Chapter 17

LONG-TERM ECONOMIC GROWTH AND THE HISTORY OF TECHNOLOGY

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Contents

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Abstract

Modern economic growth started in the West in the early nineteenth century. This survey discusses the precise connection between the Industrial Revolution and the beginnings of growth, and connects it to the intellectual and economic factors underlying the growth of useful knowledge. The connections between science, technology and human capital are re-examined, and the role of the eighteenth century Enlightenment in bringing about modern growth is highlighted. Specifically, the paper argues that the Enlightenment changed the agenda of scientific research and deepened the connections between theory and practice.

Keywords

Industrial Revolution, economic growth, technological progress, access costs, useful knowledge

JEL classification: N13, O31, O41

Some of the material in this chapter is adapted from my books *The Lever of Riches: Technological Creativity and Economic Change*, Oxford University Press, New York, 1990; *The Gifts of Athena: Historical Origins of the Knowledge Economy*, Princeton University Press, Princeton, 2002 and *The Enlightened Economy: An Economic History of Britain, 1700–1850*, Penguin Press, Harmondsworth, 2004, as well as from a number of more detailed papers available upon request.

1. Introduction

As every economist knows, the modern era is the era of economic growth. In the past two centuries, measures of output per capita have increased dramatically and in a sustained manner, in a way they had never done before. It seems by now a consensus to term the start of this phenomenon "the Industrial Revolution", although it is somewhat in dispute what precisely is meant by that term [Mokyr (1998b)]. In the past two decades an enormous literature has emerged to explain this phenomenon. A large number of "deep" questions have emerged which this literature has tried to answer. Below I list the most pertinent of these questions and in the subsequent pages, I shall make an attempt to answer them.

1. What explains the *location* of the Industrial Revolution (in Europe as opposed to the rest of the world, in Britain as opposed to the rest of Europe, in certain regions of Britain as opposed to others). What role did geography play in determining the main parameters of the Industrial Revolution?
2. What explains the *timing* of the Industrial Revolution in the last third of the eighteenth century (though the full swing of economic growth did not really start until after 1815)? Could it have started in the middle ages or in classical antiquity?
3. Is sustained economic growth and continuous change the "normal" state of the economy, unless it is blocked by specific "barriers to riches" or is the stationary state the normal condition, and the experience of the past 200 years is truly a revolutionary regime change?
4. What was the role of technology in the origins of the Industrial Revolution and the subsequent evolution of the more dynamic economies in which rapid growth became the norm?
5. What was the relation between demographic behavior (and specifically the fall in mortality after 1750 and the subsequent decline in fertility and shift toward fewer but higher-quality children) in bringing about and sustaining modern economic growth?
6. What was the role of institutions (in the widest sense of the word) in bringing about modern economic growth, and to what extent can we separate it from other factors such as technology and factor accumulation?
7. To what extent is modern growth due to "culture", that is, intellectual factors regarding beliefs, attitudes, and preferences? Does culture normally adapt to the

economic environment, or can one discern autonomous cultural changes that shaped the economy?

8. Did the “Great Divergence” really start only in the eighteenth century, and until then the economic performance and potential of occident and the orient were comparable, or can signs of the divergence be dated to the renaissance or even the middle ages?
9. Was the Industrial Revolution “inevitable” in the sense that the economies a thousand years earlier already contained the seeds of modern economic growth that inexorably had to sprout and bring it about?
10. What was the exact role of human capital, through formal education or other forms, in bringing about modern economic growth?

2. Technology and economic growth

Economists have become accustomed to associate long-term economic growth with technological progress; it is deeply embedded in the main message of the Solow-inspired growth models, which treated technological change as exogenous, and even more so in the endogenous growth models.[1] An earlier growth literature regarded technology as a deus ex machina that somehow made productivity grow miraculously a little each year. The more modern literature views it as being produced within the system by the rational and purposeful application of research and development and the growth of complementary human and physical capital. The historical reality inevitably finds itself somewhere in between those two poles, and what is interesting above all is the shift of the economies of the West in that continuum. Whatever the case may be, technology is central to the dynamic of the economy in the past two centuries. Many scholars believe that people are inherently innovative and that if only the circumstances are right (the exact nature of these conditions differs from scholar to scholar), technological progress is almost guaranteed. This somewhat heroic assumption is shared by scholars as diverse as Robert Lucas and Eric L. Jones, yet it seems at variance with the historical record before the Industrial Revolution. That record is that despite many significant, even path-breaking innovations in many societies since the start of written history, it has not really been a major factor in economic growth, such as it was, before the Industrial Revolution.

Instead, economic historians studying earlier periods have come to realize that technology was less important than institutional change in explaining pre-modern episodes of economic growth. It is an easy exercise to point to the many virtues of “Smithian Growth”, the increase in economic output due to commercial progress (as opposed to technological progress). Better markets, in which agents could specialize according to

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[1] The opening line of the standard textbook in the area states that the “most basic proposition of growth theory is that in order to sustain a positive growth rate of output per capita in the long run, there must be continual advances in technological knowledge” [Aghion and Howitt (1997, p. 11)].

their comparative advantage and take full advantage of economies of scale, and in which enhanced competition would stimulate allocative efficiency and the adoption of best-practice technology could generate growth sustainable for decades and even centuries. Even with no changes whatsoever in technology, economies can grow in the presence of peace, law and order, improved communications and trust, the introduction of money and credit, enforceable and secure property rights, and similar institutional improvements [Greif (2003)]. Similarly, better institutions can lead to improved allocation of resources: law and order and improved security can and will encourage productive investment, reduce the waste of talent on rent-seeking and the manipulation of power for the purposes of redistribution [North (1990), Shleifer and Vishny (1998) and Baumol (2002)]. Tolerance for productive "service minorities" who lubricated the wheels of commerce (Syrians, Jews and many others) played important roles in the emergence of commerce and credit. Economic history before 1750 is primarily about this kind of growth. The wealth of Imperial Rome and the flourishing of the medieval Italian and Flemish cities, to pick just a few examples, were based above all on commercial progress, sometimes referred to as "Smithian Growth".[2]

It is usually assumed by economists that sustained economic growth is a recent phenomenon simply because if modern rates of growth had been sustained, a simple backward projection suggests that income in 1500 or in 1000 would have been absurdly low.[3] Clearly, growth at the rates we have gotten used to in the twentieth century are unthinkable in the long run. Yet it is equally implausible to think that just because growth was slower, there was *none* of it – after all, there is a lot of time in the long run. One does not have to fully subscribe to Graeme Snooks' use of Domesday book and Gregory King's numbers 600 years later to accept his view that by 1688 the British economy was very different indeed from what it had been at the time of William the Conqueror. Adam Smith had no doubt that "the annual produce of the land and labour of England . . . is certainly much greater than it was a little more than century ago at the restoration of Charles II (1660) . . . and [it] was certainly much greater at the restoration than we can suppose it to have been a hundred years before" [Smith (1976 [1776], pp. 365–366)].[4] On the eve of the Industrial Revolution, large parts of Europe and some

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[2] To be sure, much of this commerce was closely related to the manufacturing bases of the surrounding area, such as woolen cloth production in Flanders or the production of glass in Venice.

[3] For instance, income per capita in the UK in 1890 was about $4100 in 1990 international dollars. It grew in the subsequent years by an average of 1.4% per year. Had it been growing at that same rate in the previous 300 years, income per capita in 1590 would have been $61, which clearly seems absurdly low.

[4] Snooks (1994) belief in pre-modern growth is based essentially on his comparison between the income per capita he has calculated from the Domesday book (1086) and the numbers provided by Gregory King for 1688. While such computations are of course always somewhat worrisome (what, exactly, does it mean to estimate the nominal income of 1086 in the prices of 1688 given the many changes in consumption items?), the order of magnitude provided by Snooks (an increase of real income by 580 percent) may survive such concerns. Maddison (2001, p. 265) estimates that GDP per capita in constant prices increased at a rate of 0.13 percent in Western Europe between 1000 and 1500 and 0.15% between 1500 and 1820. In the UK and the Netherlands growth between 1500 and 1820 was about 0.28 percent per year. Medievalists tend to agree with the

parts of Asia were enjoying a standard of living that had not been experienced ever before, in terms of the quantity, quality, and variety of consumption.[5] Pre-1750 growth was primarily based on Smithian and Northian effects: gains from trade and more efficient allocations due to institutional changes. The Industrial Revolution, then, can be regarded not as the beginnings of growth altogether but as the time at which technology began to assume an ever-increasing weight in the generation of growth and when economic growth accelerated dramatically. An average growth rate of 0.15–0.20% per annum, with high year-to-year variation and frequent setbacks was replaced by a much more steady growth rate of 1.5% per annum and better. Big differences in degree here are tantamount to differences in quality. This transition should not be confused with the demographic transition, which came later and whose relationship with technological progress is complex and poorly understood.[6]

This is not to say that before the Industrial Revolution technology was altogether unimportant in its impact on growth. Medieval Europe was an innovative society which invented many important things (including the mechanical clock, movable type, gunpowder, spectacles, iron-casting) and adopted many more inventions from other societies (paper, navigational instruments, Arabic numerals, the lateen sail, wind power). Yet, when all is said and done, it is hard to argue that the impact of these inventions on the growth of GDP or some other measure of aggregate output were all that large. The majority of the labor force was still employed in agriculture where progress was exceedingly slow (even if over the long centuries between 800 and 1300 the three-field system and the growing efficiency at which livestock was employed did produce considerable productivity gains).

Moreover, it is true for the pre-1750 era – as it was a fortiori after 1750 – that technology itself interacted with Smithian growth because on balance improved technology made the expansion of trade possible – above all maritime technology in all its many facets, but also better transport over land and rivers, better military technology to defeat

occurrence of economic growth in Britain, though their figures indicate a much slower rate of growth, about a 111 percent growth rate between 1086 and 1470 [Britnell (1996, p. 229)], which would require more economic growth in the sixteenth and seventeenth centuries than can be justified to square with Snooks' numbers. Engerman (1994, p. 116) assesses that most observers will agree with Snooks' view that by 1700 England had a high level of per capita income and was in a good position to "seek the next stage of economic growth". Yet clearly he is correct in judging that "modern" economic growth (prolonged, continuous, rapid) did not begin until the early nineteenth century.

[5] Indeed, many historians speak of a "consumer revolution" *prior to* the Industrial Revolution, which would be inexplicable without rising income before 1750. Lorna Weatherill (1988) suggests that if there was a Consumer Revolution at all, it peaked in the period 1680–1720. Moreover, consumer revolutions were taking place elsewhere in Europe. Seventeenth century Holland was, of course, the most obvious example thereof, but Cissie Fairchilds (1992) has employed pro bate records to show that France, like England, experienced a consumer revolution, albeit fifty years later.

[6] It is in that sense that the view of modern economists [e.g. Galor and Weil (2000, p. 809)] that "the key event that separates Malthusian and post-Malthusian regimes is the acceleration of the pace of technological progress" is a bit misleading, since it draws a link between technological progress and demographic change that thus far has not been closely examined.

pirates, better knowledge of remote lands, and the growing ability to communicate with strangers. A decomposition of growth into a technology component and a trade-and-institutions component must take into account such interactions.

All the same, the main reason why technological progress was at best an also-ran in the explanation of economic growth before 1750 is that even the best and brightest mechanics, farmers, and chemists – to pick three examples – knew relatively little of what could be known about the fields of knowledge they sought to apply. The pre-1750 world produced, and produced well. It made many pathbreaking inventions. But it was a world of engineering without mechanics, iron-making without metallurgy, farming without soil science, mining without geology, water-power without hydraulics, dye-making without organic chemistry, and medical practice without microbiology and immunology. Not enough was known to generate sustained economic growth based on technological change.[7] Such statements are of course to some extent provocative and perhaps even irresponsible: how can we define "what could be known" in any meaningful sense? Who knew "that which was known" and how did they use it? In what follows I shall propose a simple framework to understand how and why new technology emerges and how it was limited before the eighteenth century and then liberated from its constraints. I will then argue that "technological modernity" means an economy in which *sustained* technological progress is the primary engine of growth and that it depended on the persistence of technological progress. What is needed is a good theory of the kind of factors that make for sustained technological progress.

Such a theory needs to stress the basic complementarity between the creation and diffusion of new technology and the institutional factors that allowed this knowledge to be applied, become profitable, and lead to economic expansion. These institutional factors – such as the establishment of intellectual property rights, the supply of venture capital, the operation of well-functioning commodity and labor markets, and the protection of innovators and entrepreneurs against a technological reaction – are of central importance but they have been discussed elsewhere [Mokyr (1998a, 2003b)] and in what follows the focus will be on the growth of knowledge itself. All the same, it should be kept in mind that growth cannot result from a growth of knowledge *alone*. It needs to occur in an environment in which knowledge can be put to work.

3. A historical theory of technology

Technology is knowledge. Knowledge, as is well known, has always been a difficult concept for standard economics to handle. It is at the core of modern economic growth,

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[7] The great agronomist Arthur Young sighed hopefully in 1772 that while in his day the farmers were largely ignorant of the "peculiar biasses" of individual soils, perhaps "one day the nature of all soils and the vegetables they particularly affect will be known experimentally . . . a desideratum in natural philosophy worthy of another Bacon" [Young (1772, p. 168)].

but many characteristics make it slippery to handle. Knowledge is above all a non-rivalrous good, that is, sharing it with another person does not diminish the knowledge of the original owner. It is not quite non-excludable, but clearly excludability is costly and for many types of knowledge exclusion costs are infinite. It is produced in the system, but the motivation of its producers are rarely purely economic. Indeed, the producers of scientific knowledge almost never collect but a tiny fraction of the surplus they produce for society. It is the mother of all spillover effects. A more fruitful approach than to view knowledge as an odd sort of good, pioneered by Olsson (2000, 2003), is to model knowledge as a set, and to analyze its growth in terms of the properties of existing knowledge rather than looking at the motivations of individual agents.

The basic unit of analysis of technology is the "technique". A technique is a set of instructions, much like a cookbook recipe, on how to produce goods and services. As such, it is better defined than the concept of a stock of "ideas" that some scholars prefer [e.g., Charles Jones 2001]. The entire set of feasible techniques that each society has at its disposal is bound by the isoquant. Each point on or above the isoquant in principle represents a set of instructions on how to combine various ingredients in some way to produce a good or service that society wants. While technology often depends on artifacts, the artifacts are not the same as the technique and what defines the technique is the content of the instructions. Thus, a piano is an artifact, but what is done with it depends on the technique used by the pianist, the tuner, or the movers. Society's production possibilities are bound by what society knows. This knowledge includes the knowledge of designing and building artefacts and using them.

But who is "society"? The only sensible way of defining knowledge at a social level is as the *union* of all the sets of individual knowledge. This definition is consistent with our intuitive notion of the concept of an invention or a discovery – at first only *one* person has it, but once that happens, society as a whole feels it has acquired it. Knowledge can be stored in external storage devices such as books, drawings, and artifacts but such knowledge is meaningless unless it can be transferred to an actual person. Such a definition immediately requires a further elaboration: if one person possesses a certain knowledge, how costly is it for others to acquire it? This question, indeed is at the heart of the idea of a "technological society". Knowledge is shared and distributed, and its transmission through learning is essential for such a society to make effective use of it. Between the two extremes of a society in which all knowledge acquired by one member is "episodic" and not communicated to any other member, and the other extreme in which all knowledge is shared instantaneously to all members through some monstrous network, there was a reality of partial and costly sharing and access. But these costs were not historically invariant, and the changes in them are one of the keys to technological change.

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)]. Access costs include the costs of finding out whether an answer to a question actually exists, if so, where it can be found, then paying the cost of acquiring it, and finally verifying the correctness of the knowledge. When the access costs become very high, it could be said in the limit that social knowledge has disappeared.[8] Language, mathematical symbols, diagrams, and physical models are all means of reducing access costs. Shared symbols may not always correspond precisely 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. The other component of access cost, tightness, is largely determined by the way society deal with authority and trust. It is clear that propositional knowledge is always and everywhere far larger that any single individual can know. The concepts of trust and authority are therefore central to the role that propositional knowledge can play in society, and how it is organized is central to the economic impact of useful knowledge. In the scientific world of the late seventeenth and eighteenth centuries, a network of trust and verification emerged in the West that seems to have stood the test of time. It is well described by Polanyi (1962, pp. 216–222): the space of useful knowledge is divided in small neighboring units. If an individual B is surrounded by neighbors A and C who can verify his work, and C is similarly surrounded by B and D and so on, the world of useful knowledge reaches an equilibrium in which science, as a whole, can be trusted even by those who are not themselves part of it.

The determinants of these access costs are both institutional and technological: "open knowledge" societies, in which new discoveries are published as soon as they are made and in which new inventions are placed in the public domain through the patenting system (even if their application may be legally restricted), are societies in which access costs will be lower than in societies in which the knowledge is kept secret or confined to a small and closed group of insiders whether they are priests, philosophers, or mandarins. Economies that enjoyed a high level of commerce and mobility were subject to knowledge through the migration of skilled workmen and the opportunities to imitate and reverse-engineer new techniques. As access costs fell in the early modern period, it became more difficult to maintain intellectual property rights through high access costs, and new institutions that provided incentives for innovators became necessary, above all the patent system emerging in the late fifteenth and sixteenth centuries. The printing press clearly was one of the most significant access-cost-reducing inven-

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[8] 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.

tions of the historical past.[9] The nature of the books printed, such as topic, language, and accessibility, played an equally central role in their reduction. People normally acquired knowledge and skills vertically, but also from one another through imitation. Postdoctoral students in laboratory settings full-well realize the differences between the acquisition of codifiable knowledge and the acquisition of tacit knowledge through imitation and a certain *je ne sais quoi* we call experience.[10] Improvements in transport and communication technology, that made people more mobile and speeded up the movement of mail and newspapers also reduced access costs in the second half of the eighteenth century, a movement that continued through the nineteenth century and has not stopped since.

Techniques constitute what I have called *prescriptive* knowledge – like any recipe they essentially comprise instructions that allow people to "produce", that is, to exploit natural phenomena and regularities in order to improve human material welfare.[11] The fundamental unit of set of prescriptive knowledge has the form of a set of do-loops (often of great complexity, with many if–then statements), describing the "hows" of what we call production.

There are two preliminary observations we need to point out in this context. One is that it is impossible to specify explicitly the entire content of a set of instructions. Even a simple cooking recipe contains a great deal of assumptions that the person executing the technique is supposed to know: how much a cup is, when water is boiling, and so on. For that reason, the person executing a technique is supposed to have certain knowledge that I shall call *competence* to distinguish it from the knowledge involved in writing the instructions for the first time (that is, actually making the invention). Competence consists of the knowledge of how to read, interpret, and execute the instructions in the technique and the supplemental tacit knowledge that cannot be fully written down in the technique's codified instructions. There is a continuum between the implicit understandings and clever tricks that make a technique work we call tacit knowledge, and

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[9] 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).

