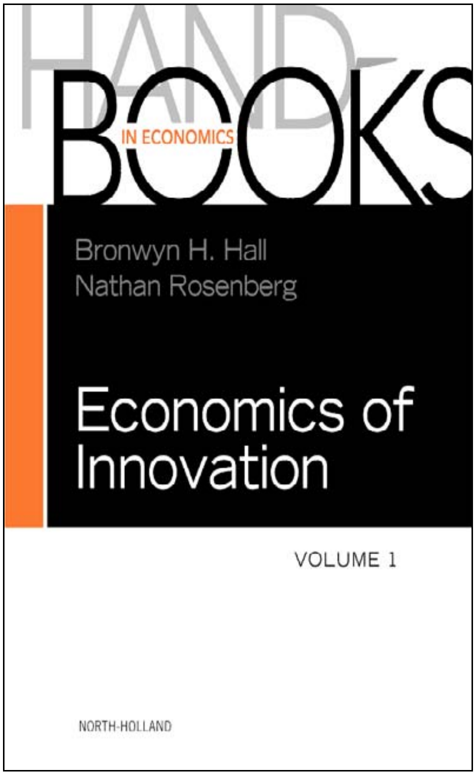

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Chapter 2

THE CONTRIBUTION OF ECONOMIC HISTORY TO THE STUDY OF INNOVATION AND TECHNICAL CHANGE: 1750–1914

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Abstract

This chapter surveys the history of modern economic growth and suggests a number of mechanisms that drove the unprecedented technological thrust that account for the discontinuities of economic modernity. The Industrial Revolution and the subsequent developments did not just raise the *level* of technological capabilities; they changed the entire dynamics of how innovation comes about and the speeds of both invention and diffusion. For much of human history, innovation had been primarily a byproduct of normal economic activity, punctuated by periodical flashing insight that produced a macroinvention, such as water mills or the printing press. The mechanisms that account for innovation becoming a routine activity in terms of the production of useful knowledge are reviewed and linked to the "Baconian program" advocated by the eighteenth-century Enlightenment.

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1. Introduction: Technology and economic modernity

There are widely different interpretations on the significance of "economic modernity." Most scholars coming from economics summarize the preindustrial experience by the somewhat casual observation that growth before 1800 was essentially nonexistent, and that modern economic growth in those economies which came to constitute the "convergence club" took off some time after 1830 (Aghion and Durlauf, eds., 2005; Lucas, 2002). Another tradition, older but with equally venerable lineage, views economic modernity as the expansion of goods and factor markets and the rising interdependence of households and firms (Polanyi, 1944; Toynbee, 1884). A third view focuses on industrial organization and places the factory at the center and considers the growing concentration of workers and their subjection to discipline and top-down coordination (Mantoux, 1928; Weber, 1923) as the essence of economic modernity. Yet none of those interpretations would be convincing without the *fundamental* change that underlay all others, namely the changes in technology that characterized the Industrial Revolution and led to modern economic growth. It were these changes that made the factory possible that allowed the creation of transportation networks and communications, the growth in life expectancy and access to information, the urbanization and changes in the quality and variety of goods and services that we associate with modernity.

How does technology advance? Modern endogenous growth theory has postulated that innovation is "produced" within the system, subject to economic incentives, and should be regarded as an output, resulting from inputs, where physical capital, human capital, R&D, and economies of scale all play major roles. The economic agents who brought this about were motivated mostly by selfish considerations of advancement, including the natural human drives of greed and ambition. The greatest technological sea change in history, which is being discussed here, supposedly constitutes a ringing affirmation of this view. Technology does not descend down on us like "manna," or better perhaps, is not given to us like the ten commandments. It was produced within the system by men and (rarely) women whose purpose was normally to achieve some kind of improvement to the process or product they were interested in. Yet the neo-neoclassical view of technological progress needs to cope with the historical parameters of technological progress, which govern a phenomenon unlike anything else in history.

In part this is for reasons quite well understood. Technology, like all forms of knowledge, is nonrivalrous (i.e., by sharing it with another person the original owner does not have less), so that the social marginal cost of sharing it is zero. Since the social marginal product is positive, the optimal static solution is one in which it is made accessible freely to all able and willing to use it. Yet under these conditions no one has much of an incentive to engage in the costly and risky R&D in the first place. The resulting dilemma has led to a debate that is now a quarter of millennium old on how best to establish optimal incentives in innovative activity. Patents and other forms of private property on useful knowledge played a role in the Industrial Revolution, but were not as essential to it as was once supposed. Instead, it has become increasingly clear that useful knowledge is often produced under conditions of "open source," that is, each person who adds to the pool of knowledge does not require or expect to receive some monetary compensation proportional to the social savings of the innovation. He or she insists, however, on receiving credit and recognition for the contribution as part of a signaling game in which the goal is to establish a reputation. Much innovation in the past functioned very similarly. The dichotomy according to which science operated according to open-source systems whereas technology was subject to private property constraints is seriously exaggerated.

