Long-term Economic growth and the History of Technology

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

Introduction

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 (Aghion and Howitt, ????, check a nice quote). Whether technology is a deus ex machina that somehow makes productivity grow a little each year, or produced within the system by the rational and purposeful application of research and development, the growth of human and physical capital that are strongly complementary with productivity growth, or even in the simple TFP computations that often equate the residual with technological progress – technology is central to the dynamic of the economy in the past two centuries.

Of course, economic historians studying earlier periods realize that technology is not the only factor underlying historical 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 their comparative advantage and take full advantage of economies of scale could generate growth sustainable for decades and even centuries. Even with no changes whatsoever in technology, economies can grow thanks to peace, the growth of law and order, improved communications and trust, the introduction of money and credit, enhanced 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; 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.

It is usually assumed by economists that sustained economic growth is a recent phenomenon simply because if modern rates of growth had been sustained, income in 1500 or in 1000 would have been absurdly low.[1] 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's 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, 1776-1976, pp. 365-66).[2] On the eve of the Industrial Revolution, large parts of Europe and some 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.[3]

This is not to say that before the Industrial Revolution technology was unimportant in its impact on growth. Medieval Europe was an innovative society which invented many important things (including movable type, gunpowder, spectacles, the mechanical clock) and adopted many more inventions from other societies (paper, navigational instruments, Arabic numerals, the lateen sail, wind power). Yet, when all

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[1] 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 percapita in 1590 would have been $ 61, which clearly seems absurdly low.

[2] Footnote to Snooks from INDUSTRIAL REVOLUTION essay.

[3] Indeed, many historians speak of a "consumer revolution" *prior to* the Industrial Revolution which would be inexplicable without rising income before 1750 [Complete this ftnt from IR].

is said and done, it is hard to see 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).

What is true for the earlier period – as it was a fortiori after 1750 – is 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 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. 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 is limited. 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.

A Historical Theory of Technology

Technology is knowledge. 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.

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 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 through some monstrous network, there was a reality of partial and costly sharing and access. But these costs were not historically invariant, and their changes 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). When the access costs become very high, it could be said in the limit that social knowledge has disappeared.[4] Language,

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[4] 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 Schr`dinger wave equations, yet it is "accessible" at low cost for advanced students of quantum mechanics. If someone "needs" to know

mathematical symbols, diagrams, and physical models are all means of reducing access costs. Shared symbols may not always correspond with the things they signify, as postmodern critics believe, but as long as they are shared they reduce the costs of accessing knowledge held by another person or storage device.

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. The printing press clearly was one of the most significant cost-reducing inventions of the historical past.[5] Yet the nature of the books that were printed, such as topic, language, and accessibility played a central role in the reduction of access costs. Techniques are, of course, "representations within the brain," as Brian Loasby notes (1999, p. 64), and the knowledge that "this is how you do that" is twice removed from the audience: first by the ability of the knower to map what he does into his own brain, and then by his ability to cast it in a language common with the audience. People *can* learn vertically, but also from one another through imitation. Postdoctoral students in laboratory students 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.[6]

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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.

[5] 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).

[6] 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.

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 regularities and phenomena in order to improve human material welfare.[7] The fundamental unit of set of prescriptive knowledge has the form of a recipe, describing the "hows" of what we call production. There are two important characteristics we need to point out in this context. One is the ratio of tacit to codifiable knowledge. It is impossible to fully specify the entire content of a set of instruction. 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). There is a continuum between the implicit understandings and clever tricks that make a technique work and that we call tacit knowledge, and minor improvements and refinements introduced subsequently that involve actual adjustments in the explicit instructions. The latter would be more properly thought off as microinventions, but clearly any 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 composing it.

The second and more central 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 is based on a set of propositions about how the world works. 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 notes that the distinction is recognized by patent law, which will patent inventions (additions to prescriptive knowledge) but not discoveries

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[7] These instructions are essentially identical 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.

(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."(1962, p. 175). Purists will object that "right" and "wrong" are judged only by socially constructed criteria, and that "successful" needs to be defined in a context, depending on the objective function that is being maximized.

The actual relation between propositional and prescriptive knowledge can be summarized in the following 9 generalizations:

1. Every technique has a minimum epistemic base, which contains the minimum 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.[8] There are and have been some techniques, invented accidentally, about which 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 need to have a minimum epistemic base that is larger than a singleton for a working technique to emerge. It is hard to imagine such techniques as nuclear resonance imaging or computer assisted design software as emerging in any society as the result of serendipitous finds or trial-and-error methods, without the designers having a clue of why and how they worked.