[10] 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.

[11] These instructions are similar to the concept of "routines" proposed by Nelson and Winter (1982). When these instructions are carried out in practice, we call it production, and then they are no longer knowledge but action. "Production" here 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. It is comparable to DNA instructions being "expressed". Much like instructions in DNA, the lines in the technique can be either "obligate" (do X) or "facultative" (if Y, do X). For more complex techniques, nested instructions are the rule.

the minor improvements and refinements introduced subsequent to invention that involve actual adjustments in the explicit instructions. The latter would be more properly thought off as microinventions, but a sharp distinction between them would be arbitrary. All the same, "competence" and "knowledge" are no less different than the differences in skills needed to play the Hammerklavier sonata and those needed to compose it. One of the most interesting variables to observe is the ratio between the knowledge that goes into the first formulation of the technique in question (invention) and the competence needed to actually carry out the technique. As we shall see, it is this ratio around which the importance of human capital in economic growth will pivot.

The second observation is the notion that every technique, because it involves the manipulation and harnessing of natural regularities, requires an *epistemic base*, that is, a knowledge of nature on which it is based. I will call this type of knowledge *propositional* knowledge, since it contains a set of propositions about the physical world. The distinction between propositional and prescriptive knowledge 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 (1962) notes that the distinction is recognized by patent law, which permits the patenting of inventions (additions to prescriptive knowledge) but not of discoveries (additions to propositional knowledge). He points out that the difference boils down to observing that prescriptive knowledge can be "right or wrong" whereas "action can only be successful or unsuccessful" (p. 175). Purists will object that "right" and "wrong" are judgments based on socially constructed criteria, and that "successful" needs to be defined in a context, depending on the objective function that is being maximized.

The two sets of propositional and prescriptive knowledge together form the set of useful knowledge in society. These sets satisfy the conditions set out by Olsson (2000) for his "idea space". Specifically, the sets are infinite, closed, and bounded. They also are subsets of much larger sets, the sets of knowable knowledge. At each point of time, the actual sets describe what a society knows and consequently what it can do. There also is a more complex set of characteristics that connect the knowledge at time t with that in the next period. Knowledge is mostly cumulative and evolutionary. The "mostly" is added because it is not wholly cumulative (knowledge *can* be lost, though this has become increasingly rare) and its evolutionary features are more complex than can be dealt with here [Mokyr (2003a)].

The actual relation between propositional and prescriptive knowledge can be summarized in the following 10 generalizations:

1. Every technique has a minimum epistemic base, which contains the least knowledge that society needs to possess for this technique to be invented. The epistemic base contains at the very least the trivial statement that technique i works.[12]

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[12] This statement is true because the set of propositional knowledge contains as a subset the list (or catalog) of the techniques that work – since that statement can be defined as a natural regularity.

There are and have been some techniques, invented accidentally or through trial and error, about whose modus operandi next to nothing was known except that they worked. We can call these techniques *singleton* techniques (since their domain is a singleton).

2. Some techniques require a minimum epistemic base larger than a singleton for a working technique to emerge. It is hard to imagine the emergence of such techniques as nuclear resonance imaging or computer assisted design software in any society from serendipitous finds or trial-and-error methods, without the designers having a clue of why and how they worked.
3. The actual epistemic base is equal to or larger than the minimum epistemic base. It is never bound from above in the sense that the amount that can be known about the natural phenomena that govern a technique is infinite. In a certain sense, we can view the epistemic base at any given time much like a fixed factor in a production function. As long as it does not change, it imposes concavity and possibly even an upper bound on innovation and improvement. On the other hand, beyond a certain point, the incremental effect of widening the actual epistemic base on the productivity growth of a given technique will run into diminishing returns and eventually be limited.
4. There is no requirement that the epistemic base be “true” or “correct” in any sense. In any event, the only significance of such a statement would be that it conforms to contemporary beliefs about nature (which may well be refuted by future generations). Thus the humoral theory of disease, now generally rejected, formed the epistemic base of medical techniques for many centuries. At the same time, some epistemic bases can be more effective than others in the sense that techniques based on them perform “better” by some agree-upon criterion. “Effective knowledge” does not mean “true knowledge” – many techniques were based on knowledge we no longer accept yet were deployed for long periods with considerable success.[13]
5. The wider the actual epistemic base supporting a technique relative to the minimum one, the more likely an invention is to occur, ceteris paribus. A wider epistemic base means that it is less likely for a researcher to enter a blind alley and to spend resources in trying to create something that cannot work.[14] Thus, a wider epistemic base reduces the costs of research and development and increases the likelihood of success.

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[13] Here one can cite many examples. Two of them are the eighteenth century metallurgical writings and inventions of René Réaumur and Tobern Bergman, firmly based on phlogiston physics, and the draining of swamps based on the belief that the “bad air” they produced caused malaria.

[14] Alchemy – the attempt to turn base metals into gold by chemical means – was still a major occupation of the best minds of the scientific revolution above all Isaac Newton. By 1780 Alchemy was in sharp decline and in the nineteenth century chemists knew enough to realize that it was a misallocation of human capital to search for the stone of the wise or the fountain of youth. The survival of astrology in our time demonstrates that the prediction of the future – always a technique based on a very narrow epistemic base – has not benefited in a similar way from a widening of the prescriptive knowledge on which it was based.

6. The wider the epistemic base, the more likely an existing technique is to be improved, adapted, and refined through subsequent microinventions. The more is known about the principles of a technique, the lower will be the costs of development and improvement. This is above all because the more is known *why* something works, the better the inventor can tweak its parameters to optimize and debug the technique. Furthermore, because invention so often consists of analogy with or the recombination of existing techniques, lower access cost to the catalog of existing techniques (which is part of propositional knowledge) stimulates and streamlines successful invention.
7. Historically, the epistemic bases in existence during the early stages of an invention are usually quite narrow at first, but in the last two centuries have often been enlarged following the appearance of the invention, and sometimes directly on account of the invention.
8. Both propositional and prescriptive knowledge can be "tight" or "untight". Tightness measures the degree of confidence and consensualness of a piece of knowledge: how sure are people that the knowledge is "true" or that the technique "works"? The tighter a piece of propositional knowledge, the lower are the costs of verification and the more likely a technique based on it is to be adopted, and vice versa. Of course, tightness is correlated with effectiveness: a laser printer works better than a dot matrix, and there can be little dispute about the characteristics here. If two techniques are based on incompatible epistemic bases, the one that works better will be chosen and the knowledge on which it is based will be judged to be more effective. But for much of history, such testing turned out to be difficult to do and propositional knowledge was more often selected on the basis of authority and tradition that effectiveness. Even today, for many medical and farming techniques it is often difficult to observe what works and what does not work as well without careful statistical analysis or experimentation.
9. It is not essential that the person writing the instructions actually knows himself everything that is in the epistemic base. 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. It is a fortiori true that the people carrying out a set of instructions do not know how and why these instructions work, and what the support for them is in propositional knowledge. No doctor prescribing nor any patient taking an aspirin will need to study the biochemical properties of prostaglandins, though such knowledge may be essential for those scientists working on a design of an analgesic with, say, fewer side effects. What counts is collective knowledge and the cost of access as discussed above. It is even less necessary for the people actually carrying out the technique to possess the knowledge on which it is based, and normally this is not the case.
10. The existence of a minimum epistemic base is a necessary but insufficient condition for a technique to emerge. A society may well accumulate a great deal of propositional knowledge that is never translated into new and improved tech-

niques. Knowledge opens doors, but it does not force society to walk through them.

4. The significance of the Industrial Revolution

Historians in the 1990s have tended to belittle the significance of the Industrial Revolution as a historical phenomenon, referring to it as the so-called Industrial Revolution, and pointing to the slowness and gradualness of economic change, as well as the many continuities that post 1760 Britain had with earlier times [for a critical survey, see Mokyr (1998b)].

Before I get to the heart of the argument, two points need to be cleared away. The first is the myth that the Industrial Revolution was a purely British affair, and that without Britain's leadership Europe today would still be largely a subsistence economy. The historical reality was that many if not most of the technological elements of the Industrial Revolution were the result of a joint international effort in which French, German, Scandinavian, Italian, American and other "western" innovators collaborated, swapped knowledge, corresponded, met one another, and read each others' work.

It is of course commonplace that in most cases the first successful economic *applications* of the new technology appeared in Britain. By 1790 Britain had acquired an advantage in the execution of new techniques. Yet an overwhelming British advantage in *inventing* – especially in generating the crucial macroinventions that opened the doors to a sustained trajectory of continuing technological change – is much more doubtful, and their advantage in expanding the propositional knowledge that was eventually to widen the epistemic bases of the new techniques is even more questionable. Britain's technological precociousness in the era of the Industrial Revolution was a function of three factors.

First, by the middle of the eighteenth century Britain had developed an institutional strength and agility that provided it with a considerable if temporary advantage over its Continental competitors: it had a healthier public finance system, weaker guilds, no internal tariff barriers, a superior internal transportation system, fairly well-defined and enforceable property rights on land (enhanced and modified by Parliamentary acts when necessary), and a power structure that favored the rich and the propertied classes. Moreover, it had that most elusive yet decisive institutional feature that makes for economic success: the flexibility to adapt its economic and legal institutions without political violence and disruptions. Britain's great asset was not so much that she had "better" government but rather that its political institutions were nimbler, and that they could be changed at low social cost by a body assigned to changing the rules and laws by which the economic game was played. Many of the rules still on the books in the eighteenth century were not enforced, and rent seeking arrangements, by comparison, were costly to attain and uncertain in their yield. British mercantilist policy was already in decline on the eve of the Industrial Revolution. Yet as the Industrial Revolution unfolded, it required further change in the institutional basis of business. The Hanoverian governments in Britain were venal and nepotist, and much of the business of government was intended to enrich politicians. On the Continent matters were no better. But with the growing notion that rent seeking was harmful, this kind of corruption weakened [Mokyr (2003b)]. As Porter (1990, p. 119) put it, with the rise of the laissez faire lobby, Westminster abandoned its long-standing mercantilist paternalism, repealing one regulation after another. Abuses may have been deep rooted, and entrenched rent-seekers resisted all they could, but from the last third of the eighteenth century on rent-seeking was on the defensive, and by 1835 many of the old institutions had vanished, and the British state, for a few decades, gave up on redistributing income as a main policy objective. Following North (1990, p. 80) we might call this adaptive efficiency, meaning not only the adaptation of the allocation of resources but of the institutions themselves. To bring this about, what was needed was a meta-institution with a high degree of legitimacy, such as parliament, that was authorized to change the rules in a consensual manner.

Second, Britain's entrepreneurs proved uncannily willing and able to adopt new inventions regardless of where they were made, free from the "not made here" mentality of other societies. Some of the most remarkable inventions made on the Continent were first applied on a wide scale in Britain. Among those, the most remarkable were gaslighting, chlorine bleaching, the Jacquard loom, the Robert continuous paper-making machine, and the Leblanc soda making process. In smaller industries, too, the debt of the British Industrial Revolution to Continental technology demonstrates that in no sense did Britain monopolize the inventive process.[15] The British advantage in application must be chalked up largely to its comparative advantage in microinventions and in the supply of the human capital that could carry out the new techniques.[16] To employ the

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[15] The great breakthrough in plate glass was made in France by a Company founded in the 1680s, which cast a far superior product by pouring it over a perfectly smooth metallic table, a concept as simple in principle as it was hard to carry out in practice but perfected by the St. Gobain company. The British tried for many decades to copy the process, but never matched the French for quality Harris (1992b, p. 38). The most important subsequent breakthrough in the glass industry was made in 1798 by Pierre Louis Guinand, a Swiss, who invented the stirring process in which he stirred the molten glass in the crucible using a hollow cylinder of burnt fireclay, dispersing the air bubbles in the glass more evenly. The technique produced optical glass of unprecedented quality. Guinand kept his process secret, but his son sold the technique to a French manufacturer in 1827, who in turn sold it to the Chance Brothers Glass Company in Birmingham, which soon became one of the premier glassmakers in Europe. The idea of preserving food by cooking followed by vacuum sealing was hit upon by the Frenchman Nicolas Appert in 1795. Appert originally used glassware to store preserved foods, but in 1812 an Englishman named Peter Durand suggested using tin-plated cans, which were soon found to be superior. By 1814, Bryan Donkin was supplying canned soups and meats to the Royal Navy.

[16] This was already pointed by Daniel Defoe, who pointed out in 1726 that "the English . . . are justly fam'd for improving Arts rather than inventing" and elsewhere in his Plan of English Commerce that "our great Advances in Arts, in Trade, in Government and in almost all the great Things we are now Masters of and in which we so much exceed all our Neighbouring Nations, are really founded upon the inventions of others". The great engineer John Farey, who wrote an important treatise on steam power, testified a century later that "the prevailing talent of English and Scotch people is to apply new ideas to use, and to bring such applications to perfection, but they do not imagine as much as foreigners".

terminology proposed earlier: Britain may not have had more propositional knowledge available for its invention and innovation process, but if it workers possessed higher levels of competence, then the new techniques that emerged were more likely to find their first applications there. Its successful system of informal technical training, through master-apprentice relationships, created workers of uncommon skill and mechanical ability [Humphries (2003)]. Britain also was lucky to have a number of successful industries that generated significant technical spillovers to other industries.[17] This system produced, of course, inventors: the most famous of these such as the clockmakers John Harrison and Benjamin Huntsman, the engineer John Smeaton, the instrument maker Jesse Ramsden, the wondrously versatile inventor Richard Roberts, the chemists James Keir and Joseph Black, and of course Watt himself were only the first row of a veritable army of people, who in addition to possessing formal knowledge, were blessed by a technical intuition and dexterity we identify as the very essence of tacit knowledge.

Third, Britain was at peace in a period when the Continent was engulfed in political and military upheaval. Not only that there was no fighting and political chaos on British soil; the French revolution and the Napoleonic era was a massive distraction of talent and initiative that would otherwise have been available to technology and industry.[18] The attention of both decision makers and inventors was directed elsewhere.[19] During the stormy years of the Revolution, French machine breakers found an opportunity to mount an effective campaign against British machines, thus delaying their adoption [Horn (2003)].

Compared to Britain, the Continental countries had to make a greater effort to cleanse their economic institutions from medieval debris and the fiscal ravages of absolutism,

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[17] A number of high-skill sectors that had developed in Britain since 1650 played important roles in later technological development. Among those instrument- and clock-making, mining, and ship yards were of central importance. Cardwell (1972, p. 74) points out that a number of basic technologies converge on mining (chemistry, civil engineering, metallurgy) and that mining sets the hard, “man-sized” problems, controlling powerful forces of nature and transforming materials on a large scale. In addition, however, British millwrights were technologically sophisticated: the engineer John Fairbairn, a millwright himself, noted that eighteenth century British millwrights were “men of superior attainments and intellectual power”, and that the typical millwright would have been “a fair arithmetician, knew something of geometry, levelling and mensuration and possessed a very competent knowledge of practical mechanics” [cited in Musson and Robinson (1969, p. 73)].

[18] The chemists Claude Berthollet and Jean-Antoine Chaptal, for instance, both directed their abilities to administration during the Empire. Their illustrious teacher, the great Lavoisier himself, was executed as a tax farmer. Another example is Nicolas de Barneville, who was active in introducing British spinning equipment into France. De Barneville repeatedly was called upon to serve in military positions and was “one of those unfortunate individuals whose lives have been marred by war and revolution … clearly a victim of the troubled times” [McCloy (1952, pp. 92–94)].

[19] The Frenchman Philippe LeBon, co-inventor of gas-lighting in the 1790s, lost out in his race for priority with William Murdoch, the ingenious Boulton and Watt engineer whose work in the end led the introduction of this revolutionary technique in the illumination of the Soho works in 1802. As one French historian sighs, “during the terrors of the Revolution … no one thought of street lights. When the mob dreamed of lanterns, it was with a rather different object in view” [cited by Griffiths (1992, p. 242)].

undo a more complex and pervasive system of rent seeking and regulation, and while extensive reforms were carried out in France, Germany, and the Low Countries after the French Revolution, by 1815 the work was still far from complete and had already incurred enormous social costs. It took another full generation for the Continent to pull even. All the same, none of the British advantages was particularly deep or permanent. They explain Britain's position as the lead car in the Occident Express that gathered steam in the nineteenth century and drove away from the rest of the world, but it does not tell us much about the source of power. Was Britain the engine that pulled the other European cars behind it, or was Western Europe like an electric train deriving its motive power from a shared source of energy?

One useful mental experiment is to ask whether there would have been an Industrial Revolution in the absence of Britain. A counterfactual industrial revolution led by Continental economies would have been delayed by a few decades and differed in some important details. It might have relied less on "British" steam and more on "French" water power and "Dutch" wind power technology, less on cotton and more on wool and linen. It would probably have had more of an *étatist* and less of a free-market flavor, with a bigger emphasis on military engineering and public projects. Civil servants and government engineers might have made some decisions that were made by entrepreneurs. But in view of the capabilities of French engineers and German chemists, the entrepreneurial instincts of Swiss and Belgian industrialists, and the removal of many institutions that had hampered the effective deployment of talents and resources on the Continent before 1789, a technological revolution would have happened not all that different from what actually transpired. Even without Britain, by the twentieth century the 1914 gap between Europe and the rest of the world would have been there [Mokyr (2000)].

The second point to note is that the pivotal element of the Industrial Revolution took place later than is usually thought. The difference between the Industrial Revolution of the eighteenth century and other episodes of a clustering of macroinventions was not just in the celebrated inventions in the period 1765–1790. While the impact of the technological breakthroughs of these years of *sturm und drang* on a number of critical industries stands undiminished, the critical difference between this Industrial Revolution and previous clusters of macroinventions is not that these breakthroughs occurred at all, but that their momentum did not level off and peter out after 1800 or so. In other words, what made the Industrial Revolution into the "great divergence" was the *persistence* of technological change after the first wave. We might well imagine a counterfactual technological steady state of throstles, wrought iron, and stationary steam engines, in which there was a one-off shift from wool to cotton, from animate power to stationary engines, and from expensive to plentiful wrought iron. It is easy to envisage the economies of the West settling into these techniques without taking them much further, as had happened in the wave of inventions of the fifteenth century.