Equally important in making innovation a unique topic in economic history is the fact that technology is produced under the kind of uncertainty that can be characterized as a combination of unintended consequences and unknown outcomes (Rosenberg, 1996). In large part this is the case because technology is normally developed when the exact *modus operandi* of the physical, biological, or chemical processes on which it is based are at best understood very partially. Many inventions have unforeseen and unforeseeable spillover effects on the environment, human health, or the social fabric. Moreover, many innovations are often combined with other techniques in ways not originally intended, to produce wholly novel hybrid techniques that do far more than the simple sum of the components. As a consequence, inventors are often surprised by the eventual outcomes of what seems successful innovation. Such surprises can be, of course, positive or negative.

The progress of technology has been explained by both internalist and externalist theories. Internalists see an autonomous logic, an evolutionary process in which one advance leads to another, in which contingency plays a major role, in which the past largely determines the future. Externalists think of technological change as determined by economic needs, by necessity stimulating invention, by induced innovation being guided by factor prices and resource endowments. In the same camp, but with a different emphasis are social constructionists who regard technology as the result of political processes and cultural transformations, in which certain ideas triumph in the marketplace because they serve certain special class or group interests and powerful lobbies. The history of technology since the Industrial Revolution provides support as well as problems for all of those approaches. A more inclusive approach would separate the process into interactive components. For instance, there is no question that economic needs serve as a "focusing device" in Rosenberg's (1976) famous simile, but the popular notion that "necessity is the mother of invention" manages to be simultaneously a platitude and a falsehood. Societies tend to be innovative and creative for reasons that have little to do with pressing economic need; our own society is a case in point. Modern Western society is by and large wealthy enough to not feel any pressing "need," yet it is innovative and creative beyond the wildest dreams of the innovators of the eighteenth century. There was no "necessity" involved in the invention of ipods or botox. The social agenda of technology is often set by market forces or national needs, but there is nothing ever to guarantee that this agenda will be successful and to make sure what it will lead to.

Technology moves at a certain speed and in certain directions, and the study of innovation helps us understand these laws of motion. Moreover, to come to grips with why technology changes the way it does, we need to be clearer about the way in which prescriptive knowledge (technology) and propositional knowledge (science and general knowledge about nature) affect one another. Knowledge about the physical environment creates an epistemic base for techniques in use. Technology, in turn, sets the agenda for scientists, creating a feedback mechanism. Why, for instance, do high-pressure engines work at higher thermal efficiency than low-pressure ones? Why does heating fresh food in tins and then vacuum-closing them prevent putrefaction? Why does injecting people with cowpox pus provide them with protection against the much nastier smallpox? These and similar issues came up during the period under discussion here, and their resolution led to further technological advances.

Technological change, like all evolutionary processes, was often wasteful, inefficient, and frequently wrong-headed. It was inevitably so, because by definition the outcome of the project was unknown, and so mistakes were made, duplicatory efforts took place, blind alleys were entered. Moreover, a great deal of what seems to us successful innovation was not adopted, often for reasons that *ex post* seem hard to fathom and at times frivolous. But the *degree* of inefficiency of the innovative process was not constant over time. As I have argued in Mokyr (2002), the amount of wastefulness in innovation can be substantially reduced if more is known about the underlying process. In that regard, the process has become hugely more efficient in the past quarter millennium. If innovation requires to "try every bottle on the shelf," an improved epistemic base of the technology can at least reduce the number of shelves. It can avoid looking for things known to be blind alleys like perpetual motion machines and processes that convert base metals into gold. It reduces the amount of intellectual energy spent on occult and other activities that the age of Enlightenment increasingly dismissed as "superstition." More and better knowledge of what is used elsewhere can also reduce duplicatory research and avoid reinventing some wheels.

This essay will not be an exercise in technological determinism. Technology does not "drive" History. Improvements in technological capabilities will only improve economic performance if and when they are accompanied by complementary changes in institutions, governance, and ideology. It is never enough to have clever ideas to liberate an economy from an equilibrium of poverty. But it is equally true that unless technology is changing, alternative sources of growth such as capital accumulation or improved allocations of resources (due, for instance, to improved institutions such as law and order and a more commerce-friendly environment) will ineluctably run into diminishing returns. Only a sustained increase in useful knowledge will in the end allow the economy to grow, and to keep growing without limit as far as the eye can see. I have explored the relation between useful knowledge and technology in Mokyr (2002).

