology.

France, Ministère du Travail et de la Prévoyance Sociale, Statistique générale de la France. 1910. *Resultats statistiques du recensement général de la population effectué le 4 Mars, 1906.* Paris: Imprimerie Nationale.

French, Roger K. 1993. "Scurvy." In Kenneth F. Kiple, ed., *The Cambridge World History of Human Disease.* Cambridge: Cambridge University Press.

Frey, Donald. 1991. "Learning the Ropes: My Life as a Product Champion." *Harvard Business Review* 69, no. 5 (Sept.–Oct.), pp. 45–56.

Friedlander, Sheldon K. 1989. "Environmental Issues: Implications for Engineering Design and Education." In Jesse H. Ausubel and Hedy E. Sladovich, eds., *Technology and Environment*, pp. 168–69. Washington, D.C.: National Academy Press.

Galor, Oded, and Omer Moav. 2001. "Das Human *Kapital*." Unpublished discussion paper 2701, CEPR, London.

———. 2002 forthcoming. "Natural Selection and the Origins of Economic Growth." *Quarterly Journal of Economics*.

Galor, Oded, and David Weil. 2000. "Population, Technology, and Growth." *American Economic Review* 90 no. 4 (Sept.), pp. 806–28.

Garfield, Simon. 2001. *Mauve: How One Man Invented a Color That Changed the World*. New York: W. W. Norton.

Gaspar, Jess, and Edward L. Glaeser. 1998. "Information Technology and the Future of Cities." *Journal of Urban Economics* 43, no. 1 (Jan), pp. 136–56.

Geraghty, Thomas M. 2001. "Technology, Organization and Complementarity: The Factory System in the British Industrial Revolution." Ph.D. dissertation, Northwestern University.

Gershuny, Jonathan, and John P. Robinson. 1988. "Historical Changes in the Household Division of Labor." *Demography* 25, no. 4 (Nov.), pp. 537–52.

Gigerenzer, Gerd, et al. 1989. *The Empire of Chance: How Probability Changed Science and Everyday Life*. Cambridge: Cambridge University Press.

Gille, Bertrand. 1978. *Histoire des techniques*. Paris: Editions Gallimard.

Gillispie, Charles C. 1957. "The Natural History of Industry." *Isis* 48, pp. 398–407.

———. 1960. *The Edge of Objectivity*. Princeton, N.J.: Princeton University Press.

———. 1983. *The Montgolfier Brothers and the Invention of Aviation*. Princeton, N.J.: Princeton. University Press.

Glendinning, Chellis. 1990. *When Technology Wounds*. New York: William Morrow.

Goldin, Claudia. 1990. *Understanding the Gender Gap: An Economic History of American Women*. New York: Oxford University Press.

Goldstone, Jack A. 1987. "Cultural Orthodoxy, Risk, and Innovation: The Divergence of East and West in the Early Modern World." *Sociological Theory* 5 (Fall), pp. 119–35.

Golinski, Jan. 1988. "Utility and Audience in Eighteenth Century Chemistry: Case Studies of William Cullen and Joseph Priestley." *British Journal for the History of Science* 21, no. 68, pt. I (March), pp. 1–31.

———. 1990. "Chemistry in the Scientific Revolution: Problems of Language and Communication" In David C. Lindberg and Robert S. Westman, eds., *Reappraisals of the Scientific Revolution,* pp. 367–96. Cambridge: Cambridge University Press.

———. 1992. *Science as Public Culture: Chemistry and Enlightenment in Britain, 1760–1820.* Cambridge: Cambridge University Press.

Gordon, Robert J. 2000a. "Does the 'New Economy' Measure Up to the Great Inventions of the Past?" *Journal of Economic Perspectives,* 14, no. 4 (Fall), pp. 49–74.

———. 2000b. "Not Much of a New Economy." *Financial Times,* July 26.

Goubert, Pierre. 1989. *The Conquest of Water: The Advent of Health in the Industrial Age.* Princeton, N.J.: Princeton University Press.

Gould, Stephen Jay. 1980. *The Panda's Thumb.* New York: W. W. Norton.

Gould, Stephen Jay, and Elisabeth S. Vrba.1982. "Exaptation—a Missing Term in the Science of Form." *Paleobiology* 8, no. 1, pp. 4–15.

Great Britain, 1806. Parliamentary Papers. "Report from the Committee on the Woolen Manufacture of England." Vol. III.

Great Britain, 1831–32. Parliamentary Papers. "Report from the Select Committee on the Labor of Children in Mills and Factories." Vol. XV.

Great Britain, 1844. Parliamentary Papers. "Reports from the Commissioners, Abstract of the Answers and Returns, 1841 Census, Occupations." Vol. XXVII.

Great Britain, 1852–53. Parliamentary Papers. "Census of Great Britain: Population Tables: Ages, Civil Condition, Occupations, and Birth Places of the People." Vol. LXXXVIII, Pt. I.

Grossman, Michael. 1972. "On the Concept of Health Capital and the Demand for Health." *Journal of Political Economy* 80, no. 2 (March/April). pp. 223–55.

Guillerme, André. 1988. "Wood vs. Iron: The Strength of Materials in early 19th Century France." *History and Technology* 6, pp. 239–52.

Hakim, Catherine. 1980. "Census Reports as Documentary Evidence: The Census Commentaries 1801–1951." *Sociological Review* 28, no. 3 (Aug.), pp. 551–80.

Hall, A. Rupert. 1974. "What Did the Industrial Revolution in Britain Owe to Science?" In Neil McKendrick, ed., *Historical Perspectives: Studies in English Thought and Society.* London: Europa Publications.

———. "On Knowing and Knowing How To..." *History of Technology* 3, pp. 91–104.

Hamlin, Christopher. 1990. *A Science of Impurity: Water Analysis in Nineteenth Century Britain.* Berkeley: University of California Press.

Handy, Susan, and Patricia L. Mokhtarian. 1996. "Forecasting Telecommuting: an Exploration of Methodologies and Research Needs." *Transportation* 23, no. 2 (May), pp. 163–90.

Hansen, Gary D., and Edward C. Prescott. 1998. "Malthus to Solow." Unpublished ms., presented to the Minneapolis Federal Reserve Bank Conference on Economic growth and Productivity, Oct. Federal Reserve Bank of Minneapolis Staff Report, no. 257.

Hardy, Anne. 1993. *The Epidemic Streets: Infectious Disease and the Rise of Preventive Medicine, 1856–1900.* Oxford: Clarendon Press.

Harris, John R. 1976. "Skills, Coal and British Industry in the Eighteenth century," *History* 61, no. 202 (June), pp. 167–82.

———. 1988. *The British Iron Industry, 1700–1850.* Houndsmill and London: Macmillan Education Ltd.

———. 1998. *Industrial Espionage and Technology Transfer.* Aldershot, Eng.: Ashgate.

Harris, Ron. 2000. *Industrializing English Law: Entrepreneurship and Business Organization, 1720–1844.* Cambridge: Cambridge University Press.

Hart, Samuel. 1890. "Invisible Assailants of Health." *Popular Science Monthly* 37 (Oct.), pp. 806–14.

Hayek, F. A. 1973–76. *Law, Legislation, and Liberty.* Chicago: University of Chicago Press.

Headrick, Daniel. 1981. *The Tools of Empire.* New York: Oxford University Press.

———. 1988. *The Tentacles of Progress.* New York: Oxford University Press.

———. 1989. *The Invisible Weapon: Telecommunications and International Politics, 1851–1945.* New York: Oxford University Press.

———. 2000. *When Information Came of Age: Technologies of Knowledge in the Age of Reason and Revolution, 1700–1850.* New York: Oxford University Press.

Heilbron, J. L. 1990. "Introductory Essay." in Tore Frängsmyr, J. L. Heilbron, and Robin E. Rider, eds., *The Quantifying Spirit in the 18th Century,* pp. 1–23. Berkeley: University of California Press.

Heller, Henry. 1996. *Labour, Science, and Technology in France, 1500–1620.* Cambridge: Cambridge University Press.

Helman, Cecil. 1978. "'Feed a Cold, Starve a Fever'—Folk Models of Infection in an English Suburban Community, and their Relation to Medical Treatment." *Culture, Medicine, and Psychiatry* 2, pp. 107–37.

Helpman, Elhanan, ed. 1998. *General Purpose Technologies.* Cambridge, Mass.: MIT Press.

Helpman, Elhanan, and Manuel Trajtenberg. 1998. "Diffusion of General Purpose Technologies." In Elhanan Helpman, ed., *General Purpose Technologies,* pp. 85–120. Cambridge, Mass.: MIT Press.

Henderson, W. O. 1954. *Britain and Industrial Europe, 1750–1870.* Leicester: Leicester University Press.

Herman, Robert, Siamak A. Ardekani, and Jesse H. Ausubel. 1989. "Dematerialization." In Jesse H. Ausubel and Hedy E. Sladovich, eds., *Technology and Environment.* Washington, D.C.: National Academy Press.

Hicks, J. R. 1969. *A Theory of Economic History.* Oxford: Oxford University Press.

Higham, Norman. 1963. *A Very Scientific Gentleman: The Major Achievements of Henry Clifton Sorby.* Oxford: Pergamon Press.

Hilaire-Pérez, Liliane. 1991. 'Invention and the State in eighteenth century France. *Technology and Culture* 32, no. 4 (Oct.), pp. 911–31.

———. 2000. *L'invention technique au siècle des lumières.* Paris: Albin Michel.

Hirschman, Albert. 1991. *The Rhetoric of Reaction.* Cambridge, Mass.: Harvard University Press.

Hitching, Wilena. 1912. *Home Management.* London: W & R Chambers.

Hobsbawm, Eric J. 1968. *Industry and Empire.* Harmondsworth, Eng.: Penguin Books.

Hobsbawm, Eric J., and George Rudé. 1973. *Captain Swing.* Harmondsworth, Eng.: Penguin Books.