But this is not what happened. The "first wave" of innovations was followed after 1820 by a secondary ripple of inventions that may have been less spectacular, but these were the microinventions that provided the muscle to the downward trend in production costs. The second stage of the Industrial Revolution adapted ideas and techniques to be applied in new and more industries, improved and refined earlier inventions, extended and deepened their deployment, and eventually these efforts showed up in the productivity statistics. Among the remarkable later advances we may list the perfection of mechanical weaving after 1820; the invention of Roberts' self-acting mule in spinning (1825); the extension and adaptation of the techniques first used in cotton and worsted to carded wool and linen; the improvement in the iron industry through Neilson's hot blast (1829) and related inventions; the continuous improvement in crucible steelmaking through coordinated crucibles (as practiced for example by Krupp in Essen); the pre-Bessemer improvements in steel thanks to the work of Scottish steelmakers such as David Mushet (father of Robert Mushet, celebrated in one of Samuel Smiles's *Industrial Biographies*), and the addition of manganese to crucible steel known as Heath's process (1839); the continuing improvement in steampower, raising the efficiency and capabilities of the low pressure stationary engines, while perfecting the high pressure engines of Trevithick, Woolf and Stephenson and adapting them to transportation; the advances in chemicals before the advent of organic chemistry (such as the breakthroughs in candle-making and soap manufacturing thanks to the work of Eugène-Michel Chevreul on fatty acids); the introduction and perfection of gas-lighting; the breakthroughs in high-precision engineering and the development of better machine-tools by Maudslay, Whitworth, Nasmyth, Rennie, the Brunels, the Stephensons, and the other great engineers of the "second generation"; the growing interest in electrical phenomena leading to electroplating and the work by Hans Oersted and Joseph Henry establishing the connection between electricity and magnetism, leading to the telegraph in the late 1830s.

The second wave of inventions was the critical period in the sense that it shows up clearly in the total income statistics. Income per capita growth after 1830 accelerates to around 1.1 percent, even though recent calculations confirm that only about a third of that growth to total factor productivity growth [Antrás and Voth (2003, p. 63) and Mokyr (2003c)]. Income growth in Britain during the "classical" Industrial Revolution was modest. This fact is less difficult to explain than some scholars make it out to be, and any dismissal of the Industrial Revolution as a historical watershed for that reason seems unwarranted. After all, the disruptions of international commerce during the quarter century of the French Wars coincided with bad harvests and unprecedented population growth. Yet the main reason is simply that in the early decades the segment of the British economy affected by technological progress and that can be regarded as a "modern sector" was simply small, even if its exact dimensions remain in dispute. After 1830 this sector expands rapidly as the new technology is applied more broadly (especially to transportation), growth accelerates, and by the mid-1840s there is clear-cut evidence that the standard of living in Britain is rising even for the working class. It also serves as a bridge between the first Industrial Revolution and the more intense and equally dramatic changes of the second Industrial Revolution.

The success of the Industrial Revolution in generating sustainable economic growth, then, must be found in the developments in the area of useful knowledge that occurred in

Europe before and around 1750. What mattered was not so much scientific knowledge itself but the method and culture involving the generation and diffusion of propositional knowledge. The Industrial Revolution and its aftermath were based on a set of propositional knowledge that was not only increasing in size, but which was becoming increasingly accessible, and in which segments that were more effective were becoming tighter. The effectiveness of propositional knowledge was increasingly tested by whether the techniques that were based on it actually worked satisfactorily either by experiment or by virtue of economic efficiency.

To sum up, then, the period 1760–1830 Western Europe witnessed a growing importance of improving technology in economic growth. The emergence and continuous improvement of new techniques that in the longer run were to have an enormous impact on productivity and growth. People started to know more about how and why the techniques they used worked, and this knowledge was widespread. Without belittling the other elements that made the Industrial Revolution possible, the technological breakthroughs of the period prepared the ground for the economic transformation that made the difference between the West and the Rest, between technological modernity and the much slower and often-reversed economic growth episodes of the previous millennia. In order to come up with a reasonable explanation of the technological roots of economic growth in this period, we must turn to the intellectual foundations of the explosion of technical knowledge.

5. The intellectual roots of the Industrial Revolution

Economic historians like to explain economic phenomena with other economic phenomena. The Industrial Revolution, it was felt for many decades should be explained by economic factors. Relative prices, better property rights, endowments, changes in fiscal and monetary institutions, investment, savings, exports, and changes in labor supply have all been put forward as possible explanations [for a full survey, see Mokyr (1998a)]. Yet the essence of the Industrial Revolution was technological, and technology is knowledge. How, then, should we explain not just the famous inventions of the Industrial Revolution but also the equally portentous fact that these inventions did not peter out fairly quickly after they emerged, as had happened so often in the past?

The answer has to be sought in the intellectual changes that occurred in Europe *before* the Industrial Revolution. These changes affected the sphere of propositional knowledge, and its interaction with the world of technology. As economic historians have known for many years, it is very difficult to argue that the scientific revolution of the seventeenth century we associate with Galileo, Descartes, Newton, and the like had a direct impact on the Industrial Revolution [McKendrick (1973) and Hall (1974)]. Few important inventions, both before and after 1800, can be directly attributed to great scientific discoveries or were dependent in any direct way on scientific expertise. The advances in physics, chemistry, biology, medicine, and other areas occurred too late to have an effect on the industrial changes of the last third of the eighteenth century.[20] The scientific advances of the seventeenth century, crucial as they were to the understanding of nature, had more to do with the movement of heavenly bodies, optics, magnetism, and the classification of plants than with the motions of machines. To say that therefore they had no economic significance is an exaggeration: many of the great scientists and mathematicians of the eighteenth century wrote about mechanics and the properties of materials. After 1800 the connection becomes gradually tighter, yet the influence of science proper on some branches of production (and by no means all at that) does not become decisive until after 1870.[21] The marginal product of scientific knowledge proper on technology varied from industry to industry and over time. Examples of useful applications of pure scientific insights in the eighteenth century can be provided [Musson and Robinson (1969)], but they tend to be specific to a few industries.[22]

All the same, the scientific revolution was in many ways the prelude to the intellectual developments at the base of the Industrial Revolution. The culture of science that evolved in the seventeenth century meant that observation and experience were placed in the public domain. Betty Jo Dobbs (1990), William Eamon (1990, 1994), and more recently Paul David (2004) 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. The sharing of knowledge within "open science" required systematic reporting of methods and materials using a common vocabulary and consensus standards, and should be regarded as an exogenous decline in access costs, which made the propositional knowledge, such as it was, available to those who might find a use for it. Those who added to useful knowledge would be rewarded by honor, peer recognition, and fame – not a monetary reward that was in any fashion proportional to their contribution. Even those who discovered matters of significant insight to

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[20] 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 (1996) 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" (pp. 140–141, emphasis added).

[21] As Charles Gillispie has remarked in the eighteenth century, whatever the interplay between science and production may have been, "it did *not* consist in the application if up-to-date theory to techniques for growing and making things" [Gillispie (1980, p. 336)]. True enough, but had progress only consisted of analyzing existing procedures, identify the best of them, try to make them work as well as possible, and then standardize them, the process would eventually have run into diminishing returns and fizzled out.

[22] Thus the most spectacular insight in metallurgical knowledge, the celebrated 1786 paper by Monge, Berthollet and Vandermonde that established the chemical properties of steel had no immediate technological spin-offs and was "incomprehensible except to those who already knew how to make steel" [Harris (1992a, p. 220)]. Harris adds that there may have been real penalties for French steelmaking in its heavy reliance on scientists or technologists with scientific pretensions.

industry, such as Claude Berthollet, Joseph Priestley and Humphry Davy, often wanted credit, not profit.

The rhetorical conventions in scientific discourse changed in the seventeenth century, with the rules of persuasions continuously shifting away from "authority" toward empirics. It increasingly demanded that empirical knowledge be tested so that useful knowledge could be both accessible and trusted.[23] Verification meant that a deliberate effort was made to make useful knowledge tighter and thus more likely to be used. It meant a willingness, rarely observed before, to discard old and venerable interpretations and theories when they could be shown to be in conflict with the evidence. Scientific method meant that in the age of enlightenment a class of experts evolved who often would decide which technique worked best.[24]

The other crucial transformation that the Industrial Revolution inherited from the seventeenth century was the growing change in the very purpose and objective of propositional knowledge. Rather than proving some religious point, such as illustrating the wisdom of the creator, or the satisfaction of that most creative of human characteristics, curiosity, natural philosophers in the eighteenth century increasingly came under the influence of the idea that the main purpose of knowledge was to improve mankind's material condition – that is, find technological applications. 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.[25] The founding members of the Royal Society justified their activities by their putative usefulness to the realm. There was a self-serving element

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

[24] 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".

[25] Robert K. Merton (1970 [1938], 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.

in this, of course, much as with National Science Foundation grant proposals today. Practical objectives in the seventeenth century were rarely the primary objective of the growth of formal science. But the changing cultural beliefs implied a gradual change in the agenda of research.

And yet, the central intellectual change in Europe before the Industrial Revolution has been oddly neglected by economic historians: the Enlightenment. Historically it bridges between the Scientific and the Industrial Revolutions. Definitions of this amorphous and often contradictory historical phenomenon are many, but for the purposes of explaining the Industrial Revolution we only to examine a slice of it, which I have termed the *Industrial Enlightenment*. To be sure, some historians have noted the importance of the Enlightenment as a culture of rationality, progress, and growth through knowledge.[26] Perhaps the most widely diffused Enlightenment view involved the notion that long-term social improvement was possible although not all Enlightenment philosophers believed that progress was either desirable or inevitable. Above all was the pervasive cultural belief in the Baconian notion that we can attain material progress (that is, economic growth) through controlling nature and that we can only harness nature by understanding her. Francis Bacon, indeed, is a pivotal figure in understanding the Industrial Enlightenment and its impact. His influence helped create the attitudes, the institutions, and the mechanisms by which new useful knowledge was generated, spread, and put to good use. Modern scholars seem agreed: Bacon was the first to regard knowledge as subject to constant growth, an entity that continuously expands and adds to itself rather than concerned with retrieving, preserving and interpreting old knowledge [Farrington (1979) and Vickers (1992, esp. pp. 496–497)].[27] The understanding of nature was a social project in which the division of knowledge was similar to Adam Smith's idea of the division of labor, another enlightenment notion.[28] Bacon's idea of bringing this about was through what he called a "House of Salomon" – a research academy in which teams of specialists collect data and experiment, and a higher level of scientists try to distill these into general regularities and laws. Such an institution

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[26] One of the most cogent statements is in McNeil (1987, pp. 24–25) who notes the importance of a "faith in science that brought the legacy of the Scientific Revolution to bear on industrial society . . . it is imperative to look at the interaction between culture *and* industry, between the Enlightenment and the Industrial Revolution".

[27] Bacon was pivotal in inspiring the Industrial Enlightenment. His influence on the Industrial Enlightenment can be readily ascertained by the deep admiration the encyclopédistes felt toward him, including a long article on Baconisme written by the Abbé Pestre and the credit given him by Diderot himself in his entries on *Art* and *Encyclopédie*. The *Journal Encyclopédique* wrote in 1756 "If this society owes everything to Chancellor Bacon, the philosopher doe not owe less to the authors of the *Encyclopédie*" [cited by Kronick (1962, p. 42)]. The great Scottish Enlightenment philosophers Dugald Stewart and Francis Jeffrey agreed on Baconian method and goals, even if they differed on some of the interpretation [Chitnis (1976, pp. 214–215)].

[28] A typical passage in this spirit was written by the British chemist and philosopher Joseph Priestley (1768, p. 7): "If, by this means, one art or science should grow too large for an easy comprehension in a moderate space of time, a commodious subdivision will be made. Thus all knowledge will be subdivided and extended, and *knowledge* as Lord Bacon observes, being *power*, the human powers will be increased . . . men will make their situation in this world abundantly more easy and comfortable".

was – at least in theory, if not always in practice – the Royal Society, whose initial objectives were inspired by Lord Bacon. Bacon was cited approvingly by many of the leading lights of the Industrial Enlightenment, including Lavoisier, Davy, and the astronomer John Herschel [Sargent (1999, pp. xxvii–xxviii)].[29]

Nothing of the sort, I submit, can be detected in the Ottoman Empire, India, Africa, or China. It touched only ever so lightly (and with a substantial delay) upon Iberia, Russia, and South America but in many of these areas it encountered powerful resistance and retreated. Invention, as many scholars have rightly stressed, had never been a European monopoly, and much of its technological creativity started with adopting ideas and techniques the Europeans had observed from others [Mokyr (1990)]. The enlightenment, however, provided the ideological foundation of invention, namely a belief that the understanding of nature was the key to growing control of the physical environment. Moreover, it laid out an agenda on how to achieve this control by demanding that this understanding take the form of general and widely applicable principles. With the success of this program came rising living standards, comfort and wealth. The historical result, then, was that eighteenth century Europe created the ability to break out of the ineluctable concavity and negative feedback that the limitations of knowledge and institutions had set on practically all economies until then. The stationary state was replaced by the steady state. It is this phenomenon rather than coal or the ghost acreage of colonies that answers Pomeranz's (2000, p. 48) query why Chinese science and technology – which did not "stagnate" – "did not revolutionize the Chinese economy".

The Industrial Enlightenment can be viewed in part as a movement that insisted on asking not just "*which* techniques work" but also "*why* techniques work" – realizing that such questions held the key to continuing progress. In the terminology introduced above, the intellectuals at its center felt intuitively that constructing and widening an epistemic base for the techniques in use would lead to continuing technological progress. Scientists, engineers, chemists, medical doctors, and agricultural improvers made sincere efforts to generalize from the observations they made, to connect observed facts and regularities (including successful techniques) to the formal propositional knowledge of the time, and thus provide 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, or if not, to catalog and classify them in such ways as to make the knowledge more organized and thus easier to access.[30] These insights would lead to extensions, refinements, and improvements, as well as speed up and

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[29] McClellan (1985, p. 52). It should be added that strictu sensu the Royal Society soon allowed in amateurs and dilettantes and thus became less of a pure "Baconian" institution than the French Académie Royale. Dear (1985, p. 147) notes that the Royal Society was "more of a club than a college".

[30] One thinks, of course, above all of the work of Carl Linnaeus. The lack of theory to explain living things similar to physics was acutely felt. Thus Erasmus Darwin, grandfather of the biologist and himself a charter member of the Lunar Society and an archtypical member of the British Industrial Enlightenment, complained in 1800 that Agriculture and Gardening had remained only Arts without a true theory to connect them [Porter (2000, p. 428)]. For details about Darwin, see especially McNeil (1987) and Uglow (2002).

streamline the process of invention.[31] Asking such questions was of course much easier than answering them. In the longer term, however, raising the questions and developing the tools to get to the answers were essential if technical progress was not to fizzle out.[32] The typical enlightenment inventor did more than tinkering and trial-and-error fiddling with existing techniques: he tried to relate puzzles and challenges to whatever *general* principles could be found, and if necessary to formulate such principles anew. To do so, each inventor needed some mode of communication that would allow him to tap the knowledge of others. The paradigmatic example of such an inventor remains the great James Watt, whose knowledge of mathematics and physics were matched by his tight connections to the best scientific minds of his time, above all Joseph Black and Joseph Priestley. The list of slightly less famous pioneers of technology who cultivated personal connections with scientists can be made arbitrarily long.

The other side of the Industrial Enlightenment had to do with the diffusion of and the access to *existing* knowledge. The *philosophes* realized that, in terms of the framework outlined above, access costs were crucial and that useful knowledge should not be confined to a select few but should be disseminated as widely as possible.[33] Diffusion needed help, however, and much of the Industrial Enlightenment was dedicated to making access to useful knowledge easier and cheaper.[34] From the widely-felt need to rationalize and standardize weights and measures, the insistence on writing in vernacular language, to the launching of scientific societies and academies (functioning as de facto clearing houses of useful knowledge), to that most paradigmatic Enlightenment triumph, the *Grande Encyclopédie*, the notion of diffusion found itself at the center of attention among intellectuals.[35] Precisely because the Industrial Enlightenment was not a national or local phenomenon, it became increasingly felt that differences in language and standards became an impediment and increased access costs. Watt, James Keir,

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

[32] George Campbell, an important representative of the Scottish Enlightenment noted that “All art [including mechanical art or technology] is founded in science and practical skills lack complete beauty and utility when they do not originate in knowledge” [cited by Spadafora (1990, p. 31)].

[33] Some Enlightenment thinkers believed that this was already happening in their time: the philosopher and psychologist David Hartley believed that “the diffusion of knowledge to all ranks and orders of men, to all nations, kindred and tongues and peoples ... cannot be stopped but proceeds with an ever accelerating velocity” [cited by Porter (2000, p. 426)].

[34] The best summary of this aspect of the Industrial Enlightenment was given by Diderot in his widely-quoted article on “Arts” in the *Encyclopédie*: “We need a man to rise in the academies and go down to the workshops and gather material about the [mechanical] arts to be set out in a book that will persuade the artisans to read, philosophers to think along useful lines, and the great to make at least some worthwhile use of their authority and wealth”.

[35] Roche (1998, pp. 574–575) notes that “if the *Encyclopédie* was able to reach nearly all of society (although ... peasants and most of the urban poor had access to the work only indirectly), it was because the project was broadly conceived as a work of popularization, of useful diffusion of knowledge”. The cheaper versions of the Diderot–d’Alembert masterpiece, printed in Switzerland, sold extremely well: the Geneva (quarto) editions sold around 8000 copies and the Lausanne (octavo) editions as many as 6000.

and the Derby clockmaker John Whitehurst, worked on a system of universal terms and standards, that would make French and British experiments "speak the same language" [Uglow (2002, p. 357)]. Books on science and technology were translated rather quickly, even when ostensibly Britain and France were at war with one another.

Access costs depended in great measure on knowing what was known, and for that search engines were needed. The ultimate search engine of the eighteenth century was the encyclopedia. Diderot and d'Alembert's *Encyclopédie* did not augur the Industrial Revolution, it did not predict factories, and had nothing to say about mechanical cotton spinning equipment or steam engines. It catered primarily to the landowning elite and the bourgeoisie of the *ancien régime* (notaries, lawyers, local officials) rather than specifically to an innovative industrial bourgeoisie, such as it was. It was, in many ways, a conservative document [Darnton (1979, p. 286)]. But the Industrial Enlightenment, as embodied in the *Encyclopédie* and similar works that were published in the eighteenth century implied a very different way of looking at technological knowledge: instead of intuition came systematic analysis, instead of mere dexterity an attempt to attain an understanding of the principles at work, instead of secrets learned from a master, an open and accessible system of training and learning. It was also a comparatively user-friendly compilation, arranged in an accessible way, and while its subscribers may not have been mostly artisans and small manufacturers, the knowledge contained in it dripped down through a variety of leaks to those who could make use of it.[36] Encyclopedias and "dictionaries" were supplemented by a variety of textbooks, manuals, and compilations of techniques and devices that were somewhere in use. The biggest one was probably the massive *Descriptions des arts et métiers* produced by the French Académie Royale des Sciences.[37] Many other specialist compilations of technical and engineering data appeared.[38] In agriculture, meticulously compiled data collections looking at such topics as yields, crops, and cultivation methods were common.[39]

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[36] Pannabecker points out that the plates in the *Encyclopédie* were designed by the highly skilled Louis-Jacques Goussier who eventually became a machine designer at the Conservatoire des arts et métiers in Paris [Pannabecker (1996)]. They were meant to popularize the rational systematization of the mechanical arts to facilitate technological progress. The parish priest in St. Hubert (in Flanders) traveled to Brussels to purchase a copy, since he had heard of its emphasis on technology and was eager to learn of new ways to extract the coal resources of his land [Jacob (2001, p. 55)].