3. The epistemic base 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. The finiteness of the epistemic base constrains the efficiency of the uses of the techniques.

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.

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[8] 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.

5. In principle, the wider the epistemic base, the more likely a technique is to be improved, adapted, and refined. If the principles of a technique are known, the costs of development and improvement are per force are lower. 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. Moreover, a wider epistemic ensures that it is less likely for one to enter a blind alley and to spend resources in trying to make something work that cannot work.[9]

6. The epistemic base in existence during the invention may be quite narrow at first but often is enlarged following the appearance of the invention, and sometimes directly on account of the invention.

7. 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 more likely the technique is to be adopted, and vice versa. Of course, tightness is closely correlated with observables: a laser printer works better than a dot matrix, and there can be little dispute about the characteristics here. But for many medical and farming techniques it is often difficult to observe what works and what does not work as well.

8. 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

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[9] 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 as it was for 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 benefitted in a similar way from a widening of the prescriptive knowledge on which it was based.

practical fruits of the insights of this knowledge to technology may still be available just as if everyone had been taught advanced physics. For the economic historian, what counts is collective knowledge and the cost of access as discussed above.

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

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 1998).

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 Europe 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 true that the first successful economic applications of the new technology appeared in Britain. Clearly in 1789 Britain had an advantage in the execution of new techniques. Yet an overwhelming British advantage in *inventing* – especially in making 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 even more questionable. Britain’s precociousness in the Industrial Revolution was a function of three factors.

First, it was at peace in a period when the Continent was engulfed in political and military upheaval. Not only that there was no fighting 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.[10] During the stormy years of the Revolution, French machine breakers found an opportunity to mount an effective campaign against British machine, thus delaying their adoption (Horn, 2002). Second, Britain's entrepreneurs proved uncannily able to adopt new inventions regardless of where they were made. 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 gas-lighting, chlorine bleaching, the Jacquard loom, the Robert continuous paper-making machine, and the Leblanc soda making process.[11] In smaller industries, too, the debt of the British Industrial Revolution to Continental technology demonstrate the folly of the belief that in some sense Britain monopolized the inventive process.[12] The British advantage in application must be

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[10] The great 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).

[11] Nicholas Leblanc, who developed the soda making process named after him. Leblanc reacted salt and sulphuric acid to produce sodium sulphate, which after heating with lime or charcoal yielded raw soda together with hydrochloric acid, a noxious by-product. The Leblanc process became the basis of the modern chemical industry and is regarded as one of the most important inventions of the time. In the adoption of soda, Britain was relatively slow, and only in the 1820s did it start to adopt Leblanc's process on a large scale. The explanation usually given for this delay is the high tax on salt, which made artificial soda more expensive than vegetable alkali. Once the salt tax was repealed, British soda production grew rapidly and by the 1850s exceeded French output by a factor of three (Haber, 1958, pp. 10-14).

[12] The most important 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

chalked largely to its comparative advantage in microinventions and in the supply of the human capital that could carry out the new techniques.[13] Its system of informal technical training, through master-apprentice relationships, created workers of uncommon skill and mechanical ability. The most famous of these such as the clockmaker John Harrison, the engineer John Smeaton, the instrument maker Jesse Ramsden, the wondrously versatile inventor Richard Roberts, and of course the great Watt himself were only the first row of a veritable army of people who possessed a great deal of formal knowledge, but whose technical intuition and dexterity cleared reached deep into the dark deeps of tacit knowledge.[14] Third, by the middle of the eighteenth century Britain had developed an institutional strength that provided it with a temporary advantage over its Continental competitors: it had a healthier public finance system, weak guilds, no internal tariff barriers, fairly well-defined and enforced property rights on land (enhanced 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 change its institutions without political violence and disruptions. Following North (1990, p. 80) we might call this adaptive efficiency, but it refers not to the adaptation of the allocation of

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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.

[13] 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."

[14] Much of this British human capital was generated in a few key industries such as mining, shipbuilding, instrument- and clock making.

resources but of the institutions themselves. To bring this about, what was needed was a meta-institution such as parliament that was authorized to change the rules in a consensual manner. The Continental countries had to make a greater effort to cleanse their economic institutions from medieval debris, and while much of this work was done in France, Germany, and the Low Countries between 1789 and 1815, the work was incomplete and had involved enormous social costs. Yet none of those British advantages was especially 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 engine.

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 possibly more on wool and linen. But in view of the capabilities of French engineers and German chemists, and the removal of many institutions that had hampered their effective deployment before 1789, it would have happened. Even without Britain, by the twentieth century the gap between Europe and the rest of the world would have been there (Mokyr, 2000).