Hodgkinson, Ruth G. 1968. "Social Medicine and the Growth of Statistical Information." In F. N. L. Poynter, ed., *Medicine and Science in the 1860s,* pp. 183–98. London: Wellcome Institute of the History of Medicine.

Holmes, Thomas J., and James A. Schmitz. 1995. "Resistance to New Technology and Trade Between Areas." Working Paper, Federal Reserve Bank of Minneapolis.

Holmström, Bengt R. 1982. "Moral Hazard in Teams." *Bell Journal of Economics* 13, no. 2 (Autumn), pp. 324–40.

Holmström, Bengt R., and Paul Milgrom. 1991. "Multitask Principal-agent Analysis: Incentive Contracts, Asset Ownership, and Job Design." *Journal of Law, Economics, and Organization* 7, no. 1 (Spring), pp. 24–52.

Holmström, Bengt R., and John Roberts. 1998. "The Boundaries of the Firm Revisited." *Journal of Economic Perspectives* 12, no. 4 (Fall), pp. 73–94.

Hopkins, Donald R. 1983. *Princes and Peasants: Smallpox in History.* Chicago: University of Chicago Press.

Hopkins, Eric. 1994. *Childhood Transformed: Working-Class Children in Nineteenth-Century England.* Manchester: Manchester University Press.

Horrell, Sara, and Jane Humphries. 1995. "Women's Labor Force Participation and the Transition to the Male-Breadwinner Family, 1790–1865." *Economic History Review* 48, no. 1 (Feb.), pp. 89–117.

Horsfield, Margaret. 1998. *Biting the Dust: The Joys of Housework.* New York: St. Martin's Press.

Hounshell, David A. 1984. *From the American System to Mass Production, 1800–1932.* Baltimore: Johns Hopkins University Press.

Howells, Jeremy. 1996. "Tacit Knowledge, Innovation and Technology." *Technology Analysis & Strategic Management* 8, no. 2 (June), pp. 91–106.

Hoy, Suellen. 1995. *Chasing Dirt: The American Pursuit of Cleanliness.* New York: Oxford University Press.

Hudson, Derek, and Kenneth W. Luckhurst. 1954. *The Royal Society of Arts, 1754–1954.* London: John Murray.

Hudson, Heather E. 1998. "Global Information Infrastructure: Eliminating the Distance Barrier." *Business Economics* 33, no. 2 (April), pp. 25–31.

Hudson, Pat. 1992. *The Industrial Revolution.* London: Edward Arnold.

Hudson, Robert P. 1983. *Disease and Its Control: The Shaping of Modern Thought.* Westport, Conn.: Greenwood.

Hughes, Thomas P. 1989. *American Genesis: A Century of Invention and Technological Enthusiasm.* New York: Penguin Books.

Humble, Jane E., Sheila M. Jacobs, and Mary Van Sell. 1995. "Benefits of Telecommuting for Engineers and other High-Tech Professionals." *Industrial Management* 37, no. 2 (March–April), pp. 15–20.

Hume, David. [1742] 1985. "Of the Rise and Progress of the Arts and Sciences (1742)." In David Hume, *Essays: Moral, Political and Literary.* Edited by Eugene F. Miller. Indianapolis: Liberty Fund.

Humphreys, Margaret. 1992. *Yellow Fever and the South.* New Brunswick, N.J.: Rutgers University Press.

Humphries, Jane. 1995. "Women and Paid Work." In June Purvis, ed., *Women's History: Britain, 1850–1945: An Introduction,* pp. 85–105. New York: St. Martin's Press.

Hunter, Holland. 1991. "Spurs and Checks in the Soviet Growth Mechanism." Presented to the annual meeting of the Economic History Association, Boulder, Colo., Sept. 27–29.

Hunter, Michael. 1989. *Establishing the New Science : the Experience of the Early Royal Society.* Woodbridge, Suffolk, and Wolfeboro, N.H.: Boydell Press.

Inkster, Ian. 1976. "The Social Context of an Educational Movement: A Revisionist Approach to the English Mechanics' Institutes, 1820–1850." *Oxford Review of Education* 2, pp. 277–307.

———. 1980. "The Public Lecture as an Instrument of Science Education for Adults—The Case of Great Britain, c. 1750–1850." *Paedagogica Historica* 20, no. 1 (June), pp. 80–107.

———. 1991. *Science and Technology in History: An Approach to Industrial Development.* New Brunswick, N.J.: Rutgers University Press.

Jacob, François. 1977. "Evolution and Tinkering." *Science* 196, no. 4295 (June), pp. 1161–66.

Jacob, Margaret. 1997. *Scientific Culture and the Making of the Industrial West.* New York: Oxford University Press.

———. 1998. "The Cultural Foundations of Early Industrialization." In Maxine Berg and Kristin Bruland, eds., *Technological Revolutions in Europe,* pp. 67–85. Cheltenham: Edward Elgar.

Jacob, Margaret, C., and David Reid. 2001. "Technical Knowledge and the Mental Universe of Manchester's Early Cotton Manufacturers." Unpublished ms., UCLA.

Jaffe, Adam B., Manuel Trajtenberg, and Michael S. Fogarty. 2000. "The Meaning of Patent Citations." Unpublished ms.

James, Harold. 1990. "The German Experience and the Myth of British Cultural Exceptionalism." In Bruce Collins and Keith Robbins, eds., *British Culture and Economic Decline,* pp. 91–128. New York: St. Martin's Press.

Jasper, James. 1992. "Three Nuclear Energy Controversies." In Dorothy Nelkin, ed., *Controversy: Politics of Technical Decisions.* London: Sage Publications.

Jewkes, John, David Sawers, and Richard Stillerman. 1969. *The Sources of Invention.* 2d ed. New York: W. W. Norton.

Johansson, Sheila Ryan. 1994. "Food for Thought: Rhetoric and Reality in Modern Mortality History." *Historical Methods* 27 no. 3 (Summer), pp. 101–25.

———. 1999. "Death and Doctors: Medicine and Elite Mortality in Britain from 1500 to 1800." Working Papers, Cambridge Group for the History of Population and Social Structure.

John, Richard. 1995. *Spreading the News: The American Postal System from Franklin to Morse.* Cambridge, Mass.: Harvard University Press.

Jones, Eric L. 1981. *The European Miracle: Environments, Economies and Geopolitics in the History of Europe and Asia.* 2d ed. 1987. Cambridge: Cambridge University Press.

———. 1988. *Growth Recurring.* Oxford: Oxford University Press.

———.1995. "Culture and Its Relationship to Economic Change." *Journal of Institutional and Theoretical Economics* 151 No. 2 (June), pp. 269–85.

———.2002. *The Record of Global Economic Development.* Cheltenham: Edward Elgar.

Jones, S.R.H. 1982. "The Organization of Work: A Historical Dimension." *Journal of Economic Behavior and Organization* 3, no. 2–3 (June–Sept.), pp. 117–37.

Jones, S.R.H. 1987. "Technology, Transaction Costs, and the Transition to Factory Production in the British Silk Industry, 1700–1870." *Journal of Economic History* 47, no. 1 (March), pp. 71–95.

Kahneman, Daniel, Paul Slovic, and Amos Tversky, eds., 1982. *Judgment under Uncertainty: Heuristics and Biases.* Cambridge: Cambridge University Press.

Kauffman, Stuart A. 1995. *At Home in the Universe: The Search for the Laws of Self-Organization and Complexity.* New York: Oxford University Press.

Keele, K. D. 1961. "The Influence of Clinical Research on the Evolution of Medical Practice in Britain." In F.N.L. Poynter, ed., *The Evolution of Medical Practice in Britain,* pp. 81–96. London: Pitman Medical Publishing

Kellenbenz, Herman. 1974. "Technology in the Age of the Scientific Revolution, 1500–1700." In Carlo Cipolla, ed., *The Fontana Economic History of Europe.* Vol. 2, London: Fontana.

Kelly, Fred C. 1943. *The Wright Brothers.* NewYork: Harcourt, Brace & Co.

Kenney, Martin, and Richard Florida. 1993. *Beyond Mass Production.* New York: Oxford University Press.

Keyser, Barbara Whitney. 1990. "Between Science and Craft: the Case of Berthollet and Dyeing." *Annals of Science* 47, no. 3 (May), pp. 213–60.

Khaifa, Mohammed, and Robert Davidson. 2000. "Exploring the Telecommuting Paradox." *Communications of the ACM* (March), pp. 29–32.

Khan, B. Zorina. 2002. *'The Fuel of Interest': Patents and Copyrights in American Economic Development.* Cambridge: Cambridge University Press.

Khan, B. Zorina, and Kenneth L. Sokoloff. 1993. "'Schemes of Practical Utility': Entrepreneurship and Innovation among 'Great Inventors' in the United States, 1790–1865." *Journal of Economic History* 53, no. 2 (June), pp. 289–307.

———. 1998. "Patent Institutions, Industrial Organization, and Early Technological Change: Britain and the United States, 1790–1850." In Maxine Berg and Kristin Bruland, eds., *Technological Revolutions in Europe,* pp. 292–313. Cheltenham, Eng.: Edward Elgar.

———. 2001. "The Early Development of Intellectual Property Institutions in the United States." *Journal of Economic Perspectives* 15, no. 2 (Spring), pp. 1–15.

Kim, Sukkoo. 2001. "Markets and Multiunit Firms from an American Historical Perspective." In Joel A. C. Baum and Henrich R. Greve, eds., *Multiunit Organization and Multimarket Strategy: Advances in Strategic Management* 18, pp. 305-326. New York: JAI Press.

Kindleberger, Charles P. 1983. "Standards as Public, Collective and Private Goods." *Kyklos* 36, no. 3, pp. 377–96.

———. 1996. *World Economic Primacy 1500–1990.* New York: Oxford University Press.