[37] 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)].

[38] An example is the detailed description of windmills (*Groot Volkomen Moolenboek*) published in the Netherlands as early as 1734. A copy was purchased by Thomas Jefferson and brought to North America [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)].

[39] William Ellis' *Modern Husbandman or Practice of Farming* published in 1731 gave a month-by-month set of suggestions, much like Arthur Young's most successful book, *The Farmer's Kalendar* (1770). Most of these writings were empirical or instructional in nature, but a few actually tried to provide the readers with

The Industrial Enlightenment realized instinctively that one of the great sources of technological stagnation was a social divide between those who knew things ("*savants*") and those who made things ("*fabricants*"). To construct pipelines through which those two groups could communicate was at the very heart of the movement.[40] The relationship between those who possessed useful knowledge and those who might find a productive use for it was changing in eighteenth-century Europe and points to a reduction in access costs. They also served as a mechanism through which practical people with specific technical problems to solve could air their needs and thus influence the research agenda of the scientists, while at the same time absorbing what best-practice knowledge had to offer. The movement of knowledge was thus bi-directional, as seems natural to us in the twenty-first century. In early eighteenth-century Europe, however, such exchanges were still quite novel.

An interesting illustration can be found in the chemical industry. Pre-Lavoisier chemistry, despite its limitations, is an excellent example of how *some* knowledge, no matter how partial or erroneous, was believed to be of use in mapping into new techniques.[41] The pre-eminent figure in this field was probably William Cullen, a Scottish physician and chemist. His work "exemplifies all the virtues that eighteenth-century chemists believed would flow from the marriage of philosophy and practice" [Donovan (1975, p. 84)]. Ironically, this marriage remained barren for many decades. 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

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some systematic analysis of the principles at work. One of those was Francis Home's *Principles of Agriculture and Vegetation* (1757). One of the great private data collection projects of the time were Arthur Young's famed *Tours* of various parts of England and William Marshall's series on *Rural Economy* [Goddard (1989)]. They collected hundreds of observations on farm practice in Britain and the continent. Although at times Young's conclusions were contrary to what his own data indicated [see Allen and O Gráda (1988)].

[40] This point was first made by Zilsel (1942) who placed the beginning of this movement in the middle of the sixteenth century. While this may be too early for the movement to have much economic effect, the insight that technological progress occurs when intellectuals communicate with producers is central to its historical explanation.

[41] 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. 272–273)]. 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.

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: the minimum epistemic base simply did not exist. All the same, Cullen personifies a social demand for propositional knowledge for economic purposes. Whether or not the supply was there, his patrons and audience in the culture of the Scottish Enlightenment believed that there was a chance he could [Golinski (1988)] and put their money behind their beliefs. At times, clever and ingenious people, especially could contribute to the solution of problems. The greatest British mathematician of the eighteenth century, Colin MacLaurin, was reputed to be at hand to resolve "whatever difficulty occurred concerning the construction or perfection of machines, the working of mines, the improvement of manufactures, or the conveying of water" [Murdoch (1750, p. xxiv)]. The great French physicist René Réaumur (1683–1757) studied in great detail the properties of Chinese porcelain and the physics of iron and steel, and produced over 200 copper plates depicting the operation of workshops, machines, and tools of a range of trades [Gillispie (1980, pp. 346–347)]. But most of this promise was not realized till after 1800.

To dwell on one more example, consider the development of steam power. The ambiguities of the relations between James Watt and his mentor, the Scottish scientist Joseph Black are well known. Whether or not Watt's crucial insight of the separate condenser was due to Black's theory of latent heat, there can be little doubt that the give-and-take between the scientific community in Glasgow and the creativity of men like Watt was essential in smoothing the path of technological progress.[42] The same was true in the South of Britain. Richard Trevithick, the Cornish inventor of the high pressure engine, posed sharp questions to his scientist acquaintance Davies Gilbert (later President of the Royal Society), and received answers that supported and encouraged his work [Burton (2000, pp. 59–60)].

The physics of energy remains one of the most striking illustrations of the interactions between propositional and prescriptive knowledge. Only in the decades after 1824 did the understanding that steam was a heat engine and not a device run by pressure break through. The work of Mancunians Joule and Rankine on thermodynamics led to the development of the two cylinder compound marine steam engine and the re-introduction of steam-jacketing. It led to a different way of looking at thermal efficiency that drove home the insight that no matter how one improved a steam engine, its efficiency would always be low – thus pointing the way to internal combustion engines as a solution. Most

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[42] Hills (1989, p. 53) explains that Black's theory of latent heat helped Watt compute the optimal amount of water to be injected without cooling the cylinder too much. More interesting, however, was his reliance on William Cullen's finding that in a vacuum water would boil at much lower, even tepid, temperatures, releasing steam that would ruin the vacuum in a cylinder. In some sense that piece of propositional knowledge was essential to his realization that he needed a separate condenser. In other areas, too, the discourse between those who controlled Ω-knowledge and those who built new techniques was fruitful. Henry Cort, whose invention of the puddling and rolling process was no less central than Watt's separate consenser, also consulted Joseph Black during his work.

important, the widening of the epistemic base pointed to what could *not* be done, prevented inventors and engineers from walking into blind alleys and working on projects that were infeasible. John Ericsson's "regenerative" engine of 1853 was still an attempt to "recycle" heat over and over again, before the ineluctable energy-accounting truths of thermodynamics had fully sunk in [Bryant (1973)]. Such advances were slow and not always monotonic. At times a little knowledge could be a dangerous thing, such as theory of latent heat which made many engineers experiment with alternative fluids whose physical properties were thought to contain less latent heat.[43]

Some of the most interesting enlightenment figures made a career out of specializing in building bridges between propositional and prescriptive knowledge. Among these facilitators was William Nicholson, the founder and editor of the first truly scientific journal, namely *Journal of Natural Philosophy, Chemistry, and the Arts* (more generally known at the time as *Nicholson's Journal*), which commenced publication in 1797. It published the works of most of the leading scientists of the time, and played the role of today's *Nature* or *Science*, that is, to announce important discoveries in short communications. In it, leading scientists including John Dalton, Berzelius, Davy, Rumford, and George Cayley communicated their findings and opinions.[44] Another was John Coakley Lettsom, famous for being one of London's most successful and prosperous physicians and for liberating his family's slaves in the Caribbean. He corresponded with many other Enlightenment figures including Benjamin Franklin, Erasmus Darwin and the noted Swiss physiologist Albrecht von Haller. He wrote about the Natural History of Tea and was a tireless advocate of the introduction of mangel wurzel into British agriculture Porter (2000, pp. 145–147). A third Briton who fits this description as a mediator between the world of propositional knowledge and that of technology was Joseph Banks, one of the most distinguished and respected botanists of his time. Banks, a co-founder (with Rumford) of the Royal Institution in 1799, was a friend to George III and president of the Royal Society for forty two years, every inch an enlightenment figure, devoting his time and wealth to advance learning and to use the learning to create wealth, "an awfully English *philosophe*" in Roy Porter's (2000, p. 149) memorable phrase.

As might be expected, in some cases the bridge between propositional and prescriptive knowledge occurred within the same mind: the very same people who also were

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[43] The example also points to the importance of tightness as a concept. In the early days of thermodynamic, there was still a lot of confusion about what was and was not feasible. Bryant (1973, p. 161) notes that "it seems strange that inventors [such as Ericsson] operating on what seems to us a pretty shaky theory were able to get financial support". The answer is that at that early stage of the theory, an authority on heat engines could be perfectly sound on thermodynamics yet still be uncertain when faced by a complicated engine supported by "data".

[44] Nicholson also was a patent agent, representing other inventors, and around 1800 ran a "scientific establishment for pupils" on London's Soho square. The school's advertisement ran that "this institution affords a degree of practical knowledge of the sciences which is seldom acquired in the early part of life" delivering weekly lectures on natural philosophy and chemistry "illustrated by frequent exhibition and explanations of the tools, processes and operations of the useful arts and common operations of society".

contributing to science made some critical inventions (even if the exact connection between their science and their ingenuity is not always clear). The importance of such dual or "hybrid" 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 from technological advances to propositional knowledge. In most cases the technology shaped 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, the invention of carbonated (sparkling) water and rubber erasers by Joseph Priestley, 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).[45]

Typical of the "dual career" phenomenon was Benjamin Thompson (later Count Rumford, 1753–1814), 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 scientific proof that heat is not a liquid (known at the time as *caloric*) 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 stove, and an improved oil lamp. He developed a photometer designed to measure light intensity and wrote about science's ability to improve cooking and nutrition [G.I. Brock (1992, pp. 95–110)]. Rumford is as good a personification of the Industrial Enlightenment as one can find. 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 map from his knowledge of natural phenomena and regularities to create things he deemed useful for mankind [Sparrow (1964, p. 162)].[46] Like Franklin and Davy, he refused to take out a patent on any of his inventions – as a true child of the Enlightenment he was committed to the concept of open and free knowledge.[47] Instead, he

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[45] 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.

[46] It is telling that Rumford helped found the London Royal Institute in 1799. This institute was explicitly aimed at the diffusion of useful knowledge to wider audiences through lectures. In it the great Humphry Davy and his illustrious pupil Michael Faraday gave public lectures and did their research.

[47] 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)].

felt that honor and prestige were often a sufficient incentive for people to contribute to useful knowledge. He established the Rumford medal, to be awarded by the Royal Society “in recognition of an outstandingly important recent discovery in the field of thermal or optical properties of matter made by a scientist working in Europe, noting that Rumford was concerned to see recognised discoveries that tended to promote the good of mankind”. Not all scientists eschewed such profits: the brilliant Scottish aristocrat Archibald Cochrane (Earl of Dundonald) made a huge effort to render the coal tar process he patented profitable, but failed and ended up losing his fortune. Incentives were, as always, central to the actions of the figures of the Industrial Enlightenment, but we should not assume that these incentives were homogeneous and the same for all.

The other institutional mechanism emerging during the Industrial Enlightenment to connect between those who possessed prescriptive knowledge and those who wanted to apply it was the emergence of meeting places where men of industry interacted with natural philosophers. So-called scientific societies, often known confusingly as literary and philosophical societies, sprung up everywhere in Europe. They organized lectures, symposia, public experiments, and discussion groups, in which the topics of choice were the best pumps to drain mines, or the advantages of growing clover and grass.[48] Most of them published some form of “proceedings”, as often meant to popularize and diffuse existing knowledge as it was to display new discoveries. Before 1780 most of these societies were informal and ad hoc, but they eventually became more formal. The British Society of Arts, founded in 1754, was a classic example of an organization that embodied many of the ideals of the Industrial Enlightenment. Its purpose was “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.[49] The society took 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.[50] It served as a communications network and clearing house for technological information, reflecting the feverish growth of supply and demand for useful knowledge.

What was true for Britain was equally true for Continental countries affected by the Enlightenment. In the Netherlands, rich but increasingly technologically backward, heroic efforts were made to set up organizations that could infuse the economy with

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[48] The most famous of these societies were the Manchester Literary and Philosophical Society (founded in 1781) and the Birmingham Lunar Society, where some of the great entrepreneurs and engineers of the time mingled with leading chemists, physicists, and medical doctors. But in many provincial cities such as Liverpool, Hull and Bradford, a great deal of similar activity took place.

[49] For details see Wood (1913) and Hudson and Luckhurst (1954).

[50] Hilaire-Pérez (2000, p. 197), Wood (1913, pp. 243–245).

more innovativeness.[51] In Germany, provincial academies to promote industrial, agricultural, and political progress through science were founded in all the significant German states in the eighteenth century. The Berlin Academy was founded in 1700 and in its early years directed by the great Leibniz, and among its achievements was the discovery that sugar could be extracted from beets (1747). Around 200 societies appeared during the half-century spanning from the Seven-Years War to the climax of the Napoleonic occupation of Germany, such as the Patriotic Society founded at Hamburg in 1765 [Lowood (1991, pp. 26–27)]. These societies, too, emphasized the welfare of the population at large and the country over private profit. Local societies supplemented and expanded the work of learned national academies.[52] Publishing played an important role in the work of societies bent on the encouragement of invention, innovation and improvement. This reflected the emergence of open knowledge, a recognition that knowledge was a non-rivalrous good the diffusion of which was constrained by access costs.

In France, great institutions were created under royal patronage, above all the *Académie Royale des Sciences*, created by Colbert and Louis XIV in 1666 to disseminate information and resources.[53] Yet the phenomenon was nationwide: 33 official learned societies were functioning in the French provinces during the eighteenth century

[51] The first of these was established in Haarlem in 1752, and within a few decades the phenomenon spread much like in England to the provincial towns. The Scientific Society of Rotterdam known oddly as the *Batavic Association for Experimental Philosophy* was the most applied of all, and advocated the use of steam engines (which were purchased in the 1770s but without success). The Amsterdam Society was known as *Felix Meritis* and carried out experiments in physics and chemistry. These societies stimulated interest in physical and experimental sciences in the Netherlands, and they organized prize-essay contests on useful applications of natural philosophy. A physicist named Benjamin Bosma for decades gave lectures on mathematics, geography, and applied physics in Amsterdam. A Dutch Society of Chemistry founded in the early 1790s helped to convert the Dutch to the new chemistry proposed by Lavoisier [Snelders (1992)]. The Dutch high schools, known as *Athenea* taught mathematics, physics, astronomy, and at times counted distinguished scientists among their staff.

[52] The German local societies were private institutions, unlike state-controlled academies, which enabled them to be more open, with few conditions of entry, unlike the selective, elitist academies. They broke down social barriers, for the established structures of Old Regime society might impede useful work requiring a mixed contribution from the membership of practical experience, scientific knowledge, and political power. Unlike the more scientifically-inclined academies, they invited anyone to join, such as farmers, peasants, artisans, craftsmen, foresters, and gardeners, and attempted to improve the productivity of these occupations and solve the economic problems of all classes. Prizes rewarded tangible accomplishments, primarily in the agricultural or technical spheres. Their goal was not to advance learning like earlier academies, but to apply useful results of human knowledge, discovery and invention to practical and civic life [Lowood (1991)].

[53] It was one of the oldest and financially best supported scientific societies of the eighteenth century, with a membership which included d'Alembert, Buffon, Clairaut, Condorcet, Fontenelle, Laplace, Lavoisier and Reaumur. It published the most prestigious and substantive scientific series of the century in its annual proceedings *Histoire et Memoires* and sponsored scientific prize contests such as the Meslay prizes. It recognized achievement and rewarded success for individual discoveries and enhanced the social status of scientists, granting salaries and pensions. A broad range of scientific disciplines were covered, with mathematics and astronomy particularly well represented, as well as botany and medicine.

counting over 6,400 members. Overall, McClellan (1981, p. 547) estimates that during the century perhaps between 10,000 and 12,000 men belonged to learned societies that dealt at least in part with science. The *Académie Royale* exercised a fair amount of control over the direction of French scientific development and acted as technical advisor to the monarchy. By determining what was published and exercising control over patents, the *Académie* became a powerful administrative body, providing scientific and technical advice to government bureaus. France, of course, had a somewhat different objective than Britain: it is often argued that the *Académie* linked the aspirations of the scientific community to the utilitarian concerns of the government creating not a Baconian society open to all comers and all disciplines but a closed academy limited primarily to Parisian scholars [McClellan (1981)]. Yet the difference between France and Britain was one of emphasis and nuance, not of essence: they shared a utilitarian optimism of mankind's ability to create wealth through knowledge. In other parts of Europe, such as Italy, scientific societies were active in the eighteenth century [Inkster (1991, p. 35) and Cochrane (1961)]. At the level of the creation of propositional knowledge, at least, there is little evidence that the *ancien régime* was incapable of generating sustained progress.

To summarize, then, the Industrial Revolution had intellectual preconditions that needed to be met if sustained economic growth could take place just as it had to satisfy economic and social conditions. The importance of property rights, incentives, factor markets, natural resources, law and order, market integration, and many other economic elements is not in question. But we need to realize that without understanding the changes in attitudes and beliefs of the key players in the growth of useful knowledge, the technological elements will remain inside a black box.

6. The dynamic of technological modernity

The essence of technological modernity is non-stationarity: many scholars have observed that technological change has become self-propelled and autocatalytic, in which change feeds on change. Unlike other forms of growth, spiraling technological progress does not appear to be bounded from above. Predictions in the vein of “everything that can be invented already has been” have been falsified time and again. The period that followed the Industrial Revolution was one in which innovation intensified, and while we can discern a certain ebb and flow, in which major breakthroughs and a cluster of macroinventions were followed by waves of microinventions and secondary extensions and applications, the dynamic has become non-ergodic, that is to say, the present and the future are nothing like the past. In the premodern past, whether in Europe or elsewhere in the world, invention had remained the exception, if perhaps not an uncommon one. In the second half of the nineteenth century and even more so in the twentieth century, change has become the norm, and even in areas previously untouched by technological innovation, mechanization, automation, and novelty have become inevitable. There is no evidence to date that technology in its widest sense converges to anything.

To oversimplify, the Industrial Revolution could be reinterpreted in light of the changes in the characteristics and structure of propositional knowledge in the eighteenth century and the techniques that rested on it. Before 1750 the human race, as a collective, did not know enough to generate the kind of sustained technological progress that could account for the growth rates we observe. In the absence of such knowledge, no set of institutions, no matter how benevolent, could have substituted for useful knowledge. Pre-modern society had always been limited by its epistemic base and suppressed by economic and social factors. The dynamics of knowledge itself were critical to the historical process. The Industrial Revolution can be seen as what physicists call a “phase transition”.[54] Useful knowledge in the decades that followed increased by feeding on itself, spinning out of control as it were.