The second point to note is that the unique element of the Industrial Revolution really takes 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 the 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 of cheap wrought iron. It is easy to imagine the economies of the West settling into these techniques without taking them much further, as had happened in 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 novel ideas and tricks to be applied in new and more industries and sectors, improved and refined the earlier and eventually showed up in the productivity statistics. Among those we may list the perfection of mechanical weaving after 1820; the invention of Roberts's self-acting mule in spinning (1825); the extension and adaptation of the techniques first used in cotton to carded wool and linen; the continuing improvement in the iron industry through Neilson's hot blast (1829) and other inventions; 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 engineering and high-precision tools by Maudslay, Whitworth, Nasmyth, Rennie, the Brunels, the Stephensons, and the other great engineers of the "second generation"; the growing interest in electrical technology leading to electroplating and later to the telegraph; 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 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, and even though recent calculations attribute only a third of that growth to total factor productivity growth (Antras and Voth, 2003, p. ??), clearly the improvements in ocean and land transport after 1830 led to the kind of synergy between technological and institutional components of growth I described above. While income growth during the "classical" Industrial Revolution was still modest in Britain, from 1830 growth accelerates, and by the mid 1840's 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 I will discuss below.

To sum up, then, the period 1760-1830 Western Europe witnessed a growing importance of invention, the emergence of new techniques that in the longer run were to have an enormous impact on productivity and growth. Without belittling the other elements that made the Industrial Revolution possible, the technological breakthroughs of the period made the difference between the West and the Rest, between technological modernity and the much slower and often-reversed economic growth phenomena 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 technical knowledge.

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, 1998). 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 more mysterious 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. The problem, as economic historians have known for many years, is that it is very difficult to argue that the scientific revolution of the seventeenth century we associate with Galileo, Descartes, Newton, and many other giants, had a direct impact on the Industrial Revolution (McKendrick, 1973). Few important inventions, both before and after 1800, can be directly attributed to great scientific discoveries. The advances in physics, chemistry, biology, medicine, and other areas occurred too late to have the desired effect. The discoveries of the seventeenth century, crucial as they were, had more to do with the movement of heavenly bodies than with the motions of machines. This is of course an exaggeration: many of the great scientists wrote about mechanics and the properties of materials.[15] Yet it is hard to see many examples of eighteenth-century inventions that owed their existence to a prior scientific discovery.[16]

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[15] From the viewpoint of the history of technology, Galileo is particularly important because his theory of mechanics and concept of force lies at the basis of all machines. Until Galileo, the idea that general laws governed all machines was not recognized; each machine was described as if it were unique. Galileo realized that all machines transmitted and applied force as special cases of the lever and fulcrum principle. As Cardwell points out, Galileo's theory of mechanics is interesting to the economist because the concept governing it is one of efficiency: "The function of a machine is to deploy and use the powers that nature makes available in the best possible way for man's purposes... the criterion is the amount of work done --- however that is evaluated --- and not a subjective assessment of the effort put into accomplishing it" (Cardwell, 1972, pp. 38-39). In the writings of Galileo, the leading scientist of his time, economic efficiency is linked with science. In his *Motion and Mechanics* he wrote that the advantage of machines was to harness cheap sources of energy because "the fall of a river costs little or nothing." In this he differed radically from his inspiration, Archimedes, and this difference between the two scientific giants who established the science of mechanics epitomizes the difference between classical and early modern society. The great French physicist RenJ RJaumur (1683-1757) studied in great detail the properties of Chinese porcelain and the physics of iron and steel.

[16] Unlike the technologies that developed in Europe and the United States in the second half of the nineteenth century, science, in this view, had little direct guidance to offer to the Industrial Revolution (Hall, 1974, p. 151). Shapin notes that "it appears unlikely that the 'high theory' of the Scientific Revolution had any substantial direct effect on economically useful technology either in the seventeenth century or in the eighteenth.... historians have had great difficulty in establishing that any of these spheres of technologically or economically inspired science bore substantial fruits" (1996, pp. 140–41, emphasis added). Gillispie (1957) wonders about the practical effect of all the works of chemists and mathematicians of eighteenth-century France and points out that the majority of scientific endeavors of the time concerned subjects of limited technological use: astronomy, botany, crystallography and early exploration of magnetism, refraction of light, and combustion. Eventually many of those discoveries found economic applications, but these took place, with few

All the same, the success of the Industrial Revolution must be found in the intellectual developments that occurred in Europe before. What mattered was not so much science itself but the method and culture involving the generation of propositional knowledge. The Scientific method 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 (1997) have pointed to the scientific revolution of the seventeenth century as the period in which "open science" emerged, when knowledge about the natural world became increasingly nonproprietary and scientific advances and discoveries were freely shared with the public at large. Thus scientific knowledge became a public good, communicated freely rather than confined to a secretive exclusive few as had been the custom in medieval Europe. This sharing of knowledge within "open science" required systematic reporting of methods and materials using a common vocabulary and consensus standards. In terms of the ideas I developed before, this change 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.