Kinghorn, Janice Rye, and John V. C. Nye, 1996. "The Scale of Production in Western Economic Development." *Journal of Economic History* 56 No. 1 (March), pp. 90–112.

Kingston, William. 2000. "Antibiotics, Invention, and Innovation." *Research Policy* 29, no. 6 (June), pp. 679–710.

König, Wolfgang. 1996. "Science-Based Industry or Industry-Based Science? Electrical Engineering in Germany before World War I." *Technology and Culture* 37, no. 1 (January), pp. 70–101.

Koyré, Alexandre. [1953] 1968. "An Experiment in Measurement." In *Metaphysics and Measurement: Essays in Scientific Revolution* pp. 89–113. Cambridge, Mass.: Harvard University Press.

Kragh, Helge. 2000. "Confusion and Controversy: Nineteenth-century Theories of the Voltaic Pile." In Fabio Bevilacqua and Lucio Fregonese, eds., *Nuova Voltiana: Studies of Volta and his Times*, pp. 133–57. Milan: Editore Ulrico Hoepli.

Kranakis, Eda. 1989. "Social Determinants of Engineering Practice: A Comparative View of France and America in the Nineteenth Century." *Social Studies of Science* 19, no. 1 (Feb.), pp. 5–70.

———. 1992. "Hybrid Careers and the Interaction of Science and Technology." In Peter Kroes and Martijn Bakker, eds., *Technological Development and Science in the Industrial Age,* pp. 177–204. Dordrecht: Kluwer.

Kraut, Robert E. 1989. "Telecommuting: The Trade-offs of Home Work." *Journal of Communications* 39, no. 3 (Summer), pp. 19–46.

Kroes, Peter. 1992. "On the Role of Designing Theories: Pambour's Theory of the Steam Engine." In Peter Kroes and Martijn Bakker, eds., *Technological Development and Science in the Industrial Age*, pp. 69–98. Dordrecht: Kluwer.

Kronick, David A. 1962. *A History of Scientific and Technical Periodicals.* New York: Scarecrow Press.

Krusell, Per, and José-Victor Ríos-Rull. 1996. "Vested Interests in a Positive Theory of Stagnation and Growth." *Review of Economic Studies* 63, no. 2 (April), pp. 301–29.

Kuhn, Thomas S. 1977. *The Essential Tension: Selected Studies in Scientific Tradition and Change.* Chicago: University of Chicago Press.

Kula, Witold. 1986. *Measures and Men.* Princeton, N.J.: Princeton University Press.

Kunitz, Stephen J. 1987. "Explanations and Ideologies of Mortality Patterns." *Population and Development Review* 13, no. 3 (Sept.), pp. 379–408.

Kuran, Timur. 1988. "The Tenacious Past: Theories of Personal and Collective Conservatism." *Journal of Economic Behavior and Organization* 10, no. 2 (Sept.), pp. 143–71.

———. 1997. "Islam and Underdevelopment: An Old Puzzle Revisited," *Journal of Institutional and Theoretical Economics* 153, no. 1 (March), pp. 41–71.

Kuznets, Simon. 1965. *Economic Growth and Structure*, New York: W. W. Norton.

———. 1971. *Economic Growth of Nations*. Cambridge, Mass.: Belknap Press.

La Berge, Ann F. 1992. *Mission and Method: The Early Nineteenth Century French Public Health Movement*. Cambridge: Cambridge University Press.

Laibson, David. 1997. "Golden Eggs and Hyperbolic Discounting." *Quarterly Journal of Economics* 112, no. 2 (May), pp. 443–77.

Lamoreaux, Naomi, and Kenneth L. Sokoloff, 1996. "Long-Term Change in the Organization of Inventive Activity." *Proceedings of the National Academy of Sciences* 93, no. 3 (Nov. 12), pp. 12686–92.

Lamoreaux, Naomi, Daniel Raff, and Peter Temin. 2002. "Beyond Markets and Hierarchies: Towards a New Synthesis of American Business History." Presented to the Annual Meeting of the Economic History Association, Los Angeles, Sept.

Landau, Ralph, Basil Achilladelis, and Alexander Scriabine. 1999. *Pharmaceutical Innovation: Revolutionizing Human Health.* Philadelphia: Chemical Heritage Foundation.

Landes, David S. 1969. *The Unbound Prometheus.* Cambridge: Cambridge University Press.

———. 1983. *Revolution in Time: Clocks and the Making of the Modern World.* Cambridge, Mass.: Harvard University Press.

———. 1986. "What Do Bosses Really Do?" *Journal of Economic History* 46, no. 3 (Sept.), pp. 585–623.

———. 1998. *The Wealth and Poverty of Nations: Why Some Are So Rich and Some So Poor.* New York: W. W. Norton.

Lang, Helmut W. 1987. "Auch im Kampf gegen die Konkurrenz, Thonets Motto: Biegen oder Brechen, Das Wilde Biedermeier 1800–1848." *Parnass* Sonderheft 4, pp. 56–67.

Langlois, Richard N. 1995. "The Coevolution of Technology and Organization in the Transition to the Factory System." In Paul L. Robertson, ed., *Authority and Control in Modern Industry.* London: Routledge.

———. 2001. "Knowledge, Consumption, and Endogenous Growth." In Ulrich Witt, ed., *Escaping Satiation: The Demand Side of Economic Growth.* Berlin: Springer Verlag.

Langlois, Richard N., and Deborah A. Savage. 2001. "Standards, Modularity, and Innovation: The Case of Medical Practice." In Raghu Garud and Peter Karnøe, eds., *Path Dependence and Path Creation*, pp. 149–68. Mahwah, N.J. Lawrence Erlbaum.

Latour, Bruno. 1987. *Science in Action.* Cambridge, Mass.: Harvard University Press.

———. 1988. *The Pasteurization of France.* Cambridge, Mass.: Harvard University Press.

———. 1990. "Drawing Things Together." in Michael Lynch and Steve Woolgar, eds., *Representation in Scientific Practice.* Cambridge, Mass.: MIT Press.

Laudan, Rachel. 1984. "Cognitive Change in Technology and Science." In Rachel Laudan, ed., *The Nature of Knowledge: Are Models of Scientific Change Relevant?* Dordrecht: Kluwer.

Layton, Edwin T. 1971. "Mirror Image Twins: The Communities of Science and Technology in Nineteenth Century America." *Technology and Culture* 12, pp. 562–80.

———. 1974. "Technology as Knowledge." *Technology and Culture* 15, pp. 31–41.

Lazear, Edward P. 1986. "Salaries and Piece Rates." *Journal of Business* 59, no. 3 (July), pp. 405–31.

Lazonick, William. 1987. "Theory and History in Marxian Economics." In Alexander J. Field ed., *The Future of Economic History*, Boston: Kluwer-Nijhoff.

———. 1990. *Competitive Advantage on the Shop Floor.* Cambridge, Mass.: Harvard University Press.

Leamer, Edward E., and Storper, Michael. 2001. "The Economic Geography of the Internet Age." *Journal of International Business Studies* 32, pp. 641–65.

LeBaron, Charles, and David W. Taylor, 1993. "Typhoid Fever." In Kenneth F. Kiple, ed., *The Cambridge World History of Human Disease.* Cambridge: Cambridge University Press.

Lebergott, Stanley. 1993. *Pursuing Happiness: American Consumers in the Twentieth Century.* Princeton, N. J. : Princeton University Press.

Lerner, Josh. 2000. "150 years of Patent Protection." Working paper 7477. National Bureau of Economic Research, Cambridge, Mass.

Lewis, Bernard. 1982. *The Muslim Discovery of Europe.* New York: W. W. Norton.

Lewis, H. W. 1989. *Technological Risk.* New York: W.W. Norton.

Lewis, Jane. 1984. *Women in England 1870–1950: Sexual Divisions and Social Change.* Sussex: Wheatsheaf Books.

Lewis, Jane. 1995. "Family Provision of Health and Welfare in the Mixed Economy of Care in the Late Nineteenth and Twentieth Centuries." *Social History of Medicine* 8, no. 1 (April), pp. 1–16.

Lewontin, Richard. 1997." Billions and Billions of Demons." *New York Review of Books*, Jan. 9.

Liebowitz, S. J., and Stephen E. Margolis. 1990. "The Fable of the Keys." *Journal of Law and Economics* 33, no. 1 (April), pp. 1–25.

Lilienfeld, David E. 1978. "'The Greening of Epidemiology': Sanitary Physicians and the London Epidemiological Society, 1830–1870." *Bulletin of the History of Medicine* 52, no. 4 (Winter), pp. 503–28.

Lindqvist, Svante. 1990. "Labs in the Woods: The Quantification of Technology during the Late Enlightenment." In Tore Frängsmyr, J. L. Heilbron, and Robin E. Rider, eds., *The Quantifying Spirit in the 18th Century*, pp. 291–314. Berkeley: University of California Press.

Livi Bacci, Massimo. 1989. *A Concise History of World Population.* Cambridge: Blackwell.

Loasby, Brian J. 1999. *Knowledge, Institutions, and Evolution in Economics.* London: Routledge.

Loewenstein, George, and Jon Elster, eds. 1992. *Choice over Time.* New York: Russell Sage Foundation.

Lohmeier, E. Andrew. 1995. "Consumer Demand and Market Responses in the German Empire, 1879–1914." Ph.D. dissertation, Northwestern University.

Lorenz, Edward H. 1991a. "An Evolutionary Explanation for Competitive Decline: the British Shipbuilding Industry." *Journal of Economic History* 51, no. 4 (Dec.), pp. 911–35.

———. 1991b. *Economic Decline in Britain: The Shipbuilding Industry.* Oxford: The Clarendon Press.

Loudon, Irvine. 1986. "Deaths in Childbed From the Eighteenth Century to 1935." *Medical History* 30, no. 1 (Jan.), pp. 1–41.