How do we explain this change in technological dynamic? In economics, phase transitions can be said to occur when a dynamic system has multiple steady states such as an economy that has a “poverty trap” (low-income equilibrium) and a high income (or rapid growth steady state). A phase transition occurs when the system switches from one equilibrium or regime to another. A simple model in which this can be illustrated is one in which capital and skills are highly complementary. In such models one equilibrium is characterized by rapid investment, which raises the demand for skills; the positive feedback occurs because the increase in the rate of return to human capital induces parents to invest more in their children, have fewer children (since they become more expensive), which raises the rate of return on physical capital even more and encourages investment. A second equilibrium is one of low investment, low skills, and high birth rates. A regime change may occur when an exogenous shock is violent enough to bump the system off one basin of attraction and move it to another one. The difficulty with this model for explaining the emergence of modern growth is to identify a historical shock that was sufficiently powerful to “bump” the system to a rapid growth trajectory.

Recent work in growth theory have produced a class of models that reproduce this feature in one form or another. Cervellati and Sunde (2002) for example assume that human capital comes in two forms, a “theoretical” form and a “practical” form, corresponding roughly to “scientific” and “artisanal” knowledge or the categories of useful knowledge proposed above. They assume that human abilities are heterogeneous but that there is a threshold at which people start to invest in “theoretical” knowledge as opposed to “crafts”, endogenously determined by life expectancy. This threshold level depends on the costs of acquiring the two types of human capital, their respective rates of return, and the life expectancy over which they are amortized. Further, they model the relationship between mortality and human capital investment. This is a little explored aspect of modernization, but one that must have been of some importance. All other things equal, longer life expectancy would encourage investment in human capital, although it is important to emphasize that a reduction in infant mortality would not directly bring this about, because decisions about human capital are made later in life. Increases in life

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[54] For a definition of phase transitions, see for instance Ruelle (1991, pp. 122–123).

expectancy at age 10 or so are more relevant here. Given their assumptions, the locus of points in the life-expectancy-ability space that define an intra-generational equilibrium is S-shaped. A second relationship in this model is that life expectancy itself depends on the level of education of the previous generation: better educated parents will be better situated to help their children survive. The model is closed by postulating a relationship between the high-quality human capital and total productivity. The neat aspect of the Cervellati–Sunde model is that if for some reason the productivity of the high-quality human capital rises, it produces the kind of observed phase transition when the old poverty trap is no longer an equilibrium and the system abruptly starts to move to a new "high-level" equilibrium. An exogenous disturbance that raises the marginal productivity of "scientific activity" will have the same effect, including an exogenous increase in the stock of propositional knowledge and an ideologically-induced change in the research agenda. Clearly, then, the Industrial Enlightenment, much like an endogenous growth in productivity, can produce an "Industrial Revolution" of this type. While under the assumptions of their paper an Industrial Revolution is "inevitable", the authors recognize that if technological progress has stochastic elements, this could imply a different prediction (p. 23). Either way, however, the emergence of technologically-based "modern growth" can be understood without the need for a sudden violent shock.

The alternative is to presume that historical processes cause the underlying parameters to change slowly but cumulatively, until one day what was a slow-growth steady state is no longer an equilibrium at all and the system, without a discernible shock, moves rather suddenly into a very different steady state. These models, pioneered by Galor and Weil (2000), move from comparative statics with respect to a parameter determining the dynamic structure, to a dynamical system in which this parameter is a latent state variable that evolves and ultimately can generate a phase transition.[55] In the Galor–Weil model, the economic *ancien régime* is not really a steady state but a "pseudo steady state" despite its long history: within a seeming stability the seeds for the phase transition are germinating invisibly.

A similar model, in which technology plays a "behind the scenes" role, is the highly original and provocative model by Galor and Moav (2002). In that model, the phase transition is generated by evolutionary forces and natural selection. The idea is that there are two classes of people, those who have many children (r-strategists) and others (K-strategists) who have relatively few but "high-quality" offspring and who invest more in education. When "quality types" are selected for, more smart and creative people are added and technology advances. Technological progress increases the rate of

[55] Another example of this type of "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.

return to human capital, induces more people to have more "high quality" (educated) children which provides the positive feedback loop. Moreover, as income advances, households have more resources to spend on education, which add to further expansion. Again, technology in this model is wholly endogenous to education and investment in human capital, and an autonomous development in the social factors governing human knowledge and the interplay between propositional and prescriptive knowledge is not really modeled. Despite the somewhat limiting assumptions of this model (the "type" is purely inherited and not a choice variable), this paper presents an innovative way of looking at the problem of human capital formation and economic growth in the historical context of the Industrial Revolution.

In some sense Galor and Moav's reliance on evolutionary logic to explain technological progress is ironic. In recent years it has been realized increasingly that knowledge *itself* is subject to evolutionary dynamics, in that new ideas and knowledge emerge much like evolutionary innovations (through mutations or recombinations) and are selected for (or not). Knowledge systems follow a highly path-dependent trajectory governed by Darwinian forces [Ziman (2000) and Mokyr (2003a)]. Yet this important insight still awaits to be incorporated in the "take-off" models of growth theorists. Evolutionary models predict that sudden accelerations or "explosions" of evolutionary change (known oddly as "adaptive radiation") occur when conditions are ripe, such as the so-called Cambrian explosion which has been compared to the Industrial Revolution [Kauffman (1995, p. 205)]. Another example of rapid evolutionary innovation is the spectacular proliferation of mammals at the beginning of the Cenozoic after the disappearance of the giant reptiles. The idea that evolution proceeds in the highly non-linear rhythm known as "punctuated equilibrium" has been suggested as a possible insight that economic historians can adapt from evolutionary biology [Mokyr (1990)].

Some of these (and other, similar) models may be more realistic than others, and economic historians may have to help to sort them out. A phase transition model without reliance on the quality of children and human capital is proposed by Charles Jones (2001) relying on earlier work by Michael Kremer (1993). In Jones' model, what matters is the size rather than the quality of the labor force. In very small populations, the few new technological ideas lead in straightforward Malthusian fashion to higher populations and not to higher income per capita. As the population gets larger and larger and the number of creative individuals increases, however, new ideas become more and more frequent, and productivity pulls ahead. The model assumes increasing returns in population and thus generates a classic multiple equilibria kind of story. The positive feedback thus works through fertility behavior responding to higher productivity, and through an increasing returns to population model. As per capita consumption increases, parents substitute away from children to consume other goods, and fertility eventually declines. In this fashion these models succeed in generating both a sudden and discontinuous growth of income per capita or consumption and the fertility transition. Jones shows that for reasonable parameter values he can simulate a world economy that reproduces the broad outlines of modern economic history (including an initial rise in fertility in the early stages of the Industrial Revolution, followed by a decline).

Yet the exact connection between demographic changes and the economic changes in the post 1750 period are far from understood, and much of the new growth literature pays scant attention to many variables that surely must have affected the demand for children and fertility behavior. These include technological changes in contraceptive technology, a decline in infant and child mortality, and changing demand for children in the household economy due to technological changes in agriculture and manufacturing. It is also open to question whether and to what extent "numbers matter", that is, whether the more people are around, the more likely – all other things equal – new technological ideas are to emerge.[56] The real question is whether the ideas that count are really a monotonic function of population size (Jones assumes a positive elasticity of 0.75 to generate his results), or whether they are generated by a negligible minority and that small changes in the fraction of creative people matters more than a rise in the raw size of population.[57] The historical record on that is subject to serious debate. It might be added that population growth in Britain was almost nil in the first half of the eighteenth century, and while it took off during the post 1750 era, the same was true for Ireland, where no Industrial Revolution of any kind can be detected.

Most endogenous growth historical models, however, depend on the notion that the variable critical to the process of "take-off" or phase transition is investment in human capital.[58] Historically, however, such a view is not unproblematic either. The idea that the fertility reduction was a consequence of changing rates of return on human capital, especially advanced by Lucas (2002), runs into what may be called the European Fertility Paradox: the first nation to clearly reduce its fertility rate through a decline in marital fertility (that is, intentional and conscious behavior) was *not* the country in which advanced technological techniques were adopted in manufacturing, but France. In Britain fertility rates come down eventually, but the decline does not start until the mid-1870s, a century after the beginning of the Industrial Revolution [e.g., Tranter (1985, chapter 4)]. Imperial Germany, which became the technological leader in many of the cutting-edge industries of the second Industrial Revolution, maintained a fertility rate far above France's and Britain's.[59] To argue, therefore, that technological progress was rooted in demographic behavior (through smaller families) seems at variance with the facts. It may well be that in the twentieth century this nexus held, but given the decline in wage premia it is hard to see the rate of return on human capital to be the driving factor. Beyond Europe, of course, population-driven theories of the "the-more-the-merrier"

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[56] The pedigree of this idea clearly goes back to the work of Julian Simon (1977, 2000).

[57] This sensitivity is reflected in Jones' simulations: the proportion inventors in the population in 1700 in his computations (set to match the demographic data) is 0.875%, but it *declines* in 1800 to less than half that number. By constraining the twentieth century data to stay at that level, Jones shows that the Industrial Revolution would be delayed by 300 years.

[58] For a similar view advanced by an economic historian before the new growth economics, see Easterlin (1981).

[59] In 1900, the total fertility rate (average number of children per woman) in Germany was 4.77, contrasting with 3.40 and 2.79 in England and France respectively. By that time, to be sure, German fertility rates were falling rapidly as they were elsewhere in the industrialized world. See e.g. Livi Bacci (2000, p. 136).

variety must confront the difficult fact that China not only had a population vastly larger than any European economy but that its population grew at a rapid rate in the very century that Europe experienced its Enlightenment: from a low point of about 100 million in 1685, it exceeded 300 million in 1790, a per annum growth of 1.05 percent, though admittedly from an unusually low base.

To understand the "phase transition" within the dynamic of useful knowledge, we need to look again at the relationship between propositional and prescriptive knowledge. 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 and creating the phase transition. During the early stages of the Industrial Revolution propositional knowledge mapped into new techniques creating what we call "inventions". This mapping should not be confused with the linear models of science and technology, popular in the mid-twentieth century, which depicted a neat flow from theory to applied science to engineering and from there to technology. Much of the propositional knowledge that led to invention in the eighteenth century was artisanal and mechanical, pragmatic, informal, intuitive, and empirical. Only very gradually did the kind of formal and consensual knowledge we think of today as "science" become a large component of it. It was, in all cases, a small fraction of what is known today. What matters is that it was subject to endogenous expansion: prescriptive knowledge in its turn enhanced propositional knowledge, and thus provided positive feedback between the two types of knowledge, leading to continuous mutual reinforcement. When powerful enough, this mechanism can account for the loss of stability of the entire system and for continuous unpredictable change.

The positive feedback from prescriptive to propositional knowledge took a variety of forms. One of those forms is what Rosenberg has called "focusing devices": technology posed certain riddles that science was unable to solve, such as "why (and how) does this technique work". It has been suggested, for instance that the sophisticated waterworks that supplied power to the famous Derby silk mills established by the Lombe brothers in the 1710s stimulated local scientists interested in hydraulics and mechanics [Elliott (2000, p. 98)]. The most celebrated example of such a loop is the connection between steam power and thermodynamics, exemplified in the well-known tale of Sadi Carnot's early formulation, in 1824, of the Second Law of Thermodynamics by watching the difference in fuel economy between a high pressure (Woolf) steam engine and a low pressure one of the Watt type.[60] The next big step was made by an Englishman, James P. Joule, who showed the conversion rates from work to heat and back.[61] Joule's work

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[60] It is interesting to note that Carnot's now famous *Reflexions sur la puissance motrice du feu* (1824) was initially ignored in France and eventually found its way second hand and through translation into Britain, where there was considerably more interest in his work because of the growing demand by builders of gigantic steam engines such as William Fairbairn in Manchester and Robert Napier in Glasgow for theoretical insights that would help in making better engines.

[61] The ways in which the growth of practical knowledge can influence the emergence of propositional knowledge are well illustrated by Joule's career: he was a child of industrial Lancashire (his father owned a brewery)

and that of Carnot were then reconciled by a German, R.J.E. Clausius (the discoverer of entropy), and by 1850 a new branch of science dubbed “thermodynamics” by William Thomson (later Lord Kelvin) had emerged [Cardwell (1971, 1974)].[62] Power technology and classical energy physics subsequently developed cheek by jowl, culminating in the career of the Scottish physicist and engineer William Rankine whose *Manual of the Steam Engine* (1859) made thermodynamics accessible to engineers and led to a host of improvements in actual engines. In steam power, then, the positive feedback can be clearly traced: the first engines had emerged in the practical world of skilled blacksmiths, millwrights, and instrument makers with only a minimum of theoretical understanding. These machines then inspired theorists to come to grips with the natural regularities at work and to widen the epistemic base. The insights generated were in turn fed back to engineers to construct more efficient engines. This kind of mutually reinforcing process can be identified, in a growing number of activities, throughout the nineteenth century. They required the kind of intellectual environment that the Industrial Enlightenment had created: a world in which technical knowledge was accessible and communicable in an international elite community, a technological invisible college that encompassed much of the Western world.

A less well-known example of this feedback mechanism, but equally important to economic welfare, is the interaction between the techniques of food-canning and the evolution of bacteriology. As noted earlier, the canning of food was invented in 1795, by Nicolas Appert.[63] He discovered that when he placed food in champagne bottles, corked them loosely, immersed them in boiling water, and then hammered the corks tight, the food was preserved for extended periods. Neither Appert nor his English emulators who perfected the preservation of food in tin-plated canisters in 1810 really understood why and how this technique worked, because the definitive demonstration of the notion that microorganisms were responsible for putrefaction of food was still in the future. It is therefore a typical example of a working technique with a narrow epistemic base. The canning of food led to a prolonged scientific debate about what caused food to spoil. The debate was not put to rest until Pasteur’s work in the early 1860s. Pasteur claimed ignorance of Appert’s experimental work, but eventually admitted that his own work

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and in the words of one historian, “with his hard-headed upbringing in industrial Manchester, was unambiguously concerned with the *economic* efficiency of electromagnetic engines . . . he quite explicitly adopted the language and concerns of the economist and the engineer” [Morus (1998, p. 187), emphasis in original]. As Ziman (1976, p. 26) remarks, the first law of thermodynamics could easily have been derived from Newton’s dynamics by mathematicians such as Laplace or Lagrange, but it took the cost accountancy of engineers to bring it to light.

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

[63] Experimental work by, among others, the Italian naturalist Lazaro Spallanzani, had earlier indicated that heating organic materials and subsequent airtight flashing would prevent putrefaction. It is unclear whether Appert and his British imitators knew of this work. See Clow and Clow (1952, p. 571).

on the preservation of wine was only a new application of Appert's method. Be that as it may, his work on the impossibility of spontaneous generation clearly settled the question of why the technique worked and provided the epistemic base for the technique in use. When the epistemic base of food-canning became wider, techniques improved: the optimal temperatures for the preservation of various foods with minimal damage to flavor and texture were worked out by two MIT scientists, Samuel Prescott and William Underwood.[64]

A different feedback mechanism from prescriptive to propositional knowledge was described by Derek Price as "Artificial Revelation". The idea is fairly simple: our senses limit us to a fairly narrow slice of the universe that has been called a "mesocosm": we cannot see things that are too far away, too small, or not in the visible light spectrum [Wuketits (1990, pp. 92, 105)]. The same is true for our other senses, for the ability to make very accurate measurements, for overcoming optical and other sensory illusions, and – perhaps most important in our own time – the computational ability of our brains. Technology consists in part in helping us overcome these limitations that evolution has placed on us and learn of natural phenomena we were not meant to see or hear.[65] The period of the Industrial Revolution witnessed a great deal of improvement in techniques whose purpose it was to enhance propositional knowledge. The great potter Josiah Wedgwood maintained a close relationship with the chemist James Keir: while Keir supplied Wedgwood with counsel, Wedgwood's factory provided Keir with the tubes and retorts he used in his laboratory near Birmingham [Stewart (2004, p. 18)]. The accuracy of instruments that measured time, distance, weight, pressure, temperature and so on increased by orders of magnitude in the eighteenth century.[66] Pumps and electrical machines allowed the study of vacuums and electrical phenomena. Lavoisier and his circle were especially good in designing and utilizing better laboratory equipment that allowed them to carry out more sophisticated experiments.[67] Alessandro Volta invented a pile of alternating silver and zinc disks that could generate an electric current in 1800.

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

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

[66] See Heilbron (1990, pp. 5–9). Interestingly, Heilbron believes that the main motives for these improvements were raisons d'etat and sheer curiosity, without allowing for the possibility that industrial and commercial application might have contributed something. But in the same volume Lundgren (1990, p. 250) points out that in Sweden the analytical quantification of assaying was a consequence of the expanding production of minerals and ores.

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

Volta's battery was soon produced in industrial quantities by William Cruickshank. Through the new tool of electrolysis, pioneered by William Nicholson and Humphry Davy, chemists were able to isolate element after element and fill in much of the detail in the maps whose rough contours had been sketched by Lavoisier and Dalton. Volta's pile, as Davy put it, acted as an "alarm bell to experimenters in every part of Europe" [cited by Brock (1992, p. **??**)]. The development of the technique of in vitro culture of micro-organisms had similar effects (the Petri dish was invented in 1887 by R.J. Petri, an assistant of Koch's). Price de Solla feels that many such advances in knowledge are "adventitious" (1984a, p. 112). Travis (1989) has documented in detail the connection between the tools developed in the organic chemical industry and advances in cell biology. These connections between prescriptive and propositional knowledge are just a few examples of advances in scientific techniques that can be seen as adaptations of ideas originally meant to serve an entirely different purpose, and they reinforce the contingent and accidental nature of much technological progress [Rosenberg (1994, pp. 251–252)].

The invention of the modern compound microscope attributed to Joseph J. Lister (father of the famous surgeon) in 1830 serves as another good example. Lister was an amateur optician, whose revolutionary method of grinding lenses greatly improved image resolution by eliminating spherical aberrations.[68] His invention and the work of others changed microscopy from an amusing diversion to a serious scientific endeavor and eventually allowed Pasteur, Koch, and their disciples to refute spontaneous generation and to establish the germ theory, a topic I return to below. The germ theory was one of the most revolutionary changes in useful knowledge in human history and mapped into a large number of new techniques in medicine, both preventive and clinical. Indeed, the widespread use of glass in lenses and instruments in the West was itself something coincidental, a "giant accident", possibly a by-product of demand for wine and different construction technology [Macfarlane and Martin (2002)]. It seems plausible that without access to this rather unique material, the development of propositional knowledge in the West would have taken a different course.[69]

A third mechanism of technology feeding back into prescriptive knowledge is through what might be called the "rhetoric of knowledge". This harks back to the idea of "tightness" introduced earlier. Techniques are not "true" or "false". Either they work according to certain predetermined criteria or they do not, and thus they can be interpreted to confirm or refute the propositional knowledge that serves as their epistemic base. Propositional knowledge has varying degrees of tightness, depending on the degree to which the available evidence squares with the rhetorical conventions for acceptance. Laboratory technology transforms conjecture and hypothesis into an accepted

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

[69] Macfarlane and Martin (2002, pp. 81–82) note that glass lenses not only made possible specific discoveries but led to a growing confidence in a world of deeper truths to be discovered, destabilizing conventional views. "The obvious was no longer true. Hidden connections and buried forces could be analyzed".

fact, ready to go into textbooks and to be utilized by engineers, physicians, or farmers. But a piece of propositional knowledge in the past was often tested simply by verifying that the techniques based on it actually worked. The earthenware manufacturer Josiah Wedgwood felt that his experiments in pottery actually tested the theories of his friend Joseph Priestley, and professional chemists, including Lavoisier, asked him for advice. Similarly, once biologists discovered that insects could be the vectors of pathogenic microparasites, insect-fighting techniques gained wide acceptance. The success of these techniques in eradicating yellow fever and malaria was the best confirmation of the hypotheses about the transmission mechanisms of the disease and helped earn them wide support.