Scientific method here also should be taken to include the changes in the rhetorical conventions that emerged in the seventeenth century, during which persuasive weight continued to shift away from "authority" toward empirics, but which also increasingly set the rules by which empirical knowledge was to be tested so that useful knowledge could be both accessible and trusted.[17] 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

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exceptions, after 1830.

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

interpretations and theories when they could be shown to be in conflict with the evidence. Scientific method meant that a class of experts evolved who often would decide which technique worked best.[18]

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, 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.[19] The founding members of the Royal Society justified their activities by their putative usefulness to the realm. There was a self-serving element to this, of course, much as with National Science Foundation grant proposals today. Practical objectives in the seventeenth century were rarely the primary objective of

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[18] As Hilaire-PJrez (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."

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

the growth of formal science. But part of the changing culture implied an almost imperceptibly slow change in the agenda of research.

The most important intellectual change in Europe before the Industrial Revolution was arguably the Enlightenment. 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*. Perhaps the most widely diffused view of the Enlightenment involves the notion that long-term social progress was possible. It surely is true that not all Enlightenment philosophers believed that progress was either desirable or inevitable. And yet their work created the attitudes, the institutions, and the mechanisms by which new knowledge was created, spread and put to good use. It is this specific aspect of the period that I have called the Industrial Enlightenment. To repeat: the movement was not the key to invention; it was the key to sustained and accelerating invention.

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. Invention, as many scholars have rightly stressed, was never a European monopoly, and much of its technological creativity started with adopting ideas and techniques the Europeans had observed from others (Mokyr, 1990). The difference was the ability to break out of the circle of concavity and negative feedback and smash the upper bound on income 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 query (2000, p. 48) why Chinese science and technology – which did not "stagnate" – "did not revolutionize the Chinese economy."

The Industrial Enlightenment was can be viewed on one side as a movement that insisted on asking not just "which techniques work" but also "why" – realizing that such questions held the key to continuing progress. In that sense, 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.[20] These insights would lead to extensions, refinements, and improvements, as well as speed up and streamline the process of invention.[21] Asking such questions was of course much easier than answering them. In the longer term, however, asking such questions and developing the tools to get to an answer were essential if technical progress was not to fizzle out.[22]

The other side of the Industrial Enlightenment had to do with the diffusion of and the access to existing knowledge. The *philosophes* fully realized that knowledge should not be confined to a select few but should be disseminated as widely as possible. Some Enlightenment thinkers believed this was already happening: 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."[23] Diffusion needed help, however, and much of the Industrial Enlightenment was dedicated to making access to useful knowledge easier and cheaper.[24] From the widely

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[20] Thus Erasmus Darwin, grandfather of the biologist and himself a charter member of the Lunar Society and a typical 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).

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

[22] 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).

[23] Cited by Porter (2000, p. 426).

[24] The best summary of this aspect of the Industrial Enlightenment was given by Diderot in his widely-quoted article on "Arts" in the *EncyclopJdie*: "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

felt need to rationalize and standardize weights and measure, 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.[25] The *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. But it did propose a very different way of looking at technological knowledge: instead of intuition came systematic knowledge, 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.

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.[26] Specialist compilations of technical and engineering data appeared, such as the detailed descriptions of windmills (*Groot Volkomen Moolenboek*) published in the Netherlands as early as 1734. A copy was purchased by Thomas Jefferson (Davids, 2001). Jacques-François Demachy's

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use of their authority and wealth."

[25] Roche (1998, pp. 574-75) notes that "if the *EncyclopJdie* 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." Pannabecker points out that the plates in the *EncyclopJdie* were designed by the highly skilled Louis-Jacques Goussier who eventually became a machine designer at the Conservatoire des arts et mJtiers in Paris (Pannabecker, 1996). They were meant to popularize the rational systematization of the mechanical arts to facilitate technological progress.