The basic proposition of this essay will be that the technological component of economic modernity was created in the century before the Industrial Revolution, not through the growth of foreign trade, the emergence of an urban bourgeoisie, or the growing use of coal (as has often been argued) but by a set of intellectual and ideological changes that profoundly altered the way Europeans interacted with their physical environment. By that I mean both how they related to and studied the physical world in which they lived and the ways they manipulated that knowledge to improve the production of goods and services.

The net result has been that the technological constraints to which premodern societies were subject simply because they did not know enough were slowly lifted. Modern economic growth has been driven by increasing useful knowledge, which is not, as far as is known, subject to decreasing returns. What makes this possible, as was already realized in the eighteenth century, was the growing "division of knowledge" or specialization, in which each person controlled an ever-declining slice of a rapidly increasing total amount of knowledge. Smith (1757, p. 570) argued outright that "speculation in the progress of society. . .like every trade, is subdivided into many different branches. . . and the quantity of science is considerably increased by it." Because total social knowledge equals the *union* of all individual pieces of knowledge, the knowledge available for technological advances was increasing, provided that those who could make best use of it were able to access it. Hence the centrality of what I have called *access costs* (Mokyr, 2005). What has assured the decline in access costs is that the technology of access itself has been improving through such discrete leaps as the invention of the printing press and the internet, as well as through many other advances, both institutional and technological in the creation of open science and the placement of useful knowledge in the public realm and its codification in languages that can be understood or translated easily.

2. Technology in a "Malthusian economy"

Pre-1800 society, both in Europe and in other parts of the world, was able to develop many extremely useful techniques without, usually, understanding why and how they worked. Ignorance did not prevent these societies from making steel without an understanding of metallurgy, brewing beer without understanding the importance of yeasts, to breed animals without genetics, to inoculate against smallpox without immunology, and to practice crop rotations and apply fertilizer without soil chemistry. Technology could change even when the underlying support in propositional knowledge (the epistemic base) was not widening. Traditional societies had developed a "culture of improvement" as Friedel (2007) has recently termed it, and were quite successful in making considerable improvements in communications, transportation, the use of materials and energy, and to enhance their control on the plants and animals that constituted the "organic economy" (Wrigley, 2004). There was more of a "mineral economy" before the Industrial Revolution than is sometimes believed. On the eve of the Industrial Revolution, both home-heating and many industrial processes in Western Europe depended heavily on coal and peat, and iron and other metals found many uses. The transition that took place in the eighteenth century was not primarily one from an organic to a mineral economy, but from a world in which useful knowledge was empirical, unsystematic, more often than not little more than a tacit set of "understandings" of how nature worked and how materials behaved and reacted to heat and motion, to a technological paradigm in which this kind of knowledge was collected and analyzed in a systematic and organized fashion and useful knowledge increasingly became the dynamic agent that changed the economy.

The informal techniques of the preindustrial age were in the end limited in their ability to affect productivity because major new insights from the outside had to be brought to bear on technology. It would be hard to see, for instance, how the bottleneck of bleaching in the late eighteenth-century textile industry would have been overcome, had it not been for the work of Karl Wilhelm Scheele who discovered chlorine in 1756 and that of Claude Berthollet who discovered its bleaching properties. Moreover, the main productivity-enhancing effects of technology take place when it is fitted and stretched to suit local needs and constraints, when it is tweaked to satisfy a somewhat different purpose and when it can be adapted to be hybridized with other techniques to constitute something entirely different. Yet it is exactly such fitting and stretching that is complementary with a more precise knowledge of the nature of the processes, no matter how partial.

The lack of basic understanding of natural processes was not the only reason why premodern Europe grew so slowly. It has been argued repeatedly that these societies were subject to Malthusian regimes, in which even if technological changes took place, they would be undone because mankind in Wells's (1923) words "spent the great gifts of science as rapidly as it got them in a mere insensate multiplication of the common life." Recent writings such as Galor and Weil (2000) and Clark (2007) have re-emphasized this feature of premodern society. Many problems remain with this interpretation (Mokyr and Voth, 2010), and it needs to be complemented by an alternative negative feedback mechanism, namely the fact that economic growth often was undone by the greed of poorer but more violent predatory neighbors and that of tax collectors, guild members, priests, monopolists, and other seekers of exclusionary rents.