Lough, John. 1971. *The Encyclopédie.* New York: David McKay.

Lucas, Robert E. 2002. *Lectures on Economic Growth.* Cambridge, Mass.: Harvard University Press.

Lundberg, Shelly, and Robert A. Pollak. 1996. "Bargaining and Distribution in Marriage." *Journal of Economic Perspectives* 10, no. 4 (Fall), pp. 139–54.

Lundgreen, Peter. 1990. "Engineering Education in Europe and the USA, 1750–1930." *Annals of Science* 47, no. 1 (January), pp. 33–75.

Lundgren, Anders. 1990. "The Changing Role of Numbers in 18th Century Chemistry." In Tore Frängsmyr, J. L. Heilbron, and Robin E. Rider, eds., *The Quantifying Spirit in the 18th Century*, pp. 245–66. Berkeley: University of California Press.

Lynn, Walter R. 1989. "Engineering Our Way Out of Endless Environmental Crises." In Jesse H. Ausubel and Hedy Sladovich, eds., *Technology and Environment.* Washington, D.C.: National Academy Press.

Lyons, John S. 1989. "Family Response to Economic Decline: Handloom Weavers in Early Nineteenth-Century Lancashire." *Research in Economic History* 12, pp. 45–91.

Lyotard, Jean-François. 1984. *The Postmodern Condition: A Report on Knowledge.* Manchester: Manchester University Press.

Macfarlane, Alan, and Gerry Martin. 2002. *Glass: A World History.* Chicago: University of Chicago Press.

Machlup, Fritz. 1980–84. *Knowledge: Its Creation, Distribution and Economic Significance.* 3 Vols., Princeton, N.J.: Princeton University Press.

MacLeod, Christine. 1988. *Inventing the Industrial Revolution: The English Patent System, 1660–1880.* Cambridge: Cambridge University Press.

———. 1991. "The Paradoxes of Patenting: Invention and its Diffusion in 18th and 19th Century Britain, France and North America." *Technology and Culture* 32, no. 4 (Oct.), pp. 885–910.

Maddison, Angus. 1982. *Phases of Capitalist Development.* Oxford: Oxford University Press.

Mahoney, Michael S. 1990. "Infinitesimals and Transcendent Relations: the Mathematics of Motion in the Late Seventeenth Century." In David C. Lindberg and Robert S. Westman, eds., *Reappraisals of the Scientific Revolution.* Cambridge: Cambridge University Press.

Manguel, Alberto. 1996. *A History of Reading.* New York: Viking.

Mantoux, Paul. [1905] 1961. *The Industrial Revolution in the Eighteenth Century.* New York: Harper Torchbooks.

Manuel, F. 1938. "The Luddite Movement in France." *Journal of Modern History* 10, no. 2 (June), pp. 180–211.

Marglin, S. A. [1974–75]. "What Do Bosses Do?" *Review of Radical Political Economy* 6(1974) and 7(1975). Reprinted in A. Gorz, ed., 1976. *The Division of Labour: the Labour Process and Class Struggle in Modern Capitalism.* Hassocks: Harvester Press.

Martin, Gerry. 2000. "Stasis in Complex Artifacts." in John Ziman, ed., *Technological Innovation as an Evolutionary Process*, pp. 90–100. Cambridge: Cambridge University Press.

Martin, Roderick. 1995. "New Technology in Fleet Street, 1975–1980." In Martin Bauer, ed., *Resistance to New Technology.* Cambridge: Cambridge University Press.

Marx, Karl. [1867] 1967. *Capital.* New York: International Publishers.

Mayr, Ernst. 1991. *One Long Argument: Charles Darwin and the Genesis of Modern Evolutionary Thought.* Cambridge, Mass.: Harvard University Press.

Mazur, Allan C. 1975. "Opposition to Technological Innovation." *Minerva* 13, no. 1 (Spring), pp. 58–81.

———. 1993. "Controlling Technology." In Albert Teich, ed., *Technology and the Future.* New York: St. Martin's Press.

McCloy, Shelby T. 1952. *French Inventions of the Eighteenth Century.* Lexington: University of Kentucky Press.

McCune, Jenny C. 1998. "Telecommuting Revisited." *Management Review* 87 (Feb.), pp. 10–17.

McGrew, Roderick E., ed. 1985. *Encyclopedia of Medical History.* London: Macmillan.

McKendrick, Neil. 1973. "The Role of Science in the Industrial Revolution." In Mikuláš Teich and Robert Young, eds., *Changing Perspectives in the History of Science.* London: Heinemann.

McKeown, Thomas. 1976. *The Modern Rise of Population.* London: Arnold.

McKibben, Bill. 1989. *The End of Nature.* New York: Random House.

McLafferty, Charles. 1952. "A Study of the Apparent Weakness of the Tucker Company." M.A. thesis, Northwestern University.

Meckel, Richard A. 1990. *Save the Babies: American Public Health Reform and the Prevention of Infant Mortality, 1850–1929.* Baltimore: Johns Hopkins University Press.

Merton, Robert K. 1961. "Singletons and Multiples in Scientific Discovery." *Proceedings of the American Philosophical Society* 105, no. 5 (Oct. 13), pp. 470–86.

———. [1938] 1970. *Science, Technology, and Society in Seventeenth century England.* 2d ed. New York: Fertig.

Metcalfe, J. Stanley. 1998a. *Evolutionary Economics and Creative Destruction.* London: Routledge.

———.1998b. "Innovation System and Endogenous Growth Theory." Working paper. University of Manchester, CRIC.

Michie, Ranald 1988. "The Finance of Innovation in Late Victorian and Edwardian Britain: Possibilities and Constraints." *Journal of European Economic History* 17, no. 3 (Winter), pp. 491–530.

Milgrom, Paul, Yingyi Qian, and John Roberts. 1991. "Complementarities, Momentum, and the Evolution of Modern Manufacturing," *American Economic Review* 81, no. 2 (May), pp. 84–88.

Miller, Thomas E. 2000. "Sizing the Small Business/Home Office Internet Universe." Cyber Dialogue, Inc., *Industry Brief* no. 1: The Internet Consumer.

Mitch, David. 1998. "The Role of Education and Skill in the British Industrial Revolution." In Joel Mokyr, ed., *The British Industrial Revolution: An Economic Perspective,* 2d ed., pp. 241–79. Boulder, Colo.: Westview Press.

Mitchell, Brian. 1975. *European Historical Statistics.* London: Macmillan.

Mokhtarian, Patricia L. 1997. "Now That Travel Can Be Virtual, Will Congestion Virtually Disappear?" *Scientific American* 277, no. 4 (Oct.), p. 93.

———. 1998. "A Synthetic Approach to Estimating the Impacts of Telecommuting on Travel." *Urban Studies* 35 , no. 2 (Feb.), pp. 215–41.

———. 2000. "Telecommunications and Travel: The Case for Complementarity." Unpublished ms., University of California, Davis.

Mokhtarian, Patricia L., and Ilan Salomon. 2002. "Emerging Travel Patterns: Do Telecommunications Make a Difference?" In Hani S. Mahmassani, ed., *Perpetual Motion: Travel Behaviour Research Opportunities and Application Challenges,* pp. 143–82. Oxford, Eng.: Pergamon Press/Elsevier.

Mokyr, Joel. 1976. "Growing-Up and the Industrial Revolution in Europe." *Explorations in Economic History* 13, no. 4 (Oct.), pp. 371–96.

———. 1990. *The Lever of Riches: Technological Creativity and Economic Progress.* New York: Oxford University Press.

———. "Is Economic Change Optimal?" *Australian Economic History Review* 32, no. 1 (March), pp. 3–23.

———. 1993. "Technological Progress and the Decline of European Mortality," *American Economic Review,* Papers and Proceedings 83, no. 2 (May), pp. 324–30.

———. 1994a. "Progress and Inertia in Technological Change." In John James and Mark Thomas, eds., *Capitalism in Context: Essays in Honor of R. M. Hartwell,* pp. 230–54. Chicago: University of Chicago Press.

———. 1994b. "Cardwell's Law and the Political Economy of Technological Progress." *Research Policy* 23, no. 5 (Sept.), pp. 561–74.

———. 1994c. "That Which We Call an Industrial Revolution." *Contention* 4, no. 1 (Fall), pp. 189–206.

———. 1995. "Urbanization, Technological Progress and Economic History." In Herbert Giersch, ed., *Urban Agglomeration and Economic Growth,* pp. 3–37. Berlin: Springer Verlag.

———. 1996a. "La tecnologia, l'informazione e le famiglie." In Renato Giannetti, ed., *Nel Mito di Prometeo. L'Innovazione Tecnologica dalla Rivoluzione Industriale ad Oggi. Temi, Inventori e Protagonisti dall'Ottocento al Duemila*, Firenze: Ponte alle Grazie, pp. 147–84.

———. 1998a. "Science, Technology, and Knowledge: What Historians can learn from an evolutionary approach." Working Papers on Economics and Evolution, # 98-03. Jena, Ger.: Max Planck Institute for Research into Economic Systems.

———. 1998b. "Induced Technical Innovation and Medical History: an Evolutionary Approach." *Journal of Evolutionary Economics* 8, no. 2 (July), pp. 119–37.

Mokyr, Joel. 1998c. "Editor's Introduction: The New Economic history and the Industrial Revolution." In Joel Mokyr, ed., *The British Industrial Revolution: An Economic Perspective,* pp. 1–127. Boulder, Colo.: Westview Press.

———. 1998d. "The Political Economy of Technological Change: Resistance and Innovation in Economic history." In Maxine Berg and Kristin Bruland, eds., *Technological Revolutions in Europe,* pp. 39–64. Cheltenham: Edward Elgar.

———. 1999. "The Second Industrial Revolution, 1870–1914." In Valerio Castronovo, ed., *Storia dell'economia Mondiale,* pp. 219–245. Rome: Laterza.