[26] 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).

l'Art du distillateur d'eaux fortes (1773) (published as a volume in the *Descriptions*) is a "recipe book full of detailed descriptions of the construction of furnaces and the conduct of distillation" (John Graham Smith, 2001, p. 6). In agriculture, meticulously compiled data collections looking at such topics as yields, crops, and cultivation methods were common.[27]

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. The relationship between those who possessed useful knowledge and those who might find a 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 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 perhaps seems natural to us in the twenty-first century. In 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. The pre-eminent figure in this field was probably William Cullen, a Scottish physician and chemist. Cullen lectured (in English) to his medical students, but many outsiders connected with the chemical industry audited his lectures. Cullen believed that as a philosophical chemist he had the knowledge needed to rationalize the processes of production (Donovan, 1975, p. 78). He argued that pharmacy, agriculture, and metallurgy were all "illuminated by the principles of philosophical chemistry" and added that "wherever any art [that is, technology] requires a matter endued with any peculiar physical properties, it is chemical philosophy which informs us of the natural bodies possessed

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

of these bodies" (cited by Brock, 1992, pp. 272–73).[28] He and his colleagues worked, among others, on the problem of purifying salt (needed for the Scottish fish-preservation industry) and that of bleaching with lime, a common if problematic technique in the days before chlorine. This kind of work "exemplifies all the virtues that eighteenth-century chemists believed would flow from the marriage of philosophy and practice" (Donovan, 1975, p. 84).

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 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 epistemic base simply did not exist. All the same, Cullen personifies a social movement that increasingly sought to increase its propositional knowledge for economic purposes, a personification of scientific culture. Whether or not he could deliver, his patrons and audience in the culture of the Scottish Enlightenment believed that there was a chance he could (Golinski, 1988) and put their money behind their beliefs.

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 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 "hybrid" or dual careers, as Eda Kranakis (1992) has termed them, is that access to the propositional knowledge that could underlie an invention is immediate, as

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

is the feedback to propositional knowledge. In all examples, the technology shapes the propositional research as much as the other way around. The idea that those contributing to propositional knowledge should specialize in research and leave its "mapping" into technology to others had not yet ripened. Among the inventions made by people whose main fame rests on their scientific accomplishments were the chlorine bleaching process invented by the chemist Claude Berthollet, and the mining safety lamp invented by the leading scientist of his age, Humphry Davy (who also, incidentally, wrote a textbook on agricultural chemistry and discovered that a tropical plant named *catechu* was a useful additive to tanning).[29]

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 Rumford stove, and an improved oil lamp. He developed a photometer designed to measure light intensity and wrote about science's ability to improve cooking and nutrition (G. I. Brown, 1999, pp. 95–110). 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, within the same mind, map from his knowledge of natural phenomena and regularities to create

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[29] 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.

things he deemed useful for mankind (Sparrow, 1964, p. 162).[30] 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.[31] Instead, he 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."

The other institutional mechanism that connected 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.[32] 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

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[30] 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.

[31] 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).

[32] The most famous of these societies were the Manchester Literary and Philosophical Society 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 activity took place.

prizes were granted between 1754 and 1784.[33] 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.[34] It served as a 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 established to infuse the economy with more innovativeness.[35] In France... (complete). In Germany ... (complete).

To summarize, then, the Industrial Revolution had intellectual roots just as much as it had economic and social conditions that needed to be met if sustained economic growth could take place. The importance of property rights, incentives, factor markets, market integration and many other economic elements is not in question. But we need to realize that without the growth of knowledge, the technological elements remain inside a black box.

The emergence of technological modernity.

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

[34] Hilaire-PJrez (2000), p. 197. Wood (1913), pp. 243-45.

[35] 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.

The essence of technological modernity is non-stationarity: 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. Various 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 distinguish a certain ebb and flow, in which major breakthroughs and a cluster of macroinventions were followed by waves of microinventions and further applications, it is clear that the modern era is one in which rapid and perhaps accelerating change has become the norm. 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 it converges to anything.

How do we explain this? During the early stages of the Industrial Revolution, as I have argued, propositional knowledge mapped into new techniques. This mapping should not be confused with the linear models of science and technology, popular in the mid-twentieth century, which depicted a neat flow from theory to applied science to engineering and from there to technology. Much of the propositional knowledge that led to invention in eighteenth century was pragmatic, informal, intuitive, and empirical. Only much later did it become the kind of formal and consensual prescriptive knowledge we think of today as "science." What matters is that prescriptive knowledge in its turn enhanced propositional knowledge, and thus provided positive feedback between the two types of knowledge, leading to continuous mutual reinforcement. This positive feedback mechanism 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 work." 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.[36] The next big step was made by an Englishman, James P. Joule, who showed the conversion rates from work to heat and back.[37] Joule's work and that of Carnot were then reconciled by a German, R. J. E. Clausius (the discoverer of entropy), and by 1850 a new branch of science dubbed "thermodynamics" by William Thomson (later Lord Kelvin) had emerged (Cardwell, 1971, 1994).[38] Power technology and classical energy physics subsequently developed hand-in-hand, 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 steam power, then, the positive feedback can be clearly traced: the first engines had emerged in the practical world of skilled blacksmiths, mechanics, 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. These insights were in turn fed back to engineers to construct more efficient engines. This kind of mutually reinforcing process can be

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[36] 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.