Or consider the question of heavier-than-air flight. Much of the knowledge in aeronautics in the early days was experimental rather than theoretical, such as attempts to tabulate coefficients of lift and drag for each wing shape at each angle. It might be added that the epistemic base supporting the first experiments of the Wright brothers was quite untight: in 1901 the eminent astronomer and mathematician Simon Newcomb (the first American since Benjamin Franklin to be elected to the Institute of France) opined that flight carrying anything more than "an insect" would be impossible.[70] The success at Kitty Hawk persuaded all but the most stubborn doubting Thomases that human flight in heavier-than-air fixed wing machines was possible. Clearly their success subsequently inspired a great deal of research on aerodynamics. In 1918 Ludwig Prandtl published his magisterial work on how wings could be scientifically rather than empirically designed and the lift and drag precisely calculated [Constant (1980, p. 105) and Vincenti (1990, pp. 120–125)]. Even after Prandtl, not all advances in airplane design were neatly derived from first principles in an epistemic base in aerodynamic theory, and the ancient method of trial and error was still widely used in the search for the best use of flush riveting in holding together the body of the plane or the best way to design landing gear [Vincenti (1990, pp. 170–199; 2000)].

It is important not to exaggerate the speed and abruptness of the transition. Thomas Edison, a paradigmatic inventor of the 2nd Industrial Revolution, barely knew any science, and in many ways should be regarded an old-fashioned inventor who invented by trial-and-error through intuition, dexterity and luck. Yet he knew enough to know what he did not know, and that there were others who knew what he needed. Among those who supplied him with the propositional knowledge necessary for his research were the mathematical physicist Francis Upton, the trained electrical engineer Hermann Claudius, the inventor and engineer Nikola Tesla, the physicist Arthur E. Kennelly (later professor of electrical engineering at Harvard), and the chemist Jonas W. Aylsworth. Yet by that time access costs had declined enough so that he could learn for instance of the

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[70] He was joined in that verdict by the Navy's chief engineer, Admiral George Melville [Kelly (1943, pp. 116–117) and Crouch (1989, p. 137)]. Nor were the inventors themselves all that certain: in a widely quoted remark, Wilbur Wright in a despondent mood remarked to his brother that "not within a thousand years would men ever fly" [Kelly (1943, p. 72)].

work of the great German physicist Hermann von Helmholtz through a translated copy of the latter's work on acoustics.

The positive feedback from technology to prescriptive knowledge entered a new era with development of the computer. In the past, the practical difficulty of solving differential equations limited the application of theoretical models to engineering. A clever physicist, it has been said, is somebody who can rearrange the parameters of an insoluble equation so that it does not have to be solved. Computer simulation can evade that difficulty and help us see relations in the absence of exact closed-form solutions and may represent the ultimate example of Bacon's "vexing" of nature. In recent years simulation models have been extended to include the effects of chemical compounds on human bodies. Combinatorial chemistry and molecular biology are both equally unimaginable without fast computers. It is easy to see how the mutual reinforcement of computers and their epistemic base can produce a virtuous circle that spirals uncontrollably away from its basin of attraction. Such instability is the hallmark of Kuznets' vision of the role of "useful knowledge" in economic growth.

In addition to the positive feedback within the two types of knowledge, one might add the obvious observation that *access costs* were themselves a function of improving techniques, through better communications, storage, and travel techniques. In this fashion, expansions in prescriptive knowledge not only expanded the underlying supporting knowledge but made it more accessible and thus more likely to be used. As already noted, this is particularly important because so much technological progress consists of combinations and applications of existing techniques in novel ways, or parallels from other techniques in use. Precisely for this reason, cheap and reliable access to the monster catalog of all feasible techniques is an important element in technological progress. As the total body of useful knowledge is expanding dramatically in our own time, it is only with the help of increasingly sophisticated search engines that needles of useful knowledge can be retrieved from a haystack of cosmic magnitude.

Technological modernity is created when the positive feedback from the two types of knowledge becomes self-reinforcing and autocatalytic. We could think of this as a phase transition in economic history, in which the old parameters no longer hold, and in which the system's dynamics have been unalterably changed. There is no necessity for this to be true even in the presence of positive feedback; but for certain levels of the parameters, the system as a whole becomes unstable. It may well that this instability in the knowledge-producing system are what is behind what we think of as "technological modernity". Kuznets, of course, felt that the essence of modern growth was the increasing reliance of technology on modern science. This view, as I have argued above, needs clarification and amplification. Inside the black box of technology is a smaller black box called "research and development" which translates inputs into the output of knowledge. This black box itself contains an even smaller black box which models the available knowledge in society, and it is this last box I have tried to pry open. Yet all this is only part of the story: knowledge creates opportunities, but it does not guarantee action. Knowledge is an abstract concept, it glosses over the human agents who possess it and decide to act upon it. What motivates them, and why did some societies seem to be so much more inclined to generate new knowledge and to exploit the knowledge it had? To understand why during the past two centuries the “West” has been able to take advantage of these opportunities we need to examine the institutional context of innovation.

7. Human capital and modern economic growth

The role of education and human capital in the Industrial Revolution is more ambiguous than much of the New Growth literature would suggest. Britain, the most advanced industrial nation in 1850, was far from being the best educated, the most literate, or in some other way the best-endowed in traditional human capital. Increases in male literacy in Britain during the Industrial Revolution were in fact comparatively modest and its educational system as a whole lagging behind [Mitch (1998)]. The Lutheran nations of the Continent – Germany and the Scandinavian nations – were far more literate and, in one formulation, “impoverished sophisticates”.[71] Jewish minorities throughout European history were unusually well-endowed in human capital [Botticini and Eckstein (2003)], yet contributed little or nothing to the Industrial Revolution before 1850. Clearly human capital as a concept is indispensable, but we need to be far more specific as to what *kind* of human capital was produced, for and by whom, what was the source of the demand for it, and how it was distributed over the population. In his recent survey, the social historian Peter Kirby (2003, p. 118) concludes that the idea that nineteenth century education and literacy emerged as a response to a need for a trained labor force is misleading. There was a significant gap between formal ‘education’ and ‘occupational training’, the latter remaining embedded in the workplace in the form of apprenticeships and trainee positions. Before 1870, at least, the rate of return on formal education in his view was so low that its benefits did not outweigh the costs. That is not to say that being literate did not convey advantages in terms of social and occupational mobility [Long (2003)], but many of the skills that we associate with formal schooling could be attained informally.

The historical role of human capital in economic growth in the past must then be reexamined with some care. In terms of the framework delineated here its importance was first in reducing access costs: literate and educated innovators could and did read articles, books and personal letters from scientists, as well as familiarize themselves with techniques used elsewhere. They could understand mathematical and chemical notation, interpret figures, read blueprints, and follow computations and mechanical arguments. Moreover, by knowing more, the cost of *verification* fell: some obviously bogus and ineffective pieces of propositional knowledge could be rejected offhand. Secondly, a more literate and better educated labor force is assumed to be more competent, that is, be able to execute instructions contained in more and more complex techniques. Yet because

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[71] This is a term used by Lars Sandberg in a pathbreaking paper (1979).

the total set of useful knowledge could be divided up more and more thanks to better access, the actual amount of such knowledge that a *single* worker had to control may not have increased, it may have just changed, becoming more specialized, a smaller slice of a bigger whole. Human capital may have been more important in learning *new* instructions, than in executing more complex and difficult techniques: as technology changed more rapidly, technical tricks had to be learned and unlearned at more rapid rates.

Above all, investment in human capital is supposed to have created the conditions for faster innovation. It made for the prepared minds that, as Pasteur famously said, are favored by Fortune. Much technological progress consisted of fumbling and stumbling into some lucky find – but only systematic training allowed inventors to recognize what they found and how to apply it most fruitfully. Yet it is a fair question to ask of all economists who draw links between demographic change and human capital on the one hand and technological progress on the other – whether through the quality–quantity trade-off or otherwise – how many inventors and technically competent people were needed to generate sustained technological progress.

The answer, of course, depends, on what we mean by “competent”. Eighteenth century Britain did have a cadre of highly skilled technicians and mechanics, almost all of them trained in the apprenticeship system rather than in formal academies, and these contributed materially to its technological development. The Continent, too, had its share of skilled and well-trained craftsmen, although if we are to judge from the net migration flow of talent, Britain may have had an edge, especially in coal-using industries.[72] But the process of training apprentices did not always correspond to the neoclassical depiction of human capital formation. In addition to imparting skills, it was a selection process in which naturally gifted mechanics would teach themselves from whatever source was available as much as learn from their masters. Such sources multiplied as a direct result of the Industrial Enlightenment. In the eighteenth century the publishing industry supplied a large flow of popular science books, encyclopedias, technical dictionaries and similar “teach-yourself” kind of books.[73] These mechanics and technicians were the ones that made the Industrial Revolution possible by generating a stream of microinventions that accounted for the actual productivity gains when the great breakthroughs or macroinventions created the opportunities to do so and by providing the competence to carry out the new instructions, that is, to build and construct the new devices according to specifications.[74]

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[72] Britain received as much as she gave in terms of skilled artisans and applied scientists: among the foreigners who settled in Britain during the Industrial Revolution were the French inventor Aimé Argand, the Portuguese applied scientists, instrument maker and merchant Jean-Hyacinthe de Magellan, the Italian physicist Tiberius Cavallo, the German inventors Friedrich Koenig and Frederic Winsor (né Winzer), the Swiss engineer J.G. Bodmer, and the great French engineer and machine builder, Marc I. Brunel.

[73] Among the many eminent self-educated scientists was Michael Faraday, whose interests in electricity were first stimulated by reading an article in the *Encyclopedia Britannica*.

[74] An apt description of the importance of competence is provided by the early nineteenth-century steel industry: controlling the pace at which coal was fed to the furnace and its placing on the hearth [the skilled

How many such people were necessary? Better not teach the peasants how to read, Voltaire reputedly said, someone has to plow the fields.[75] Technological change in the era of the Industrial Revolution, based on invention, innovation, and implementation, did not necessarily require that the entire labor force, or even most of it, much less the population at large, be highly educated; that depended on whether the relation between innovation and the growth of competence was strong and positive. An economy that is growing technologically more sophisticated and more productive may end up using techniques that are more difficult to invent and artefacts that are more complex in design and construction, but may be easier to actually use and run on the shop floor. Production techniques became more modular and standardized, meaning that labor might become more specialized and that each worker had to know less rather than more. If much of the new technology introduced after 1825 was like the self-actor – simpler to use if more complex to build – it may well be that the best models to explain technological progress (in the sense of inventing new techniques rather than implementing existing ones) focus not on the *mean* level of human capital (or, as model-builders have it, the level of human capital of a representative agent), but just on the *density in the upper tail* of the distribution, that is, the level of education and sophistication of a small and pivotal elite of engineers, mechanics, and chemists. Dexterous, motivated, well-trained technically, and imaginative, with some understanding of the science involved, these workers turned the ideas of the "Great Men" into production. The new technological system depended on the increased skills of low-level technicians, supervisors, foremen, and skilled artisans that the factories relied on to introduce new techniques on the shop floor and to make the necessary adjustments to specific tasks and usages. What knowledge the firms could not supply from its own workforce, it purchased from the outside in the form of consulting engineers.[76]

Technical education for the masses might have been beneficial because among the working classes there might have been "diamonds in the rough", technically gifted

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worker] had to cope with variations in the quality of the fuel and adjust his stoking accordingly and sometimes add coal of various sizes and grades . . . all this was a matter of judgement, but in many instances this judgement governed the efficiency or even the practicability of the process. This sort of judgment was not the kind of thing one learned from books" [Harris (1992a, p. 26)].

[75] This is the way Darnton (2003, p. 5) phrases it. Actually, Voltaire view was a bit more involved. In his *Dictionaire Philosophique* he noted that even in the most enlightened villages at most two peasants could read and write, but that in no way affected their ability to build, plant and harvest. Adam Smith expressed the same idea in his "Early Draft" for the *Wealth of Nations* when he noted that "to think or to reason comes to be, like every other employment, a particular business, which is carried on by very few people who furnish the public with all the thought and reason possessed by the vast multitudes that labour". The benefits of the "speculations of the philosopher . . . may evidently descend to the meanest of people" if they led to improvements in the mechanical arts [Smith (1978, pp. 569–572)].

[76] Such outside professional consultants included the famous British "coal-viewers" who advised coal mine owners not only on the optimal location and structure of coal mines but also on the use of the Newcomen steam pumps employed in mines in the eighteenth century [Pollard (1968, pp. 152–153)]. "Civil engineers" was a term coined by the great engineer John Smeaton, who spent much of his life "consulting" to a large number of customers in need of technical advice.

lads who, with the proper training, might have become part of the creative elite. The sample of 316 industrialists assembled by Crouzet (1985) – admittedly only the tip of a largely unknown pyramid – contained only 31 persons whose occupations were “unskilled workmen” and only 16 fathers out of 226 “founders of large industrial undertakings” were working class. The bulk of the labor force consisted of rank- and file-workers whose ex post technical skills may have mattered but little, and thus any model that relates human capital to demographic behavior runs into a serious dilemma. Technological progress and competence had a complex relation because ingenuity and detailed propositional knowledge could be frontloaded in the instructions or artefacts, thus reducing the competence needed to carry out the actual production.[77]

It stands to reason that the ratio of competence to knowledge was higher in agriculture than in manufacturing and in services, since a great deal of competence concerned uncodified knowledge about very local and time-specific conditions of soil and weather. As the share of agriculture in the labor force and total output declined, this may be one reason why the relative importance of this form of human capital has declined in the twentieth century. It has also been suggested [Harris (1992a)] that the importance of tacit skills was especially prominent in coal-using industries such as glass and iron, which explains Britain’s initial advantage in these industries and the need for Continental Europe to import British skilled workers during the years of “catching-up” after 1800.

The human capital argument can be tested, at a rudimentary level, by looking at the ratio between skilled and unskilled wages (or “wage premium”). The problem is of course that without estimating a complete model of the market for skills, the historical course of that ratio cannot be assigned to demand or supply factors. If, however, we assume that technology is the prime mover in this market and we keep in mind that the supply of skills will lag considerably behind a rise in wages (since the acquisition of skills takes time), it would stand to reason that if the Industrial Revolution led to a net increase in the demand for skilled labor, we should observe some increase in the skill premium during the Industrial Revolution. No such change can be observed. Indeed, recent research into the wage premium has established that it changed little between 1450 and 1900, yet it was much lower in Western Europe than in either Southern and Eastern Europe or Asia, indicating perhaps that Europe was more capable in generating the kind of skills and abilities we associate with human capital in an age in which literacy mattered less [Van Zanden (2004)]. It is even more surprising that in the twentieth century this skill ratio declined precipitously [Knowles and Robertson (1951)]. This

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[77] An interesting example of such a technique is the construction of the *Nautical Almanacs*, detailed tables that allowed sailors to calculate their longitude before Harrison’s clocks were cheap enough to be made widely available, a technique pioneered by the German Astronomer Tobias Mayer in 1755. Nevil Maskelyne, the Astronomer Royal, designed tables put together by highly numerate “computers” that would allow seamen to compute with accuracy their location at sea in 30 minutes instead of the four hours required by Mayer’s original technique [Croarken (2002)].

could be caused by an (otherwise unexplained) increase in supply, but it is at least consistent with a story that stresses the ability of unskilled labor to operate effectively in a sophisticated technology environment.

The argument I propose, that technological progress is driven by a relatively small number of pivotal people, is not a call for a return to the long-defunct "heroic inventor" interpretation of the Industrial Revolution. The great British inventors stood on the shoulders of those who provided them with the wherewithal of tools and workmanship. John Wilkinson, it is often remarked, was indispensable for the success of James Watt, because his Bradley works had the skilled workers and equipment to bore the cylinders exactly according to specification. Mechanics and instrument makers such as Jesse Ramsden, Edward Nairn, Joseph Bramah, and Henry Maudslay; clock-makers such as Henry Hindley, Benjamin Huntsman (the inventor of the crucible technique in making high-quality steel), John Whitehurst (a member of the Lunar Society), and John Kay of Warrington (not to be confused with his namesake, the inventor of the flying shuttle, who was trained as a reed- and comb-maker), engineers such as John Smeaton, Richard Roberts, and Marc I. Brunel; ironmasters such as the Darbys, the Crowleys, and the Crawshays; steam engine specialists such as William Murdoch and Richard Trevithick; chemists such as John Roebuck, Alexander Chisholm, and James Keir were as much part of the story as the "textbook superstars" Arkwright, Cort, Crompton, Hargreaves, Cartwright, Trevithick, and Watt.[78] These were obviously men who could squeeze a great deal out of a narrow epistemic base and who could recognize more effective useful knowledge and base better techniques on them. Eventually, however, there was no escaping a more formal and analytical approach, in which a widening reliance on physics and mathematics was inevitable. Oddly enough, this approach originated in France more than in Britain.[79] Over the nineteenth century, the importance of advantages in competence (tacit skills and dexterity) declined, and that of formal codified useful knowledge increased, eroding the advantages Britain may have had through its skilled craftsmen that other nations envied and coveted in the years before 1815.

Below the great engineers came a much larger contingent of skilled artisans and mechanics, upon whose dexterity and adroitness the top inventors and thus Britain's technological success relied. These were the craftsmen, highly skilled clock- and instrument-makers, woodworkers, toymakers, glasscutters, and similar specialists, who could accurately produce the parts, using the correct dimensions and materials, who could read blueprints and compute velocities, understood tolerance, resistance, friction, and the interdependence of mechanical parts. These were the applied chemists

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[78] A good description of this class of people is provided by Griffiths' judgment of William Murdoch (the gifted and ingenious Watt and Boulton employee, credited with the invention of the famous Sun-and-Planets gear): "his inventiveness was instinctive, not analytical. He had an innate sense of mechanical propriety, of the chose juste, which led him to simple, robust and highly original solutions" [Griffiths (1992, p. 209)].