———. 2000a. "The Industrial Revolution and the Netherlands: Why did it not happen?" *De Economist* (Amsterdam) 148, no. 4 (Oct.), pp. 503–20.

———. 2000b. "Knowledge, Technology, and Economic growth During the Industrial Revolution."In Bart Van Ark, Simon K. Kuipers, and Gerard Kuper, eds., *Productivity, Technology and Economic Growth,* pp. 253-92. The Hague: Kluwer Academic Press.

———. 2000d. "Innovation and Selection in Evolutionary Models of Technology: Some Definitional Issues." In John Ziman, ed., *Technological Innovation as an Evolutionary Process,* pp. 52–65. Cambridge: Cambridge University Press.

———. 2002, forthcoming. "King Kong and Cold Fusion: Counterfactual analysis and the History of Technology." In Philip Tetlock, Ned Lebow, and Geoffrey Parker, eds., *Counterfactual Analysis in History and the Social Sciences.*

Mokyr, Joel, and Rebecca Stein. 1997. "Science, Health and Household Technology: The Effect of the Pasteur Revolution on Consumer Demand." In Robert J. Gordon and Timothy Bresnahan, eds., *The Economics of New Products,* pp.143–205. Chicago: University of Chicago Press and NBER.

Morison, Elting E. 1966. "Gunfire at Sea: A Case Study of Innovation." In *Men, Machines, and Modern Times.* Cambridge, Mass.: MIT Press.

Morris, Morris D. 1983. "The Growth of Large-Scale Industry till 1947." In Dharma Kumar, ed., *The Cambridge Economic History of India.* Vol. 2. Cambridge: Cambridge University Press.

Morris, William. 1973. "Useful Work versus Useless Toil." In *The Political Writings of William Morris.* Edited by A. L. Morton. London: Lawrence and Wishart.

Morus, Iwan Rhys. 1998. *Frankenstein's Children : Electricity, Exhibition, and Experiment in Early-Nineteenth-Century London.* Princeton, N.J.: Princeton University Press.

Mowery, David C., and Nathan Rosenberg. 1989. *Technology and the Pursuit of Economic Growth.* Cambridge: Cambridge University Press.

———. 1998. *Paths of Innovation: Technological Change in Twentieth- Century America.* Cambridge: Cambridge University Press.

Murmann, Johann Peter. 1998. "Knowledge and Competitive Advantage in the Synthetic Dye Industry, 1850–1914." Ph. D. dissertation, Columbia University.

Murmann, Johann Peter, and Ralph Landau. 1998. "On the Making of Competitive Advantage: The Development of the Chemical Industries of Britain and Germany since 1850." In Ashish Arora, Ralph Landau, and Nathan Rosenberg, eds., *Chemicals and Long-Term Economic Growth,* pp. 27–70. New York: John Wiley.

Murphy, Kevin M., Andrei Shleifer, and Robert W. Vishny. 1991. "The Allocation of Talent: Implications for Growth." *Quarterly Journal of Economics* 106, no. 2 (May), pp. 503-30.

Musson, A. E. 1978. *The Growth of British Industry.* London: Batsford.

Musson, A. E., and Eric Robinson. 1969. *Science and Technology in the Industrial Revolution.* Manchester: Manchester University Press.

Needham, Joseph. 1959. *Mathematics and the Sciences of Heaven.* In Joseph Needham, ed., *Science and Civilization in China.* Vol. 3. Cambridge: Cambridge University Press.

———. 1969. *The Grand Titration.* Toronto: University of Toronto Press.

Nelkin, Dorothy. 1992. "Science, Technology and Political Conflict." In Dorothy Nelkin, ed., *Controversy: Politics of Technical Decisions.* London: Sage Publications.

Nelkin, Dorothy, and Michael Pollack. 1981. *The Atom Besieged.* Cambridge, Mass.: MIT Press.

Nelson, Katherine, and Richard Nelson. 2002. "On the Nature and Evolution of Human Know-how." *Research Policy* 31, No. 5, (July), pp. 719-33.

Nelson, Marie C., and John Rogers, 1992. "Cleaning Up the Cities: the First Comprehensive Public Health Law in Sweden." Unpublished paper. Presented to the SSHA meetings, Chicago.

Nelson, Richard R. 1994. "Economic Growth through the Co-evolution of Technology and Institutions." In Loet Leydesdorff and Peter Van Den Besselaar, eds., *Evolutionary Economics and Chaos Theory: New Directions in Technology Studies.* New York: St. Martin's Press.

———. 1995. "Recent Evolutionary Theorizing about Economic Change." *Journal of Economic Literature* 33, no. 1 (March), pp. 48–90.

———. 1996. *The Sources of Economic Growth.* Cambridge, Mass.: Harvard University Press.

———. 2000a. "Selection Criteria and Selection Processes in Cultural Evolution Theories." In John Ziman, ed., *Technological Innovation as an*

Evolutionary Process, pp. 66–74. Cambridge: Cambridge University Press.

———. 2000b. "Knowledge and Innovation Systems." Unpublished manuscript, Columbia University.

Nelson, Richard R., and Nathan Rosenberg. 1993. "The U.S. National Innovation System." In Richard Nelson, ed., *National Innovation Systems: a Comparative Analysis,* pp. 3–21. New York: Oxford University Press.

Nelson, Richard R., and Sidney Winter. 1982. *An Evolutionary Theory of Economic Change.* Cambridge, Mass.: The Belknap Press.

Newman, George. 1907. *Infant Mortality: A Social Problem.* New York: E. P. Dutton and Company.

Nicholson, John. 1826. *The Operative Mechanic and the British Machinist.* Philadelphia: H. C. Carey.

Nicolaou, K.C., and Christopher N. C. Boddy. 2001. "Behind Enemy Lines." *Scientific American* 284, no. 5 (May), pp. 52–61.

Nieto-Galan, Agustí. 1997. "Calico Printing and Chemical Knowledge in Lancashire in the Early Nineteenth century: The Life and 'Colors' of John Mercer." *Annals of Science* 54, no. 1 (January), pp. 1–28.

Noble, David F. 1984. *Forces of Production: A Social History of Industrial Automation.* New York: Alfred A. Knopf.

Nooteboom, Bart. 1999. "Innovation, Learning and Industrial Organization." *Cambridge Journal of Economics* 23, no. 2 (March), pp. 127–150.

Nordhaus, William D. 1997. "Do Real-Output and Real-Wage Measures Capture Reality? The History of Lighting Suggests Not." In Robert J. Gordon and Timothy Bresnahan, eds., *The Economics of New Goods,* pp. 29–65. Chicago: University of Chicago Press and NBER.

Nordhaus, William D., and James Tobin. 1973. "Is Growth Obsolete?" In Milton Moss, ed., *The Measurement of Economic and Social Performance.* New York: Columbia University Press for the NBER.

North, Douglass C. 1981. *Structure and Change in Economic History.* New York: W. W. Norton.

———. 1990. *Institutions, Institutional Change, and Economic Performance.* Cambridge: Cambridge University Press.

North, Douglass C., and Barry Weingast. 1989. "Constitutions and Commitment: The Evolution of Institutions Governing Public Choice in Seventeenth Century England." *Journal of Economic History* 49, no. 4 (Dec.), pp. 803–32.

Nuland, Sherwin B. 1988. *Doctors: The Biography of Medicine.* New York: Alfred A. Knopf.

O'Brien, Patrick, Trevor Griffiths, and Philip Hunt. 1991. "Political Components of the Industrial Revolution: Parliament and the English Cotton Textile

Industry, 1660–1774." *Economic History Review* 44, no. 3 (Aug.), pp. 395–423.

O'Shea, M. V., and J. H. Kellogg. 1921. *Health and Cleanliness.* New York: Macmillan.

Olson, Mancur. 1982. *The Rise and Decline of Nations.* New Haven: Yale University.

Owen, Robert. [1857] 1920. *The Life of Robert Owen by Himself.* London: G. Bell and Sons.

Pannabecker, John R. 1998. "Representing Mechanical Arts in Diderot's *Encyclopédie.*" *Technology and Culture* 39, no. 1 (Jan.), pp. 33–73.

Papillon, Ferdinand. 1874. "Ferments, Fermentation, and Life." *Popular Science Monthly* 5 (September), pp. 542–56.

Parente, Stephen L., and Edward C. Prescott, 2000. *Barriers to Riches.* Cambridge, Mass.: MIT Press.

Parker, William N. 1984. *Europe, America, and the Wider World.* Cambridge: Cambridge University Press.

Partridge, William. [1823] 1973. *A Practical Treatise on Dying of Woollen, Cotton, and Skein Silk.* Edington, Wiltshire: Pasold Research Fund.

Pavitt, Keith, and W. Edward Steinmueller. 2002. "Technology in Corporate Strategy: Change, Continuity and the Information Revolution." In Andrew Pettigrew, Howard Thomas, and Richard Whittington, eds., *The Handbook of Strategy and Management.* New York: Sage Publications.

Payne, Peter. 1990. "Entrepreneurship and British Economic Decline." In Bruce Collins and Keith Robbins, eds., *British Culture and Economic Decline*, pp. 25–58. New York: St. Martin's Press.

Perkin, Harold. 1969. *The Origins of Modern English Society 1780–1880*, London: Routledge & Kegan Paul.

Perrin, Noel. 1979. *Giving Up the Gun: Japan's Reversion to the Sword, 1543–1879.* Boston: David R. Godine.

Perutz, M. F. 1992."The Fifth Freedom" *New York Review of Books*, Oct. 8, 1992.

Petty, William. 1679. *A Treatise of Taxes and Contributions.* London: Obadiah Blagrave.

Picon, Antoine. 2001. "Technology." In Michel Delon, ed., *Encyclopedia of the Enlightenment*, pp. 1317–23. Chicago: Fitzroy Dearborn.