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

[38] 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.

identified, in a growing number of activities, throughout the nineteenth century.

A less well known example of this feedback mechanism, but equally important to economic welfare, is the interaction between the techniques of food-canning and the evolution of bacteriology. The canning of food was invented in 1795, right in the middle of the Industrial Revolution, by a French confectioner named Nicolas Appert. He discovered that when he placed food in champagne bottles, corked them loosely, immersed them in boiling water, and then hammered the corks tight, the food was preserved for extended periods. Neither Appert nor his English emulators who perfected the preservation of food in tin-plated canisters in 1810 knew why and how this technique worked, because the definitive demonstration of the notion that microorganisms were responsible for putrefaction of food was still in the future. It is therefore a typical example of a technique with 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 knew of Appert's work, and eventually admitted that his own work on the preservation of wine was only a new application of Appert's method. Be that as it may, his work on the impossibility of spontaneous generation clearly settled the question of why the technique worked 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.[39]

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,

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[39] 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).

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.[40] Lavoisier and his circle designed and used better laboratory equipment that allowed them to carry out more sophisticated experiments.[41] Alessandro Volta invented a pile of alternating silver and zinc disks that could generate an electric current in 1800. Volta's battery was soon produced in industrial quantities by William Cruickshank. Through the new tool of electrolysis, pioneered by Humphry Davy, chemists were able to isolate element after element and fill in much of the detail in the maps whose rough contours had been sketched by Lavoisier and Dalton. Volta's pile, as Davy put it, acted as an "alarm bell to experimenters in every part of Europe" (cited by Brock, 1992, p. 147).Or consider the development of the technique of in vitro culture of micro-organisms (the Petri dish was invented in 1887 by R. J. Petri, an assistant of Koch's). Price feels that such advances in knowledge are "adventitious"(1984a, p. 112). Indeed, the widespread use of glass in lenses and instruments in the West was itself something coincidental, a "giant accident," possibly a by-product of demand for wine and different construction technology (Macfarlane and Martin, 2002). It seems plausible that without access to this rather unique material, the development of propositional knowledge in the West would have taken a different course. 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,

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

[41] 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.

and they reinforce the contingent and accidental nature of much technological progress (Rosenberg, 1994, pp. 251–52).

The invention of the modern compound microscope by Joseph J. Lister (father of the famous surgeon) in 1830 serves as another good example. Lister was an amateur optician, whose revolutionary method of grinding lenses greatly improved image resolution by eliminating spherical aberrations.[42] His invention changed microscopy from an amusing diversion to a serious scientific endeavor and eventually allowed Pasteur, Koch, and their disciples to refute spontaneous generation and to establish the germ theory, a topic I return to below. The germ theory was one of the most revolutionary changes in useful knowledge in human history and mapped into a large number of new techniques in medicine, both preventive and clinical.

A third mechanism in why technology fed 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 as expected or they do not, and thus they can confirm or refute the propositional knowledge that serves as their epistemic base. Prescriptive knowledge has varying degrees of tightness, depending on the degree to which the available evidence squares with the rhetorical conventions for acceptance. Laboratory technology transforms conjecture and hypothesis into an accepted fact, ready to go into textbooks and to be utilized by engineers, physicians, or farmers. But a piece of propositional knowledge can be also be tested simply by verifying that the techniques based on it actually work. Wedgwood felt that his experiments in the pottery actually tested the theories of his friend Joseph Priestley, and professional chemists, including Lavoisier, asked him for advice. During the nineteenth century, the general confidence in the efficacy of science generated was reinforced by the undeniable fact that the techniques based on it worked. Thus, once biologists discovered that insects could be the vectors of pathogenic microparasites, insect-fighting techniques gained wide acceptance. The success of these techniques in eradicating yellow

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[42] 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.