[79] The "Big Three *polytechnicien*" engineers of the early nineteenth century, Gustave-Gaspard Coriolis, Jean-Victor Poncelet, and Louis Navier, placed mechanical and civil engineering on a formal base, and supported practical ideas with more mathematical analysis than their more pragmatic British colleagues.

who could manipulate laboratory equipment and acids, the doctors whose advice sometimes saved lives even if nobody quite yet understood why, agricultural specialists who experimented with new breeds of animals, fertilizers, drainage systems, and fodder crops. These anonymous but capable workers produced a cumulative torrent of small, incremental, but cumulatively indispensable micro inventions without which Britain would not have become the "workshop of the world". They were artisans, but they were the skilled aristocracy of the trained craftsmen, not the average man in his workshop. It is perhaps premature to speak of an "invention industry" by this period, but technical knowledge at a level beyond the reach of the run-of-the-mill artisan became increasingly essential to create the inventions associated with the Industrial Revolution.

The average "quality" of the majority of the labor force – in terms of their technical training – may thus be less relevant to the development and adoption of the new techniques less than is commonly believed. The distribution of knowledge within society was highly skewed, but as long as access costs were sufficiently low, such a skewedness would not impede further technological progress. Rosenberg has pointed out that in Adam Smith's view the *modal* level of knowledge may be low, the highest levels of scientific attainment were remarkable and the *collective* intelligence of a civilized society is great and presents unprecedented opportunities for further technological progress [Rosenberg (1965, p. 137)]. A venerable tradition in economic history, in fact, has argued that technological progress in the first stages of the Industrial Revolution was "deskilling", requiring workers who were able to carry out repetitive routine actions instead of the skilled labor of skilled craftsmen.[80] The "factory system" required workers to be supervised and assisted by skilled mechanics, and hence the variance of the skill level may have increased even if we cannot be sure whether *average* skills had to go up or down. Much innovation, both historically and in our time, has been deliberately aimed to be *competence-reducing*, that is made more user-friendly and requiring less skill and experience to use even if it took far more knowledge to design.[81] Human capital was instrumental in creating competence rather than useful knowledge itself, in teaching how to carry out instructions rather than writing them. Yet given that much of what I termed above competence consisted of tacit knowledge and experience, and given that much of the competence could be front-loaded into the equipment by a small number of brilliant designers, the role of either the size of the population or their "mean"

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[80] Deskilling probably commenced already in the century before the Industrial Revolution, when much of the manufacturing in Europe was carried out in the homes of unskilled rural workers. Yet the cottage industries of Europe were certainly capable of technological change even if their limited size in the end imposed a binding constraint. See especially Berg (1994).

[81] An earlier example of such competence-reducing innovation was the introduction of fire-arms in Europe in the fifteenth century. Early fire-arms were not as effective as the longbow, but the latter took an inordinate amount of skill and strength to operate, whereas the use of fire-arms could be taught in a few weeks. In that regard, there is an interesting parallel between the "military revolution" of the fifteenth century and the Industrial Revolution.

level of human capital should be questioned. It seems plausible that the degree of networking and the level of access costs *within* the relatively small community of highly trained engineers and scientists may have been of greater importance.

Furthermore, the term "skill" may be too confining. Human capital was in part produced in schools, but what future workers were taught in schools may have had as much to do with behavior as with competence. Docility and punctuality were important characteristics that factory owners expected from their workers. "The concept of industrial discipline was new, and called for as much innovation as the technical inventions of the age", writes Pollard (1968 [1965], p. 217). Early factories designed incentives to bring about the discipline, but they also preferred to hire women and children, who were believed to be more docile. Skill may have mattered less than drill. Some of the literature by economists on human capital acquisition may have to be reinterpreted in this fashion.

8. Institutions and technological progress

Beyond the interaction of different kinds of knowledge was the further level of interaction and feedback between human knowledge and the institutional environment in which it operates. Before 1750, economic progress of any kind had tended to run into what could best be called negative institutional feedback. One of the few reliable regularities of the pre-modern world was that whenever a society managed, through thrift, enterprise, or ingenuity to raise its standard of living, a variety of opportunistic parasites and predators were always ready to use power, influence, and violence to appropriate this wealth. Such rent-seekers, who redistributed wealth rather than created it, came either from within the economy in the form of tax-collectors, exclusive coalitions, and thugs, or they came from outside as alien pillagers, mercenaries, and plunderers. The most obvious and costly form of negative institutional feedback before 1815 was, of course, war. Rent-seeking and war often went in hand-in-hand. Britain, France, the United Provinces and most other Continental powers fought one another constantly in hugely costly attempts to redistribute taxable real estate, citizens and activities from one to the other, a typical "mercantilist" kind of policy.[82] Economic growth indirectly helped instigate these conflicts. Wealth accumulation, precisely because it was mostly the result of "Smithian Growth", was usually confined to a region or city and thus created an incentive to greedy and well-armed neighbors to engage in armed rent-seeking. It surely is no accident that the only areas that had been able to thwart off such marauders with some success were those with natural defenses such as Britain and the Netherlands. Yet the Dutch United Provinces were weakened by the relentless aggressive mercantilist

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[82] O'Brien (2003, p. 5) notes that between the Nine-Years War (starting in 1688) and the Congress of Vienna in 1815, Britain and France were at or on the brink of war for more than half the period, justifying the term "Second Hundred-Years War".

policies of powerful neighbors.[83] The riches of the Southern Netherlands – unfortunately easier to invade – were repeatedly laid to waste by invading mercenary soldiers after 1570. More subtle forms of rent-seeking came from local monopolists (whose claims to a right to exclude others were often purchased from strongmen), guilds with exclusionary rights, or nobles with traditional rights such as *banalités*. A particularly harmful form of rent-seeking were price controls on grain that redistributed resources from the countryside to the city by keeping grain prices at below equilibrium levels [Root (1994)].

Had institutional feedback remained negative, as it had been before 1750, the economic benefits of technological progress would have remained limited. Mercantilism, as Ekelund and Tollison (1981, 1997) have emphasized, was largely a system of rent seeking, in which powerful political institutions redistributed wealth from foreigners to themselves as well between different groups and individuals within the society. The political economy associated with the Enlightenment increasingly viewed the old rent-seeking traditions of exclusionary privileges as both unfair and inefficient. Mercantilism had been a game of international competition between rival political entities. To defeat an opponent, a nation had to outcompete it, which it often did by subsidizing exports and raw materials imports, and imposing a tariff on finished goods. As it dawned upon people that higher productivity could equally outcompete other producers, they switched to a different policy regime, one that economists certainly would recognize as more enlightened.[84] In the decades around 1750, mercantilism had begun to decline in certain key regions in Western Europe, above all in Britain, where many redistributive arrangements such as guilds, monopolies, and grain price regulations were gradually weakening, though their formal disappearance was still largely in the future. The Age of Enlightenment led to some pre-1789 reforms on the Continent thanks to a few enlightened despots, but it was the French Revolution and the ensuing political turmoil that did more than anything else to transform Enlightenment ideas into genuine institutional changes that paved the road for economic growth. The Enlightenment also advocated more harmonious and cosmopolitan attitudes in international relations and its influence may have contributed to the relative calm that settled upon Europe after the Congress of Vienna. Political reforms that weakened privileges and permitted the emergence of freer and more competitive markets had an important effect on economic performance. The

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[83] The standard argument is that national defense was so costly that high indirect taxes led to high nominal wages, which rendered much of Dutch manufacturing uncompetitive. See for example Charles Wilson (1969). De Vries and Van Der Woude (1997, p. 680) point out that in 1688 the Dutch committed huge resources to an invasion of England because the future economic well-being on the Republic depended on the destruction of French mercantilism and the establishment of an international order in which the Dutch economy could prosper, yet it "proved to be a profitless investment". More recently, Ormrod (2003) has confirmed the view that the decline of the Dutch Republic was a direct consequence of the mercantilist policies of its neighbors, especially Britain.

[84] In 1773, the steam engine manufacturer Matthew Boulton told Lord Harwich that mechanization and specialization made it possible for Birmingham manufacturers to defeat their Continental competitors [cited by Uglow (2002, p. 212)].

institutional changes in the years between 1770 and 1815 saw to it that the Industrial Revolution was not followed by a surge in rent-seeking and violence that eventually could have reversed the process [Mokyr (2003b)].

The positive feedback between technological and institutional change is central to the process of historical change. The co-evolution of technological knowledge and institutio ns during the second Industrial Revolution has been noticed before.[85] Above all, three kind of institutions were important in facilitating the sustained technological progress central to economic growth: (1) those that provided for connections between the people concerned mostly with propositional knowledge and those on the production side; (2) those that set the agenda of research to generate new propositional knowledge that could be mapped into new techniques; and (3) those institutions that created and safeguarded *incentives* for innovative people to actually spend efforts and resources in order to map this knowledge into techniques and specifically that weakened the effective social and political resistance against new techniques. As noted above, even some of the formal endogenous growth models require a growing proportion of labor in the "invention sector", a condition that clearly demands that their profits not be expropriated altogether.

The formal institutions that created the bridges between prescriptive and propositional knowledge in late eighteenth and nineteenth century Europe are well understood: scientific societies, universities, polytechnic schools, publicly funded research institutes, museums, agricultural research stations, research departments in large financial institutions. Improved access to useful knowledge took many forms. Cheap and widely diffused publications disseminated it. All over the Western world, textbooks of applied science (or "experimental philosophy" in the odd terminology of the time), professional journals, technical encyclopedias, and engineering manuals appeared in every field and made it easier to "look things up". Technical subjects penetrated school curricula in every country in the West (although Britain, the leader in the first Industrial Revolution, lost its momentum in the Victorian era). The professionalization of expertise meant increasingly that anyone who needed some piece of useful knowledge could find someone who knew, or who knew someone who knew. Learned technical journals first appeared in the 1660s and by the late eighteenth century had become one of the main vehicles by which prescriptive knowledge was diffused. In the eighteenth century, most scientific journals were in fact deliberately written in an accessible style, because they more often

[85] Nelson (1994) has pointed to a classic example, namely the growth of the large American business corporation in the closing decades of the nineteenth century, which evolved jointly with the high-throughput technology of mass production and continuous flow. In their pathbreaking book, Fox and Guagnini (1999) have pointed to the growth of practically-minded research laboratories in academic communities, which increasingly cooperated and interacted successfully with industrial establishments to create an ever-growing stream of technological adaptations and microinventions. Many other examples can be cited, such as the miraculous expansion of the British capital market which emerged jointly with the capital-hungry early railroads and the changes in municipal management resulting from the growing realization of the impact of sanitation on public health [Cain and Elyce (2001)].

than not catered to a lay audience and thus were media of education and dissemination rather than repositories of original contributions [Kronick (1962, p. 104)]. Review articles and book reviews that summarized and abstracted books and learned papers (especially those published overseas and were less accessible), another obvious example of an access-cost reduction, were popular.[86] In the nineteenth century, specialized scientific journals became increasingly common and further reduced access costs, if perhaps more and more requiring the intermediation of experts who could decode the jargon.

To be sure, co-evolution did not always quickly produce the desired results. The British engineering profession found it difficult to train engineers using best-practice knowledge, and the connections between science and engineering remained looser and weaker than elsewhere. In 1870 a panel appointed by the Institute of Civil Engineers concluded that "the education of an Engineer [in Britain] is effected by ... a simple course of apprenticeship to a practicing engineer ... it is not the custom in England to consider *theoretical* knowledge as absolutely essential" [cited by Buchanan (1985, p. 225)]. A few individuals, above all William Rankine at Glasgow, argued forcefully for more bridges between theory and practice, but significantly he dropped his membership in the Institute of Civil Engineers. Only in the late nineteenth century did engineering become a respected discipline in British universities.

Elsewhere in Europe, the emergence of universities and technical colleges that combined research and teaching advanced rapidly, thus simultaneously expanding propositional knowledge and reducing access costs. An especially good and persuasive example is provided by Murmann (2003), who describes the co-evolution of technology and institutions in the chemical industry in imperial Germany, where the new technology of dyes, explosives, and fertilizers emerged in constant interaction with the growth of research and development facilities, institutes of higher education, and large industrial corporations with a knack for industrial research.[87] Institutions remained a major determinant of access costs. To understand the evolution of knowledge, we need to ask who talked to whom and who read what. Yet the German example illustrates that progress in this area was halting and complex; it needs to be treated with caution as a causal factor in explaining systematic differences between nations. The famed *technische Hochschulen*, in some ways the German equivalent of the French *polytechniques*, had lower social prestige than the universities and were not allowed to award engineering diplomas and doctorates till 1899. The same is true for the practical, technically oriented *Realschulen*, which had lower standing than the more classically inclined *Gymnasien*. Universities conducted a great deal of research, but it goes too far to state that what

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[86] This aspect of the Industrial Enlightenment was personified by the Scottish writer and mathematician John Playfair (1748–1819) whose textbooks and review essays in the *Edinburgh Review* made a special effort to incorporate the work of Continental mathematicians, as witnessed by the essays in 1807 on the work of Mechain and Delambre on the Earth's meridian, and his 1808 review of Laplace's *Traité de Mécanique Celeste* [Chitnis (1976, pp. 176–177, 222)].

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

they did was a *deliberate* application of science to business problems.[88] Universities and businesses co-evolved, collaborating through personal communications, overlapping personnel, and revolving doors. The second Industrial Revolution rested as much on industry-based science as on the more common concept of science-based industry [König (1996)].

Designing institutions that create the correct ex ante motivations to encourage invention is not an easy task. Economists believe that agents respond to economic incentives. A system of relatively secure property rights, such as emerged in Britain in the seventeenth century, is widely regarded as a prerequisite. Without it, even if useful knowledge would expand, the investment and entrepreneurship required for a large scale implementation of the new knowledge would not have been forthcoming. On a more specific level, the question of the role of intellectual property rights and rewards for those who add to the stock of useful knowledge in generating economic growth is paramount. Some of the best recent work in the economic history of technological change focuses on the working of the patent system as a way of preserving property rights for inventors. In a series of ingenious papers, Kenneth Sokoloff and Zorina Khan have shown how the American patent system exhibited many of the characteristics of a market system: inventors responded to demand conditions, did all they could to secure the gains from their invention and bought and sold licenses in what appears to be a rational fashion. It was far more accessible, open, and cheaper to use than the British system, and attracted ordinary artisans and farmer as much as it did professional inventors and eccentrics [Khan and Kenneth (1993, 1998, 2001) and Khan (2002)].

Whether this difference demonstrates that a well-functioning system of intellectual property rights was essential to the growth of useful knowledge remains an open question. For one thing, the American system was far more user-friendly than the British patent system prior to its reform in 1852. Yet despite the obvious superiority of the U.S. system and the consequent higher propensity of Americans to patent, there can be little doubt that the period between 1791 and 1850 coincides roughly with the apex of British superiority in invention. The period of growing American technological leadership, after 1900, witnessed a stagnation and then a decline in the American per capita patenting rate. Other means of appropriating the returns on R&D became relatively more attractive. In Britain, MacLeod (1988) has shown that the patent system during the Industrial Revolution provided only weak and erratic protection to inventors and that large areas of innovation were not patentable. Patenting was associated with commercialization and

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[88] James (1990, p. 111) argues that Germany's "staggering supremacy" was not due to scientists looking for applicable results but came about "because her scientists experimented widely without any end in mind and then discovered that they could apply their new information". This seems a little overstated, but all the same we should be cautious in attributing too much intent and directionality in the growth of knowledge. Much of it was in part random or the unintended consequence of a different activity, and it was the selection process that gave it its technological significance. In that respect, the evolutionary nature of the growth in useful knowledge is reaffirmed.

the rise of a profit-oriented spirit, but its exact relation to technological progress is still obscure.[89]

What is sometimes overlooked is that patents placed technical information in the public realm and thus reduced access costs. Inventors, by observing what had been done, saw what was possible and were inspired to apply the knowledge thus acquired to other areas not covered by the patent. In the United States, *Scientific American* published lists of new patents from 1845, and these lists were widely consulted. Despite the limitations that patents imposed on applications, these lists reduced access costs to the knowledge embodied in them. The full specification of patents was meant to inform the public. In Britain this was laid out in a decision by chief justice Lord Mansfield, who decreed in 1778 that the specifications should be sufficiently precise and detailed so as to fully explain it to a technically educated person. In the Netherlands, where patenting had existed from the 1580s, the practice of specification was abandoned in the mid-1630s but revived in the 1770s [Davids (2000, p. 267)].

In at least two countries, the Netherlands and Switzerland, the complete absence of a patent system in the second half of the nineteenth century does not seem to have affected the rate of technological advance [Schiff (1971)]. Of course, being small, such countries could and did free-ride on technological advances made elsewhere, and it would be a fallacy to infer from the Dutch and Swiss experience that patents did not matter. It also seems plausible that reverse causation explains part of what association there was between the propensity to patent and the generation of new techniques: countries in which there were strong and accessible bridges between the *savants* and the *fabricants* would feel relatively more need to protect the offspring of these contacts. Lerner (2000) has shown that rich and democratic economies, on the whole, provided more extensive patent protection. The causal chain could thus run from technological success to income and from there to institutional change rather than from the institutions to technological success, as Khan and Sokoloff believe. It may well be true, as Abraham Lincoln said, that what the patent system did was "to add the fuel of interest to the fire of genius" [cited by Khan and Kenneth (2001, p. 12)], but that reinforces the idea that we need to be able to say something about how the fire got started in the first place.

Other institutions have been widely recognized as aiding in the generation of new techniques. Among those are relatively easy entry and exit from industries, the availability of venture capital in some form, the reduction of uncertainty by a large source of assured demand for a new product or technique (such as military procurement or

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[89] In fact, economists have argued that for countries that are technologically relatively backward, strict patent systems may be on balance detrimental to economic welfare [for a summary, see Lerner (2000)]. In a different context, Hilaire-Pérez (2000) has shown how different systems of invention encouragement in eighteenth-century Europe were consistent with inventive activity: whereas in France the state played an active role of awarding "privileges" and pensions to inventors deemed worthy by the French Academy, in Britain the state was more passive and allowed the market to determine the rewards of a successful inventor. These systems were not consistently enforced (some British inventors whose patents for one reason or another failed to pay off were compensated by special dispensation) and, as Hilaire-Pérez shows, influenced one another.

captive colonial markets), the existence of agencies that coordinated and standardized the networked components of new techniques, and revolving doors between industry and organizations that specialize in the generation of propositional knowledge such as universities and research institutes.