Pinault Sørensen, Madeleine. 2001. "Encyclopedia." In Michel Delon, ed., *Encyclopedia of the Enlightenment*, pp. 439–44. Chicago: Fitzroy Dearborn.

Piore, Michael J, and Charles F. Sabel. 1984. *The Second Industrial Divide.* New York: Basic Books.

Pirenne, Henri. 1936. *Economic and Social History of Medieval Europe.* New York: Harcourt Brace & World.

Planck, Max. 1949. *Scientific Autobiography and Other Papers.* New York: Philosophical Library.

Plotkin, Henry. 1993. *Darwin, Machines, and the Nature of Knowledge.* Cambridge, Mass.: Harvard University Press.

Plunkett, H. M. (Mrs.). 1885. *Women, Plumbers, and Doctors.* New York: Appleton.

Polanyi, Michael. 1962. *Personal Knowledge: Towards a Post-Critical Philosophy.* Chicago: Chicago University Press.

Pollard, Sidney. [1965] 1968. *The Genesis of Modern Management.* London: Penguin.

Pollock, Linda A. 1983. *Forgotten Children: Parent-Child Relations from 1500–1900.* Cambridge: Cambridge University Press.

Pomeranz, Kenneth. 2000. *The Great Divergence: China, Europe, and the Making of the Modern World Economy.* Princeton, N.J.: Princeton University Press.

Porter, Roy. 1973. "The Industrial Revolution and the Rise of the Science of Geology." In Mikuláš Teich and Robert Young, eds., *Changing Perspectives in the History of Science.* London: Heinemann.

———. 1995. "The Eighteenth century." In Lawrence Konrad et al., eds. *The Western Medical Tradition, 800* BC *to* AD *1800.* Cambridge: Cambridge University Press.

———. 1997. *The Greatest Benefit to Mankind: A Medical History of Humanity.* New York: W. W. Norton.

Porter, Theodore. 1986. *The Rise of Statistical Thinking, 1820–1900.* Princeton, N.J.: Princeton University Press.

Preston, Samuel H., and Michael R. Haines. 1991. *Fatal Years: Child Mortality in Late Nineteenth Century America.* Princeton, N. J.: Princeton University Press.

Price, Derek J. de Solla. 1984a. "Notes towards a Philosophy of the Science/Technology Interaction" In Rachel Laudan, ed., *The Nature of Knowledge: are Models of Scientific Change Relevant?* Dordrecht: Kluwer.

———. 1984b. "Of Sealing Wax and String." *Natural History,* no. 1, pp. 49–56.

Pyenson, Lewis, and Susan Sheets-Pyenson. 1999. *Servants of Nature: A History of Scientific Institutions, Enterprises and Sensibilities.* New York: W. W. Norton.

Radkau, Joachim. 1995. "Learning from Chernobyl for the Fight against Genetics?" In Martin Bauer, ed., *Resistance to New Technology,* pp. 335–55. Cambridge: Cambridge University Press.

Randall, Adrian J. 1986. "The Philosophy of Luddism: The Case of the West of England Workers, ca. 1790–1809." *Technology and Culture* 27, no. 1 (Jan.), pp. 1–17.

———. 1989. "Work, Culture and Resistance to Machinery in the West of England Woollen Industry." In Pat Hudson, ed., *Regions and Industries: A Perspective on the Industrial Revolution in Britain*, pp. 175–98. Cambridge: Cambridge University Press.

———. 1991. *Before the Luddites.* Cambridge: Cambridge University Press.

Rankine, William J. M. [1859] 1873. *A Manual of the Steam Engine and other Prime Movers.* 6th ed., London: Charles Griffin.

Reddy, William M. 1984. *The Rise of Market Culture: The Textile Trade and French Society, 1750–1900.* Cambridge: Cambridge University Press.

Redelmeier, Donald A., and Amos Tversky. 1996. "On the Belief That Arthritis Pain Is Related to Weather." *Proceedings of the National Academy of Sciences* 93, no. 7 (April 2), pp. 2895–96.

Redelmeier, Donald A., Derek J. Koehler, Varda Liberman, and Amos Tversky. 1995. "Probability Judgment in Medicine." *Medical Decision Making* 15, no. 3 (July–Sept.), pp. 227–30.

Redford, Arthur. [1926] 1976. *Labour Migration in England, 1800–1850.* Manchester: Manchester University Press.

Reid, Margaret. 1934. *Economics of Household Production.* New York: John Wiley.

Reilly, Robin. 1992. *Josiah Wedgwood 1730–1795.* London: Macmillan.

Reiser, Stanley Joel. 1978. *Medicine and the Reign of Technology.* Cambridge: Cambridge University Press.

Reiter, Stanley. 1992. "Knowledge, Discovery and Growth." Discussion Paper 1011. Northwestern University Center for Mathematical Studies in Economics and Management Sciences.

Reynolds, Terry S. 1983. *Stronger Than a Hundred Men: A History of the Vertical Water Wheel.* Baltimore: Johns Hopkins University Press.

Richards, Robert J. 1987. *Darwin and the Emergence of Evolutionary Theories of Mind and Behavior.* Chicago: University of Chicago Press.

Rider, Robin E. 1990. "Measure of Ideas, Rule of Language: Mathematics and Language in the eighteenth Century," in Tore Frängsmyr, J. L. Heilbron and Robin E. Rider, eds., *The Quantifying Spirit in the 18th Century*, pp. 113–40. Berkeley: University of California Press.

Rifkin, Jeremy. 1983. *Algeny: A New Word, A New World.* Harmondsworth, Eng.: Penguin Books.

———. 1985. *Declaration of a Heretic.* Boston: Routledge & Kegan Paul.

Riley, James C. 1987. *The Eighteenth-Century Campaign to Avoid Disease.* New York: St. Martin's Press.

———. 1991. "Working Health Time: A Comparison of Preindustrial, Industrial, and Post-Industrial Experience in Life and Health." *Explorations in Economic History* 28, no. 2 (April), pp. 169–91.

Riley, James. 2001. *Rising Life Expectancy: A Global History.* Cambridge: Cambridge University Press.

Roberts, Elizabeth. 1984. *A Woman's Place: An Oral History of Working-Class Women, 1890–1940.* Oxford: Blackwell.

Roberts, Kristin, and Peter Rupert. 1995. "The Myth of the Overworked American." *Economic Commentary.* Federal Reserve Bank of Cleveland. January 15.

Robinson, Eric, and Douglas McKie, eds. 1970. *Partners in Science: Letters of James Watt and Joseph Black.* Cambridge, Mass.: Harvard University Press.

Robinson, John P. 1980. "Housework Technology and Household Work." In Sarah Fenstermaker Berk, ed., *Women and Household Labor.* New York: Russell Sage Foundation.

Robinson, John P., and Geoffrey Godbey.1997. *Time for Life: The Surprising Ways Americans Use Their Time.* University Park: Pennsylvania State University Press.

Rogers, Naomi. 1989. "Germs with Legs: Flies, Disease and the New Public Health." *Bulletin of the History of Medicine* 63, no. 4 (Winter), pp. 599–617.

———. 1992. *Dirt and Disease: Polio before FDR.* New Brunswick, N.J.: Rutgers University Press.

Rollet-Echalier, Catherine. 1990. *La politique a l'égard de la petite enfance sous la III^e République.* Paris: Presses Universitaires de France.

Rosen, George. 1947. "What Is Social Medicine? A Genetic Analysis of the Concept." *Bulletin of the History of Medicine* 21, no. 5 (Sept.–Oct.), pp. 674–733.

———. 1993. *A History of Public Health.* New ed. Baltimore: Johns Hopkins University Press.

Rosenband, Leonard N. 2000. *Papermaking in Eighteenth Century France.* Baltimore: Johns Hopkins University Press.

Rosenberg, Nathan. 1976. *Perspectives on Technology.* Cambridge: Cambridge University Press.

———. 1982. "How Exogenous is Science?" In *Inside the Black Box: Technology and Economics.* Cambridge: Cambridge University Press.

———. 1994. *Exploring the Black Box.* New York: Cambridge University Press.

———. 1996."Uncertainty and Technological change." In Jeffrey C. Fuhrer and Jane Sneddon Little, *eds., Technology and Growth,* pp. 91–110. Federal Reserve Bank of Boston, Conference Series, no. 40.

———. 1998a. "Chemical Engineering as a General Purpose Technology." In Elhanan Helpman, ed., *General Purpose Technologies,* pp. 167–92. Cambridge, Mass.: MIT Press. 1998.

———. 1998b. "Technological Change in Chemicals: The role of University-Industry Relations." In Ashish Arora, RalphLandau, and Nathan Rosenberg, eds., *Chemicals and Long-Term Economic Growth*, pp. 193–230. New York: John Wiley.

Rosenberg, Nathan, ed., 1969. *The American System ofManufactures: The Report of the Committee on the Machinery of the United States, 1855.* Edinburgh: Edinburgh University Press.

Rosenberg, Nathan, and L. E. Birdzell. 1986. *How the West Grew Rich: The Economic Transformation of the Industrial World.* New York: Basic Books.

Rosenberg, Nathan, and Walter G. Vincenti. 1978. *The Britannia Bridge: The Generation and Diffusion of Technological Knowledge.* Cambridge, Mass.: MIT. Press.

Ross, Lee, and Craig A. Anderson. 1982. "Shortcomings in the Attribution Process: On the Origins and Maintenance of Erroneous Social Assessments." In Daniel Kahneman, Paul Slovic, and Amos Tversky, eds., *Judgment under Uncertainty: Heuristics and Biases,* pp. 128–52. Cambridge: Cambridge University Press.

Rothstein, William G. 1972. *American Physicians in the Nineteenth Century.* Baltimore: Johns Hopkins University Press.

Rumsey, Henry. 1875. *Essays and Papers on Some Fallacies of Statistics Concerning Life and Death, Health and Disease.* London: Smith, Elder & Co.

