The Gifts of Athena

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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 Lieb, Jason Long, John Nye, Rebecca Stein, James Stewart, Rick Szostak, and Simone Wegge. Chapter 4 is deeply indebted to Tom Geraghty's dissertation, "Technology, Organization and Complementarity: The Factory System in the British Industrial Revolution." Tom Geraghty and Jason Long generously provided me with information collected for the purpose of their dissertation research.

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.

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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

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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 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

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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).

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 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

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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.

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 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

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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).

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 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

[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.

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 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.

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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.

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 continuous 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

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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.

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

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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.

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 "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,

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[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.

[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).

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 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 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

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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 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).

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 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

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[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).

[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).

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 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

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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.

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 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

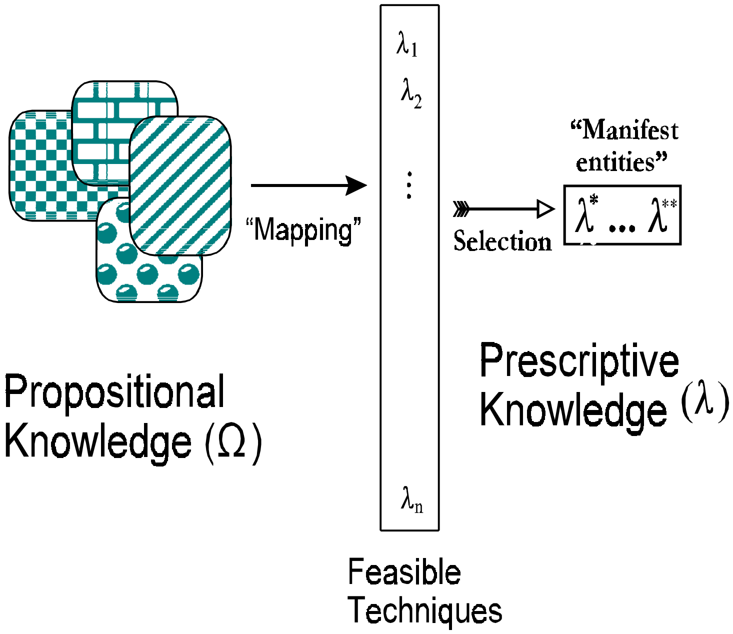

Figure 1: Propositional and Prescriptive Knowledge

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

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

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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

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 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

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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.

[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).

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 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 pro--

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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.

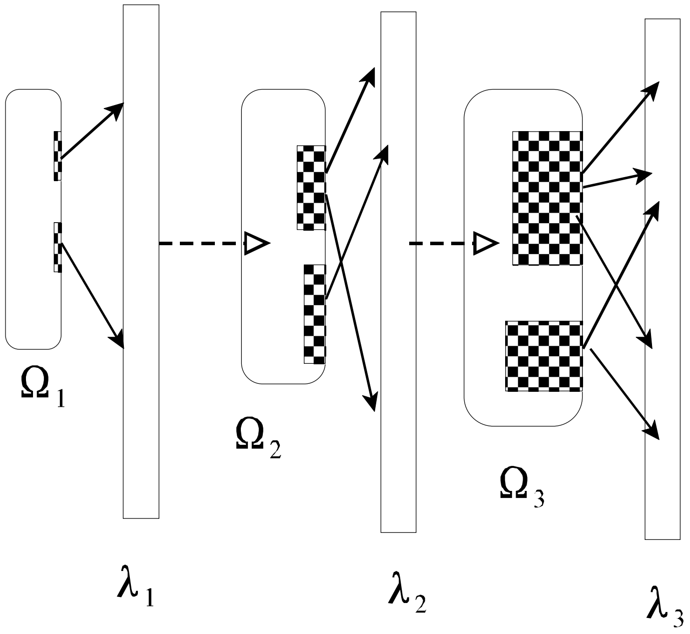

Figure 2: Feedback between Propositional and Prescriptive Knowledge

duction 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 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

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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).

would be equally irresponsible to ignore that new technology and useful knowledge have some commodity-like attributes and 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 is enormous.

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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).

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]

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

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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.

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 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.

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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.

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 micro-inventions 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.

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

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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).

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 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,

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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.

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 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

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

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 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

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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.

[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)

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 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

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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.

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 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

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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.

[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.

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 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

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[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 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.

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 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] 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

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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 (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).

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 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

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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.

"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 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

[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

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 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

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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 [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 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 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

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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).

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 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

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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.

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. 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 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

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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).

[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).

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 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

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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).

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 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

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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.

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 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

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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).

system of discovery about nature, driven by curiosity or other "internal factors" only weakly motivated by the economic needs they 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

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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).

techniques that happen to "express" information adapted to a new environment.

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

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 reliable

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writers on the topic. William Hamilton, the translator of Berthollet's *Art of Dyeing*, 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).

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 *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

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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).

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] 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

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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.

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 Measures codifying much of the existing system.[46] Standardizations had been attempted

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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).

[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.

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 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

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[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.

"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 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,

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[50] Alder (1998, p. 513) distinguishes between three levels of mechanical drawing in pre-revolutionary 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).

[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).

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 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

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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).

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 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 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

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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.

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]

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

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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.

[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).

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 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

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[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 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).

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 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,

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[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).

[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.

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 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*

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[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 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 unrelated 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.

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 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

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[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).

[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).

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. 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

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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).

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 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

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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

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 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

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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.

[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).

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 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

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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).

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 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

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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).

reasons for such lateness, and Spain, Ireland, and the Netherlands—all "Western" societies—proved in one way or another 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 non-linear 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