There is a fundamental complementarity between knowledge growth and institutional change in the economic growth of the West. Augmenting and diffusing knowledge produced the seeds that germinated in the fertile soils that economic incentives and functional markets created. Without the seeds, improved incentives for innovation would have been useless. Commercial, entrepreneurial, and even sophisticated capitalist societies have existed that made few important technical advances, simply because the techniques they employed rested on narrow epistemic bases and the propositional knowledge from which these bases were drawn was not expanding. The reasons for this could be many: the agendas of intellectual activity may not have placed a high priority on *useful* knowledge, or a dominant conservative religious philosophy might have stifled a critical attitude toward existing propositional knowledge. Above all, there has to be a belief that such knowledge may eventually be socially useful even if the gains are likely to be reaped mostly by persons others than the ones who generate the novel propositional knowledge. Given that increasing this knowledge was costly and often regarded as socially disruptive, the political will by agents who controlled resources to support this endeavor, whether they were rich aristocratic patrons or middle-class taxpayers, was not invariably there. The amounts of resources expended on R&D, however, are not more important than questions about how they were spent, on what, and what kind of access potential users had to this knowledge.

One specific example of an area in which technological innovation and institutional change interacted in this fashion was in the resistance of vested interests to new technology [Mokyr (1994, 2002)]. Here institutions are particularly important, because by definitions such resistance has to operate outside the market mechanism. If left to markets to decide, it seems likely that superior techniques and products will inexorably drive out existing ones. For the technological status quo to fight back thus meant to use non-market mechanisms. These could be legal, through the manipulation of the existing power structure, or extralegal, through machine-breaking, riots, and the use of personal violence against inventors and the entrepreneurs who tried to adopt their inventions.

At one level, eighteenth-century Enlightenment thinking viewed technological change as “progress” and implicitly felt that social resistance to it was socially undesirable. Yet there was a contrary strand of thought, associated with Rousseau and with later elements of romanticism such as Cobbett and Carlyle continuing with the Frankfurt school in the twentieth century, that sincerely viewed industrialization and modern technology and the enlightenment that spawned them as evil and destructive. Such ideological qualms often found themselves allied with those whose human and physical capital was jeopardized by new techniques. Mercantilist thought, with its underlying assumptions of a zero-sum society, was hugely concerned with the employment-reducing effects of technological progress. The ensuing conflict came to a crashing crescendo during the Industrial Revolution. The Luddite rebellion – a complex set of events that involved a variety of grievances, not all of which were related to rent-seeking – was mercilessly suppressed. It would be a stretch to associate the harsh actions of the British army in the midlands in 1812 with anything like the Enlightenment. All the same, it appears that rent-seeking inspired resistance against new technology had been driven into a corner by that time by people who believed that "freedom" included the freedom to innovate and that higher labor productivity did not necessarily entail unemployment.

The British example is quite telling.[90] In the textile industries, by far the most resistance occurred in the woolen industries. Cotton was a relatively small industry on the eve of the Industrial Revolution and had weakly entrenched power groups. There were riots in Lancashire in 1779 and 1792, and a Manchester firm that pioneered a powerloom was burnt down. Yet cotton was unstoppable and must have seemed that way to contemporaries. Wool, however, was initially far larger and had an ancient tradition of professional organization and regulation. Laborers in the wool trades tried to use the political establishment for the purposes of stopping the new machines. In 1776 workers petitioned the House of Commons to suppress the jennies that threatened the livelihood of the industrious poor, as they put it. After 1789, Parliament passed sets of repressive laws (most famously the Combination Act of 1799), which in Horn's (2003) view were not only intended to save the regime from French-inspired revolutionary turmoil, but also to protect the Industrial Revolution from resistance "from below". Time and again, groups and lobbies turned to Parliament requesting the enforcement of old regulations or the introduction of new legislation that would hinder the machinery. Parliament refused. The old laws regulating the employment practices in the woolen industry were repealed in 1809, and the 250 year old Statute of Artificers was repealed in 1814. Lacking political support in London, the woolworkers tried extralegal means. As Randall has shown, in the West of England the new machines were met in most places by violent crowds, protesting against jennies, flying shuttles, gig mills, and scribbling machines [Randall (1986, 1989)]. Moreover, in these areas magistrates were persuaded by fear or propaganda that the machine breakers were in the right. The tradition of violence in the West of England, writes Randall, deterred all but the most determined innovators. Worker resistance was responsible for the slow growth and depression of the industry rather than the reverse [Randall (1989)]. The West of England, as a result, lost its supremacy to Yorkshire. Resistance in Yorkshire was not negligible either, but there it was unable to stop mechanization. Violent protests, such as the Luddite riots, were forcefully suppressed by soldiers. As Paul Mantoux put it well many years ago, "Whether [the] resistance was instinctive or considered, peaceful or violent, it obviously had no chance of success" [Mantoux (1961 [1928], p. 408)]. Had that not been the case, sustained progress in Britain would have been severely hampered and possibly brought to an end.[91]

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[90] Some of the following is based on Mokyr (1994).

[91] As Randall has shown, in the West of England the new machines were met by violent crowds, protesting against jennies, flying shuttles, gig mills, and scribbling machines [Randall (1986, 1989)]. Moreover, in these

In other industries, too, resistance appeared, sometimes from unexpected corners. When Samuel Clegg and Frederick Windsor proposed a central gas distribution plan for London, they were attacked by a coalition that included the eminent scientist Humphry Davy, the novelist Walter Scott, the cartoonist George Cruickshank, insurance companies, and the aging James Watt [Stern (1937)]. The steam engine was resisted in urban areas by fear of "smoky nuisances", and resistance to railroads was rampant in the first years of their incipience. Mechanical sawmills, widely used on the Continent, were virtually absent from Britain until the nineteenth century.[92] Even in medical technology, where the social benefits were most widely diffused, the status quo tried to resist. When Edward Jenner applied to the Royal Society to present his findings, he was told "not to risk his reputation by presenting to this learned body anything which appeared so much at variance with established knowledge and withal so incredible" [Keele (1961, p. 94)].[93] In medical technology, in general, resistance tended to be particularly fierce because many of the breakthroughs after 1750 were inconsistent with accepted doctrine, and rendered everything that medical professionals had laboriously learned null and void. It also tended, more than most other techniques, to incur the wrath of ethical purists who felt that some techniques in some way contradicted religious principles, not unlike the resistance to cloning and stem-cell research in our own time. Even such a seemingly enormously beneficial and harmless invention as anesthesia was objected on a host of philosophical grounds [Youngson (1979, pp. 95–105; 190–198)].

With the rise in the factory and the strengthening of the bargaining power of capitalists, authority and discipline might have reduced, at least for a while, the ability of labor to resist technological progress. The factory, however, did not solve the problem of resistance altogether; unions eventually tried to undermine the ability of the capitalist to exploit the most advanced techniques. Collective action by workers imposed an effective limit on the "authority" exercised by capitalists. Workers' associations tried to ban some new techniques altogether or tried to appropriate the entire productivity gains

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areas magistrates were persuaded by fear or propaganda that the machine breakers were in the right. The tradition of violence in the West of England, writes Randall, deterred all but the most determined innovators. Worker resistance was responsible for the slow growth and depression of the industry rather than the reverse [Randall (1989)]. The West of England, as a result, lost its supremacy in the wool industry to Yorkshire.

[92] The resistance against sawmills is a good example of attempts to use both legal and illegal means. It was widely believed in the eighteenth century that sawmills, like gigmills, were illegal although there is no evidence to demonstrate this. When a wind-powered sawmill was constructed at Limehouse (on the Thames, near London) in 1768, it was damaged by a mob of sawyers "on the pretence that it deprived many workmen of employment" [Cooney (1991)].

[93] Jenner's famous discovery of the smallpox vaccine ran into the opposition of the inoculators concerned about losing their lucrative trade [Hopkins (1983, p. 83)]. The source of the vaccine, infected animals, was a novelty and led to resistance in and of itself: Clergy objected to the technique because of the "iniquity of transferring disease from the beasts of the field to Man" [Cartwright (1977, p. 86)]. Cartoonists depicted people acquiring bovine traits, and one woman complained that after he daughter was vaccinated she coughed like a cow and grew hairy [Hopkins (1983, p. 84)]. Despite all this, of course, the smallpox vaccine was one of the most successful macroinventions of the period of the Industrial Revolution and its inventor became an international celebrity.

in terms of higher piece wages, thus weakening the incentive to innovate. On the other hand, laborers' industrial actions often led to technological advances aimed specifically at crippling s trikes [Bruland (1982) and Rosenberg (1976, pp. 118–119)].[94]

9. Conclusions: Technology, growth, and the rise of the occident

In economic history, more so perhaps than in other disciplines, everything is a matter of degree, and there are no absolutes. The arguments made in this survey represent an interpretation that is by no means generally accepted. Many scholars have argued eloquently and persuasively for continuity rather than radical and abrupt change in western society between 1760 and 1830. Almost every element we associate with the Industrial Revolution can be seen to have precedent and precursor. Some of these are quite valid (episodes of growth and "modernity" can be found in earlier periods; the use of coal and non-animate energy was expanding already in the centuries before the Industrial Revolution; agricultural productivity may have been as high in 1290 as it was in 1700; factory-like settings can be found in earlier periods). Others are based on misapprehensions (the aeolipiles built by Hero of Alexandria were *not* atmospheric steam engines). In the end, the debate on continuity can only be settled if we accept a criterion by which to judge the degree of continuity. If the criterion is economic growth, the continuity faction in the end will have to concede defeat, even if the victory is one in overtime. The Industrial Revolution *itself* was not a period of rapid economic growth, but it is clear beyond question that it set into motion an economic process that by the middle of the nineteenth century created a material world that followed a dynamic not hitherto experienced.

Not only that growth was faster and more geographically dispersed (covering by 1914 most of Europe, North America, other European offshoots, and Japan) than had been experienced by any economy before, it was sustainable. Unlike previous episodes, it kept rolling through the twentieth century. A moment of reflection will underline the enormity of this achievement. The twentieth century was in many ways a very bad century for the Western world: two horrid World Wars, a hugely costly depression, the collapse of international trade after 1914, the disastrous collectivist experiment in Russia extended to all of Eastern Europe in 1945, and the loss of its Colonial Empire – all of these should have pointed to catastrophe, misery, and a return to economic barbarism for the *Abendland*. Something similar may have happened in the fourteenth century, the disasters of which in some views set Europe's economy back for a century or more. Yet by the early years of the twenty first century, the gap between rich and poor nations is bigger than ever and Danny Quah's "twin peaks" are getting further and further apart. Despite the huge setbacks, the engine that drove the Occident express

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[94] The most famous example of an invention triggered by a strike was that of the self-acting mule, invented in 1825 by Richard Roberts at the prompting of Manchester manufacturers plagued by a strike of mule operators.

had become so immensely powerful that it easily overwhelmed the twentieth century roadblocks that bad luck and human stupidity placed on its tracks. The Great Divergence train stormed on, undaunted.

Social scientists and historians discussing this issue are often accused of "triumphalism" and "teleologies", which are paired with "Eurocentricity" or "Western-centricity". Whether the scholars who make such accusations actually mean to argue that the gap in income and living standards is imaginary (or ephemeral), or whether they just feel that it is unjust and unfair, is sometimes hard to tell.[95] Yet it seems otiose to gainsay the importance of the topic. If the rest of the world is to eventually enjoy the material comforts available to most people in the West or not, we should not give up on our attempt to understand "how the West did it".

If we want to understand *why* the West did what it did we should ask questions about the *when*. The consensus is that by 1750, the gap between the twin peaks was much smaller than it was today. If Europe was richer than the rest of the world, it was so by a margin that looks thin compared to what it is today. The so-called "California School" has been arguing indeed that living standards and measurable indicators of economic performance between China and Europe were not all that different by 1750.[96] If this is accepted, and if we are willing to take the Yang-Zhi delta as indicative of economic conditions of the non-European world, the current gap between rich and poor is largely the result of the Industrial Revolution and the events that followed it. Be that as it may, underneath its surface the European soil in 1500 already contained the seeds of the future divergence in 1750. There was, however, nothing inexorable about what happened after: the seeds need not have sprouted, they could have been washed away by the flood of wars, or the young sprouts of future growth might have been pulled out by rapacious tax collectors or burned by intolerant religious authorities. There could have been a Great *Convergence* after 1800 instead of what actually took place, in which Europe would have reverted back to the kind of economic performance prevalent in 1500. In the end, the economic history of technology – like all evolutionary sequences – contains a deep and irreducible element of contingency. Not all that was had to be.

The question of "when" is important because it makes geographical explanations that explain Europe's success by its milder climate or conveniently located coal reserves less powerful, because these differences are time-invariant. Something had changed in Europe before the Industrial Revolution that destabilized the economic dynamic in the West, but not elsewhere. The question of "where" is also important. Britain was not "Europe", and even today there are some European regions that clearly are not part of the Western economic development pattern or very recent arrivals. On the other hand, a number of non-European nations have been able to join the "convergence club".

There are two alternative scenarios of the emergence of the gap. One is that, regardless of living standards and income in 1750, Europe was already deeply different from

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[95] Such confusions mark especially the literature associated with Gunder Frank (1998) and Blaut (1993).

[96] See especially Wong (1997), Pomeranz (2000) and Goldstone (2002).

the rest of the world in 1750 in many respects. In their different ways, David Landes (1998), Eric Jones (1981, 1988), Avner Greif (2003) and Angus Maddison (1998) subscribe to this view. By 1750 Europe had already had Calvin and Newton, Spinoza and Galileo, Bacon and Descartes. It had a commercial capitalism thriving especially in Atlantic Ports, an institutional structure that supported long-distance trade, a well-functioning monetary system, and the ability of rulers to tax their subjects and suppress nonconformists and heretics had been constrained in complex but comparatively effective ways. It had universities, representative parliamentary bodies, embryonic financial institutions, powerful navies and armies, microscopes and printing presses. Its agriculture was gradually switching to more productive rotations, adopting new crops, and experimenting with animal breeding. Its manufacturing system was market-oriented and competitive. It had established the beginning of a public health system that had conquered the plague (still rampant elsewhere) and was making inroads against smallpox. Its ships, aided by sophisticated navigational instruments and maps, had subjugated and colonized already some parts of the non-European world and neither the Mongols nor the Ottoman Turks were a threat anymore. It drank tea, ate sugar, smoked tobacco, wore silk and cotton, and ate from better plates in coal- or peat-heated homes. Its income per capita, as well as we can measure it, may have been little different from what it had been in the late Middle Ages (though Adam Smith disagreed), yet it was already ahead.

The alternative school emphasizes that many of these European features could be found in other societies, especially in China and Japan, and that when Europe and the Orient differed, the difference was not always necessarily conducive to economic growth. Ch'ing China may not have been an open economy, but it had law and order, a meritocratic bureaucracy, peace, effective property rights, and a great deal of medium- and long-distance trade within its borders. We need to be wary from the logical fallacy that all initial differences between Europe and China contributed to the outcome. Some of the initial difference may have actually worked the other way, so that the Great Divergence took place despite them. Others were ambiguous in their effect.[97] In order to understand what triggered Europe's economic miracle, we need to identify an event that happened before the Industrial Revolution, happened in the right areas, and which can be connected logically to subsequent growth.

I have identified this event as "the Industrial Enlightenment" and have attempted to show how it affected the two central elements of the Industrial Revolution, technology and institutions, and how these two elements then affected one another. Not everything that is normally included in the historians' idea of the Enlightenment mattered, and not everything that mattered could be attributed to the Industrial Enlightenment. John Stuart Mill's reflection that "the great danger in the study of history is not so much mistaking falsehood for truth, as to mistake a part for the whole" should be pertinent here.

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[97] An example is the European States System, often hailed as the element of competition which constrained and disciplined European governments into a more rational behavior, lest they weaken their military power. Yet the costs of wars may well have exceeded the gains, and the mercantilist policies that the States System triggered in the seventeenth century had doubtful effects on economic performance.

The emphasis on the Enlightenment illustrates how economists should think about culture and cultural beliefs as discussed in great length by Greif (2003). Culture mattered to economic development – how could it not? But we have to show the exact ways in which it mattered and through which channels it operated. I have argued that cultural beliefs changed in the eighteenth century, but beyond Greif's notion of beliefs about other people's behavior, I would include the metaphysical beliefs that people held about their environment and the natural world, and their attitudes toward the relationship between production and useful knowledge. It should also include their cultural beliefs about the possibility and desirability of progress and their notions of economic freedom, property, and novelty.

In that sense, at least, the Enlightenment may have been the missing link that economic historians have hitherto missed. Greif (2003, XIII-17) points out that many of the institutional elements of modern Europe were already in place in the late Middle Ages: individualism, man-made formal law, corporatism, self governance, and rules that were determined through a legislative process in which those who were subject to them could be heard and had an input. Yet these elements did not trigger modern growth at that time, and it bears reflecting why not. The technological constraints were too confining, and the negative feedbacks too strong.

The story of the growth of the West is the story of the dissolution of these constraints. The Baconian belief that the universe is logical and understandable, that the understanding of nature leads to its control, and that control of nature is the surest route to increased wealth, was the background of a movement that, although it affected but a minute percentage of Europe's population, played a pivotal role in the emergence of modern growth. If culture can be said to matter, it did so because the prevailing ideology of knowledge among those who mattered started to change in a way it did not elsewhere. The eighteenth century Enlightenment, moreover, brought back many of the institutional elements of an orderly and civil society, together with the growing realization, most eloquently expressed by Adam Smith, that economic activity was not a zero-sum game and that redistributive institutions and rent-seeking are costly to society.

All the same, ideological changes and cultural developments are not the entire story. A desire for improvement and even the "right" kind of institutions by themselves do not produce *sustained* growth unless society produces new useful knowledge and unless the growth of knowledge can be sustained over time. Useful knowledge grows because in each society there are people who are creative and original, and motivated by some combination of greed, ambition, curiosity, and altruism. All four of those motives can be seen to be operating among the people who helped make the Industrial Revolution, often in the same people. Given that the generation of innovations was not yet dominated by large corporations, the relative weight of "greed" may have been smaller than in the twentieth-first century, and that of curiosity and altruism correspondingly higher, though these motives are hard to gauge. Yet in order to be translated from personal predilections to facts on the ground, and from there to economic growth, an environment that produced the correct incentives and the proper access to knowledge had to exist. The uniqueness of the European Enlightenment was that it created that kind of environment in addition to the useful knowledge that revolutionized production.

The experience of the past two centuries in the western world supports the view that useful knowledge and its application to production went through a phase transition in which it entered a critical region in which equilibrium concepts may no longer apply. This means that as far as future technological progress and economic growth are concerned, not even the sky is the limit. Science Fiction writers have known this all along.

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