Rupreht, J., and Th. E. Keys, 1985. "Anaesthesiology: its Origins and its Mission." In J. Rupreht et. al., eds., *Anaesthesia: Essays on Its History,* pp. 3–8. Berlin: Springer Verlag.

Rusnock, Andrea A. 1990. "The Quantification of Things Human: Medicine and Political Arithmetic in Enlightenment England and France." Ph.D. dissertation, Princeton University.

Russell, Cheryl. 1996. "How Many Home Workers?" *American Demographics* 18, no. 5 (May), pp. 6–7.

Ruttan, Vernon W. 2001. *Technology, Growth, and Development: An Induced Innovation Perspective.* New York: Oxford University Press.

Ryle, Gilbert. 1949. *The Concept of Mind.* Chicago: University of Chicago Press.

Sabel, Charles, and Jonathan Zeitlin. 1985. "Historical Alternatives to Mass Production: Politics, Markets, and Technology in Nineteenth-Century Industrialization." *Past and Present* no. 108 (Aug.), pp. 133–176.

Sachs, Jeffrey, and Andrew Warner. 1995. "Economic Reform and the Process of Global Integration." *Brookings Papers on Economic Activity* no. 1, pp. 1–95.

Sale, Kirkpatrick. 1995. *Rebels against the Future: The Luddites and Their War on the Industrial Revolution.* Reading, Mass.: Addison Wesley.

Saviotti, Pier Paolo. 1996. *Technological Evolution, Variety, and the Economy.* Cheltenham, Eng.: Edward Elgar.

Scerri, Eric R. 1998. "The Evolution of the Periodic System." *Scientific American* 279, no. 3 (Sept.), pp. 78–83.

Schaffer, Simon. 1999. "Enlightened Automata." In William Clark, Jan Golinski, and Simon Schaffer, eds., *The Sciences in Enlightened Europe,* pp. 126–65. Chicago: University of Chicago Press.

Scheffler, Israel. 1965. *Conditions of Knowledge.* Chicago: Scott, Foresman and Co.

Schelling, Thomas C. 1992. "Self-Command: A New Discipline." In George Loewenstein and Jon Elster, eds., *Choice over Time,* pp. 167–76. New York: Russell Sage Foundation.

Schiff, Eric. 1971. *Industrialization without National Patent.* Princeton, N.J.: Princeton University Press.

Schofield, Robert. 1972. "The Industrial Orientation of Science in the Lunar Society of Birmingham." in A. E. Musson, ed., *Science, Technology and Economic Growth in the Eighteenth Century.* London: Methuen.

Schor, Juliet B. 1991. *The Overworked American.* New York: Basic Books.

Schumpeter, J. A. 1950. *Capitalism, Socialism and Democracy.* New York: Harper and Row.

———. [1934] 1969. *The Theory of Economic Development.* London: Oxford University Press.

Schweber, Silvan S. 1980. "Darwin and the Political Economists: Divergence of Character." *Journal of the History of Biology* 13, no. 2 (Fall), pp. 195–289.

———. 1985. "The Wider British Context in Darwin's Theorizing." In David Kohn, ed., *The Darwinian Heritage.* Princeton, N.J.: Princeton University Press.

Scranton, Philip. 1997. *Endless Novelty: Specialty Production and American Industrialization, 1865–1925.* Princeton, N.J.: Princeton University Press.

Sella, Domenico. 1979. *Crisis and Continuity: The Economy of Spanish Lombardy in the Seventeenth Century.* Cambridge, Mass.: Harvard University Press.

Shackle, G.L.S. 1972. *Epistemics and Economics: A Critique of Economic Doctrines.* Cambridge: Cambridge University Press.

Shapin, Steven. 1994. *The Social History of Truth.* Chicago: University of Chicago Press.

———. 1996. *The Scientific Revolution.* Chicago: University of Chicago Press.

Shaw, George Bernard. 1913. *The Doctor's Dilemma.* New York: Brentano's.

Shiva, Vandana. 1991. *The Violence of the Green Revolution.* London: Zed Books.

Simon, Herbert. 1996. "Economic Rationality: Adapted Artifice." In *The Sciences of the Artificial.* Cambridge Mass.: MIT Press.

Slovic, Paul, Baruch Fischoff, and Sarah Lichtenstein. 1982. "Facts vs. Fears: Understanding perceived Risks." In Daniel Kahneman, Paul Slovic, and Amos Tversky, eds., *Judgment under Uncertainty: Heuristics and Biases.* Cambridge: Cambridge University Press.

Smelser, Neil J. 1959. *Social Change in the Industrial Revolution.* Chicago: University of Chicago Press.

Smil, Vaclav. 2001. *Enriching the Earth: Fritz Haber, Carl Bosch and the Transformation of World Food Production.* Cambridge, Mass.: MIT Press.

Smiles, Samuel. 1891. *Lives of the Engineers.* London: Clowes and Sons.

———. [1863] 1967. *Industrial Biography: Iron Workers and Tool Makers.* Newton-Abbot: David & Charles.

Smith, Adam. [1776] 1976. *The Wealth of Nations.* Edited by Edwin Cannan. Chicago: University of Chicago Press.

———. [1795] 1982. "The History of Astronomy." In *Essays on Philosophical Subjects.* Indianapolis: Liberty Classics.

Smith, Crosbie. 1990. "Energy." In R. C. Olby et al., eds., *Companion to the History of Science.* London: Routledge.

Smith, Crosbie, and M. Norton Wise. 1989. *Energy and Empire: a Biographical Study of Lord Kelvin.* Cambridge: Cambridge University Press.

Smith, Cyril Stanley. 1960. *A History of Metallography.* Chicago: University of Chicago Press.

———. 1967. "Metallurgy in the Seventeenth and Eighteenth Century." In Melvin Kranzberg and Carroll W. Pursell, Jr., eds., *Technology in Western Civilization.* Vol. 1, pp. 142–67. New York: Oxford University Press.

Smith, F. B. 1979. *The People's Health 1830–1910.* New York: Holmes & Meier.

Smith, John Graham. 1979. *The Origins and Early Development of the Heavy Chemical Industry in France.* Oxford: Clarendon Press.

———. 2001. "Science and Technology in the Early French Chemical Industry." Unpublished paper, presented to the colloquium on "Science, techniques, et Sociétés," Paris.

Smith, Merritt Roe. 1977. *Harper's Ferry Armory and the New Technology.* Ithaca: Cornell University Press.

———. 1994. "Technological Determinism in American Culture." In Merritt Roe Smith and Leo Marx, eds., *Does Technology Drive History?* pp. 2–35. Cambridge Mass.: MIT Press.

Sparrow, W. J. 1964. *Knight of the White Eagle.* London: Hutchinson and Co.

Spielman, Andrew, and Michael D'Antonio. 2001. *Mosquito: a Natural History of our most Persistent and Deadly Foe.* New York: Hyperion.

Stage, Sarah, and Virginia Vincenti, eds. 1997. *Home Economics: Women and the History of a Profession.* Ithaca, N.Y.: Cornell University Press.

Staudenmaier, John M. 1989. "Perils of Progress Talk: Some Historical Considerations." In Steven Goldman, ed., *Science, Technology, and Social Progress,* pp. 268–93. Bethlehem, Penn.: Lehigh University Press.

Steedman, Carolyn. 1992. "Bodies, Figures, and Physiology: Margaret McMillan and the Late Nineteenth-Century Remaking of Working-Class Childhood." In Roger Cooter, ed., *In the Name of the Child: Health and Welfare, 1880–1940.* London: Routledge.

Stenseth, N. C. 1985. "Darwinian Evolution in Ecosystems: the Red Queen View." In P. J. Greenwood, P. H. Harvey, and M. Slatkin, eds., *Evolution: Essays in Honour of John Maynard Smith,* pp. 55–72. Cambridge: Cambridge University Press.

Stephens, Trent, and Rock Brynner. 2001. *Dark Remedy: The Impact of Thalidomide and Its Revival as a Vital Medicine.* Cambridge, Mass.: Perseus Publishing.

Stern, Bernhard J. 1937. "Resistances to the Adoption of Technological Innovations." In *Technological Trends and National Policy.* Washington, D.C.: United States Government Printing Office.

Stern, Fritz. 1961. *The Politics of Cultural Despair. A Study in the Rise of the Germanic Ideology.* Berkeley: University of California Press.

Stevens, Edward W., Jr. 1995. *The Grammar of the Machine: Technical Literacy and Early Industrial Expansion in the United States.* New Haven, Conn.: Yale University Press.

Stevenson, John. 1979. *Popular Disturbances in England, 1700–1870.* New York: Longman.

Stewart, Larry. 1992. *The Rise of Public Science.* Cambridge: Cambridge University Press.

Stokes, Donald E. 1997. *Pasteur's Quadrant: Basic Science and Technological Innovation.* Washington, D.C.: Brookings Institution.

Strasser, Susan M. 1980. "An Enlarged Human Existence? Technology and Household Work in Nineteenth Century America." In Sarah Fenstermaker Berk, ed., *Women and Household Labor,* New York: Russell Sage Foundation.

Strickland, Amanda. 1999. "Telecommuters Raise Productivity." *Triangle Business Journal* (Raleigh, N.C.) 15 (Oct.), p. 24.

Styles, John. 1983. "Embezzlement, Industry, and the Law in England, 1500–1800." In Maxine Berg, Pat Hudson, and Michael Sonenscher, eds., *Manufacture in Town and Country before the Factory,* pp. 173–208. Cambridge: Cambridge University Press.

Sugden, Robert. 1989. "Spontaneous Order." *Journal of Economic Perspectives* 3, no. 4 (Fall), pp. 85–97.

Szostak, Rick. 1989. "The Organization of Work: The Emergence of the Factory Revisited." *Journal of Economic Behavior and Organization* 11, no. 3 (May), pp. 343–58.