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 astronomer and mathematician Simon Newcomb (the first American since Benjamin Franklin to be elected to the Institute of France) opined that flight carrying anything more than "an insect" would be impossible. He was joined in that verdict by the Navy's chief engineer, Admiral George Melville (Kelly, 1943, pp. 116–17; Crouch, 1989, p. 137). Nor were the inventors themselves all that certain: in a widely quoted remark, Wilbur Wright in a despondent mood remarked to his brother that "not within a thousand years would men ever fly" (Kelly, 1943, p. 72). 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 publish his magisterial work on how wings could be scientifically rather than empirically designed and the lift and drag precisely calculated (Constant, 1980, p. 105; Vincenti, 1990, pp. 120–25). Even after Prandtl, not all advances in airplane design were neatly 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. 170–99; Vincenti, 2000).

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.[43] 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's vision of the role of "useful knowledge" in economic growth.

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 obvious necessity for this to be true even if there is 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 peek into above. Yet all this is only part of the story: knowledge creates opportunities, but it does not guarantee action. 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.

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

Institutions and Technological progress

The positive feedback between growth in propositional and prescriptive knowledge was one element destabilizing a small part of a previously homeostatic world. Beyond that, again, 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 parasites and predators were always ready to use 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, thugs, and mercenaries, or they came from outside as alien pillagers and plunderers. 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*. Many episodes of growth before 1750 came in some way to an inglorious end by some greedy ruffian with a high discount rate, who did not mind slaughtering the geese that lay the golden eggs.[44] 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 even the Dutch United Provinces were weakened through the aggressive mercantilist policies of powerful neighbors. The riches of the

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[44] Jacques Coeur, perhaps the most successful entrepreneur of the fifteenth century, was exiled and his possessions confiscated by a greedy King in 1451. Jones (1981) has described the Ottoman Empire as a "plunder machine" and the "voluptuous selfishness and conspicuous waste" of both Mughal and native princes in India. In China, on the other hand, taxation before 1800 was relatively light and deliberately kept from interfering with the development of markets and internal trade. Officials were concerned with monopolists pushing up grain prices and thus possibly unleashing social instability. All the same, there was rent-seeking, not only in the state-run salt monopoly that made "a small number of merchants extremely wealthy" (Wong, 1997, p. 137) but above all in the large mandarinate which by the time of the notoriously corrupt imperial favorite Ho-shen (1750-99) became increasingly corrupt, and by the nineteenth century the trend toward systematic corruption became irreversible (Hucker, 1975, p. 323).

Southern Netherlands – unfortunately easier to invade – were repeatedly laid to waste by invading mercenary soldiers after 1570.

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 (1982, 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 Industrial Enlightenment meant that the old rent-seeking traditions of exclusionary privileges were increasingly viewed as both unfair and inefficient. Political reforms that weakened those privileges and permitted the emergence of freer and more competitive markets had an important effect on efficiency, but here it is especially important to stress that the Industrial Revolution was not followed by a surge in rent-seeking that negated the process. To the contrary, it was followed by a pax Britannica in which some kind of respect for international property rights was established, and within most of the Western countries a set of reforms were introduced that strengthened property rights.

What is central to the argument here is the feedback between technological and institutional change. The co-evolution of technological knowledge and institutions during the second Industrial Revolution has been noticed before.[45] Above all, three kind of institutions were important: those that provided for connections between the people concerned mostly with propositional knowledge and those on the production side; those that created *incentives* for people to actually spend resources in order to map propositional knowledge into new techniques; and those institutional

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

changes that weakened the effective social and political resistance against new techniques.

The institutions that created the bridges between prescriptive and propositional knowledge in nineteenth century Europe are well understood: universities, polytechnic schools, publicly funded research institutes, museums, agricultural research stations, research departments in large financial institutions. Improved access to useful knowledge took many forms: cheap and widely diffused publications disseminated it. Technical subjects penetrated school curricula in every country in the West (although Britain, the leader in the first Industrial Revolution, lost its momentum in the last decades of the Victorian era). All over the Western world, textbooks, professional journals, technical encyclopedias, and engineering manuals appeared in every field and made it easier to "look things up." The professionalization of expertise meant increasingly that anyone who needed some piece of useful knowledge could find someone who knew, or who knew who knew. The learned journal first appeared in the 1660s and by the late eighteenth century had become one of the main vehicles by which prescriptive knowledge became accessible, if perhaps through the intermediation of experts who could decode the jargon. Review articles that summarized and abstracted the learned papers began appearing, an obvious example of an access-cost reduction.