———. 1991. *The Role of Transportation in the Industrial Revolution.* Montreal: McGill-Queen's University Press.

Szreter, Simon. 1988. "The Importance of Social Intervention in Britain's Mortality Decline, c. 1850–1914: A Re-interpretation of the Role of Health." *Social History of Medicine* 1, no. 1 (April), pp. 1–37.

Tann, Jennifer. 1970. *The Development of the Factory.* London: Cornmarket Press.

Taton, R. 1957. *Reason and Chance in Scientific Discovery.* New York: Philosophical Library.

Teece, David, Richard Rumelt, Giovanni Dosi, and Sidney Winter. 1994. "Understanding Corporate Coherence." *Journal of Economic Behavior and Organization* 23, no. 1 (Jan.), pp. 1–30.

Tegmark, Max, and John Archibald Wheeler. 2001. "One Hundred Years of Quantum Mysteries." *Scientific American,* 284 no. 2 (Feb.), pp. 68–75.

Temin, Peter. 1997. "Is It Kosher to Talk about Culture?" *Journal of Economic History* 57, no. 2 (June), pp. 267–87.

Tenner, Edward. 1997. *Why Things Bite Back: Technology and the Revenge of Unintended Consequences.* New York: Alfred A. Knopf.

Thomas, Carol. 1995. "Domestic Labour and Health: Bringing It All Back Home." *Sociology of Health and Illness* 17, no. 3 (June), pp. 328–52.

Thomis, Malcolm. 1972. *The Luddites.* New York: Schocken.

Thompson, E. P. 1963. *The Making of the English Working Class.* New York: Vintage Books.

Thompson, Silvanus P. 1898. *Michael Faraday: His Life and Work.* London: Cassell and Co.

Thomson, Ross. 2002. "The Birth and Significance of the Machinist." Unpublished ms., Stanford University.

Thorne, Stuart. 1986. *The History of Food Preservation.* Totowa, N.J.: Barnes and Noble Books.

Thurston, Robert. 1878. *A History of the Growth of the Steam Engine.* New York: D. Appleton.

Tomes, Nancy. 1990. "The Private Side of Public Health: Sanitary Science, Domestic Hygiene, and the Germ Theory." *Bulletin of the History of Medicine* 64, no. 4 (Winter), pp. 509–39.

———. 1998. *The Gospel of Germs: Men, Women and the Microbe in American Life.* Cambridge, Mass.: Harvard University Press.

Travis, Anthony. 1989. "Science as Receptor of Technology: Paul Ehrlich and the Synthetic Dyestuff Industry," *Science in Context* 3, no. 2 (Autumn), pp. 383–408.

Tuttle, Carolyn. 1999. *Hard at Work in Factories and Mines: The Economics of Child Labor during the British Industrial Revolution.* Boulder, Colo.: Westview Press.

Unwin, George. [1924] 1968. *Samuel Oldknow and the Arkwrights.* New York: Kelley.

Ure, Andrew. 1835. *The Philosophy of Manufactures; or, An Exposition of the Scientific, Moral, and Commercial Economy of the Factory System of Great Britain.* London: C. Knight.

———. 1839. *Dictionary of Arts, Manufactures and Mines.* London: Longman and Co.

Usher, Abbott Payson. 1920. *An Introduction to the Industrial History of England.* Boston: Houghton Mifflin.

———. 1954. *A History of Mechanical Inventions.* Cambridge, Mass.: Harvard University Press.

Vanek, Joann. 1974. "Time Spent in Housework." *Scientific American* 231, no. 5 (Nov.), pp. 116–20.

Vermeij, Geerat J. 1994. "The Evolutionary Interaction among Species: Selection, Escalation, and Coevolution." *Annual Review of Ecological Systems* 25, pp. 219–236.

Vigarello, Georges. 1988. *Concepts of Cleanliness: Changing Attitudes in France since the Middle Ages.* Translated by Jean Birrell. Cambridge: Cambridge University Press.

Vincenti, Walter. 1990. *What Engineers Know and How They Know It.* Baltimore: Johns Hopkins University Press.

———. 2000. "Real-World Variation-Selection in the Evolution of Technological Form: Historical Examples." In John Ziman, ed., *Technological Innovation as an Evolutionary Process,* pp. 174–89. Cambridge: Cambridge University Press.

Vinikas, Vincent. 1992. *Soft Soap, Hard Sell: American Hygiene in an Age of Advertisement.* Ames: Iowa State University.

Viscusi, W. Kip. 1992. *Smoking: Making the Risky Decision.* New York: Oxford University Press.

Volkov, Shulamit. 1978. *The Rise of Popular Antimodernism in Germany.* Princeton, N.J.: Princeton University Press.

Von Tunzelmann, G. N. 1995. *Technology and Industrial Progress.* Aldershot, Eng.: Edward Elgar.

Voth, Hans-Joachim. 1998. "Time and Work in Eighteenth Century London." *Journal of Economic History* 58, no. 1 (March), pp. 29–58.

Wadsworth, A. P., and J. De Lacy Mann. 1931. *The Cotton Trade and Industrial Lancashire.* Manchester: Manchester University Press.

Ward, Barbara. 1964. *India and the West.* New York: W. W. Norton.

Weber, Max. [1923] 1961. *General Economic History.* New York: Collier Books.

Weinberg, Steven. 2001. "Can Science Explain Everything? Anything?" *New York Review of Books* 48, no. 9 (May 31), pp. 47–50.

Weitzman, Martin. 1996. "Hybridizing Growth Theory." *American Economic Review* 86, no. 2, (May), pp. 207–13.

Wengenroth, Ulrich. 2002 forthcoming. "Science, Technology, and Industry in the Nineteenth Century." In David Cahan, ed., *From Natural Philosophy to the Sciences: Historiography of Nineteenth-Century Science*, Chicago: University of Chicago Press.

Wesson, Robert. 1991. *Beyond Natural Selection.* Cambridge, Mass.: MIT Press.

White, Lynn. 1968. *Dynamo and Virgin Reconsidered.* Cambridge, Mass.: MIT Press.

———. 1978. *Medieval Religion and Technology.* Berkeley: University of California Press.

Wiener, Martin J. 1981. *English Culture and the Decline of the Industrial Spirit, 1850–1980.* Cambridge: Cambridge University Press.

Wildavsky, Aaron. 1991. *The Rise of Radical Egalitarianism.* Washington, D.C.: The American University Press.

Williams, Perry. 1991. "The Laws of Health: Women, Medicine and Sanitary Reform, 1850–1890." In Marina Benjamin, ed., *Science and Sensibility: Gender and Scientific Enquiry,* pp. 60–88. Oxford: Basil Blackwell.

Williams, Raymond. 1958. *Culture and Society, 1780–1950.* New York: Columbia University Press.

Williamson, Oliver. 1980. "The Organization of Work: A Comparative Institutional Assessment." *Journal of Economic Behavior and Organization* 1, pp. 5–38.

Winchester, Simon. 2001. *The Map That Changed the World.* New York: Harper Collins.

Winner, Langdon. 1977. *Autonomous Technology: Technics-out-of-Control as a Theme in Political Thought.* Cambridge, Mass.: MIT Press.

Wise, M. Norton. 1988. "Mediating Machines." *Science in Context* 2, no. 1 (Spring), pp. 77–113.

Wohl, Anthony S. 1983. *Endangered Lives: Public Health in Victorian Britain.* Cambridge, Mass.: Harvard University Press.

Wolcott, Susan. 1994. "The Perils of Lifetime Employment Systems: Productivity Advance in the Indian and Japanese Textile Industries, 1920–1938." *Journal of Economic History* 54, no. 2 (June), pp. 307–24.

Wood, Henry Trueman. 1913. *A History of the Royal Society of Arts.* London: John Murray.

Woods, Robert, I. 1984. "Mortality Patterns in the Nineteenth Century." In Robert Woods and John Woodward, eds., *Urban Disease and Mortality in Nineteenth Century England,* pp. 19–36. New York: St. Martin's Press.

Woods, Robert I., P. A. Watterson, and J. H. Woodward. 1988–89. "The Causes of Rapid Infant Mortality Decline in England and Wales, 1861–1921." *Population Studies* 42, no. 3 (Nov.), pp. 343–66 and 43, no. 1 (March), pp. 113–32.

Woolrich, A. P. 2000. "John Farey and His *Treatise on the Steam Engine* of 1827." *History of Technology* 22, pp. 63–106.

Wright, Esmond. 1986. *Franklin of Philadelphia.* Cambridge, Mass.: Harvard University Press.

Wrigley, E. A. 2000. "The Divergence of England: the Growth of the English Economy in the Seventeenth and Eighteenth Centuries." *Transactions of the Royal Historical Society* 10 (6th series), pp. 117–41.

Wrigley, Julia. 1986. "Technical Education and Industry in the Nineteenth Century." In Bernard Elbaum and William Lazonick, eds., *The Decline of the British Economy,* pp. 162–88. Oxford: Clarendon Press.

Wuketits, Franz. 1990. *Evolutionary Epistemology and Its Implications for Humankind.* Albany: SUNY Press.

Youngson, A. J. 1979. *The Scientific Revolution in Victorian Medicine.* New York: Holmes and Meier Publishers.

Zelizer, Viviana A. 1985. *Pricing the Priceless Child: The Changing Social Value of Children.* New York: Basic Books.

Zilsel, Edgar. 1942. "The Sociological Roots of Science." *American Journal of Sociology* 47, no. 4 (Jan.), pp. 544–60.

Ziman, John. 1976. *The Force of Knowledge.* Cambridge: Cambridge University Press.

———. 1978. *Reliable Knowledge: An Exploration of the Grounds for Belief in Science.* Cambridge: Cambridge University Press.

———. 2000. "Selectionism and Complexity." In John Ziman, ed., *Technological Innovation as an Evolutionary Process,* pp. 41–51. Cambridge: Cambridge University Press.

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