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

Elsewhere in Europe, the emergence of universities and technical colleges that combined research and teaching, thus simultaneously expanding propositional knowledge and reducing access costs, advanced rapidly. An especially good and persuasive example is provided by

Murmann (1998), who describes the co-evolution of technology and institutions in the chemical industry in imperial Germany, where the new technology of dyes, explosives, and fertilizers emerged in constant interaction with the growth of research and development facilities, institutes of higher education, and large industrial corporations with a knack for industrial research.[46] 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*, the German equivalent of the French *polytechniques,* had lower social prestige than the universities and were not allowed to award engineering diplomas and doctorates till 1899. The same is true for the practical, technically oriented *Realschulen* which had lower standing than the more classically inclined *Gymnasien*. Universities conducted a great deal of research, but it goes too far to state that what they did was a *deliberate* application of science to business problems.[47]

Designing institutions that create the correct ex ante motivations to encourage invention is not an easy task. Economists typically believe that agents respond to economic incentives. Some of the best recent work in the economic history of technological change focuses on the working of the patent system as a way of preserving property rights for inventors. In a series of ingenious papers, Kenneth Sokoloff and Zorina Khan have shown how the American patent system exhibited many of the characteristics of a market system: inventors responded to demand conditions, did all they

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[46] 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.

[47] 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, 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.

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 Sokoloff, 1993, 1998, 2001; Khan, 2002).

Whether this difference demonstrates that a well-functioning system of intellectual property rights is truly essential to the growth of useful knowledge remains an open question. For one thing, the American system was far more user-friendly than the British patent system prior to its reform in 1852. Yet despite the obvious superiority of the U.S. system and the consequent higher propensity of Americans to patent, there can be little doubt that the period between 1791 and 1850 coincides roughly with the apex of British superiority in invention. The period of growing American technological leadership, after 1900, witnessed a stagnation and then a decline in the American per capita patenting rate. Other means of appropriating the returns on R&D became relatively more attractive. In Britain, MacLeod (1988) has shown that the patent system provided only weak and erratic protection to inventors and that large areas of innovation were not patentable. Patenting was associated with commercialization and the rise of a profit-oriented spirit, but its exact relation to technological progress is still obscure.[48] 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, they reduced

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[48] 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-PJrez (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-PJrez shows, influenced one another.

access costs to the knowledge embodied in them. This function of the patent system apparently was fully realized in the 1770s. The full specification of patents was meant to inform the public. In Britain this was laid out in a decision by chief justice Lord Mansfield, who decreed in 1778 that the specifications should be sufficiently precise and detailed so as to fully explain it to a technically educated person. In the Netherlands, where patenting had existed from the 1780s, the practice of specification was abandoned in the mid-1630s but revived in the 1770s (Davids, 2000, p. 267).

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

Other institutions have been widely recognized as aiding in the generation of new techniques. Among those are relatively easy entry and exit from industries, the availability of venture capital in some form, the reduction of uncertainty by a large source of assured demand for a new product or technique (such as military procurement), the existence of agencies that coordinate and standardize the evolution of new techniques, and revolving doors between industry and organizations that specialize in the generation of propositional knowledge such as universities and research institutes. Behind these institutions and the inventions they stimulate, however, is the propositional knowledge on which they rest. Augmenting this knowledge opens the door that economic incentives and markets push societies through. If the doors are closed, however, any incentives for innovation will be useless. Commercial, entrepreneurial, and even sophisticated capitalist societies have existed that made few important technical advances, simply because the techniques they employed rested on narrow epistemic base and the propositional knowledge from which these bases were drawn was not expanding. Given that increasing this knowledge was costly and often socially disruptive, the political will by agents who controlled resources to actually do so, whether they were rich aristocratic patrons or middle-class taxpayers, was not invariably there. The amounts of resources expended on R&D, however, are not more important than how they are spent, on what, and what kind of access potential users have to this knowledge.

The third area in which technological innovation and institutional change interacted was in the resistance of vested interests to new technology (Mokyr, 1994, 2002). At one level, Enlightenment thinking viewed technological change as "progress" and implicitly felt that social resistance to it was socially undesirable. Yet there was a strand of thought, associated with Rousseau and with later elements in romanticism such as Cobbett and Carlyle that viewed industrialization as evil and destructive. All the same, rent-seeking lobbies that tried to block innovations were in the long run unsuccessful in the West, although this battle is not over quite yet. This battle came to a crashing crescendo during the Industrial Revolution when the old regulations in the wool industry were repealed in 1809, followed by the abolition of the 250- year old Statute of Artificers in 1814. 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 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. Had that not been the case, sustained progress would have been severely hampered and possibly brought to an end.[49] Technological progress was a necessary but

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[49] 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 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

insufficient condition for sustained growth; without concomitant institutional change, it seems likely to have petered out.

[INCOMPLETE, April 7, 2003].

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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.