The paradox of a Malthusian economy is that, in its most fundamentalist interpretation, any productivity growth fails to lead to long-term improvements in living standards, and that in the long run the "iron law" of wages rules. Yet it is clearly inconsistent with much of evidence on the preindustrial economies. There was growth before the Industrial Revolution, and even if it was relatively slow, over the centuries it was compounded. It simply will not do to argue, as implied by these arguments, that by any set of measurements the standard of living in Western Europe at the time of the Glorious Revolution was comparable to that during the Norman Conquest. Snooks (1994) and Britnell (1996) have both pointed to substantial growth over the long run before 1700. Smith (1776, pp. 365–366) was certain that by the time of *Wealth of Nations* "the annual produce of the land and labour of England" was higher than a century ago, and that it had been growing steadily since the Norman Conquest and even before. The rates of growth, to be sure were low, and progress uneven and at times reversible. Yet in the span of six centuries, even low rates will compound. To what extent was technology responsible for this? The consensus is that before the Industrial Revolution most gains in output and income can be attributed to the growth of commerce and markets. This "Smithian growth" might explain the dynamic characteristics of pre-1800 growth. After all, advances due to commercial expansion were more easily undone and reversed through pointless violence, predatory neighbors, and greedy rent-seekers than technological advances.

Technology, however, was not stagnant. Advances in farming, textiles, shipbuilding, communications, metallurgy, and energy usage were cumulative, and given that British population in 1700 was not more than 50% higher than at its medieval peak, it stands to reason that Smith's view held true. All the same, these advances were limited, as they were based on a combination of serendipity and patient experimentation, and not on anything that a modern economist would ever recognize as research and development.

In the Malthusian economy, most inventions were made by artisans. Artisans were usually organized in craft guilds. Guilds have had a bad reputation in the history of innovation and are often depicted as conservative organizations. In many cases they were, but it has been argued in recent years that guilds were not inevitably conservative but often permitted and even encouraged innovation and were instrumental in its diffusion (Epstein, 1998; Epstein and Prak, 2008). Whatever the role of the guilds in their training and organization, there seems to be little doubt that the presence of a large number of well-trained skilled craftsmen was one of the great advantages that Britain enjoyed in the eighteenth century. Their capabilities made it possible for the most creative minds of the time to actually have their ideas carried out and the devices they designed built according to specifications, not just once but over and over again. They were mechanics, highly skilled clock and instrument makers, metalworkers, woodworkers, toymakers, glasscutters, and similar specialists, who could accurately produce the parts using the correct dimensions and materials, who could read blueprints and compute velocities, understood tolerance, resistance, friction, lubrication, and the interdependence of mechanical parts. These were the applied chemists who could manipulate laboratory equipment and acids, the doctors whose advice sometimes saved lives even if nobody yet quite understood why, the expert farmers who experimented with new breeds of animals, fertilizers, drainage systems, and fodder crops. This level of knowledge is different from the kind of knowledge needed to make scientific discoveries or inventions, and I have used the term *competence* to denote it. Yet the question remains whether skilled artisans *alone* were capable of generating something like the Industrial Revolution. On that matter there should be serious doubt.

Hilaire-Pérez (2007) and Berg (2007) have argued that "an economy of imitation" based on skilled craftsmen led to a self-sustaining process of improvement. This is certainly not a self-evident statement.

Artisans normally reproduced existing technology and in that process incremental microinventive sequences could lead to some improvements, but eventually will fizzle out. Many societies we associate with technological stasis were full of highly skilled artisans, not least of all Southern and Eastern Asia. A purely artisanal-knowledge society will eventually settle down in a technological equilibrium, in contrast to a society where the world of artisans is constantly shocked with infusions of new knowledge from outsiders. To be sure, some of the more famous "great inventors" of the age—starting with Newcomen and his assistant John Calley and the clockmaker John Harrison—were artisans themselves. Yet artisans, unless they were as prodigiously gifted and as well educated as James Watt or the French gunmaker–inventor Edme Régnier, were good at making incremental improvements to existing processes, not in expanding the epistemic base of the techniques they used or applying state of the art knowledge to their craft. Artisans were also normally not well positioned to rely on the two processes of analogy and recombination, in which technology improves by adopting or imitating tricks and gimmicks from other, unrelated, activities. If all that were needed for the Industrial Revolution had been creative artisans, it could have occurred centuries earlier. Artisans, after all, had been around for centuries, and relying on their innovativeness without the infusion of more formalized and systematic useful knowledge for an explanation of the Industrial Revolution would make it difficult to understand why things moved so rapidly after 1750. In textiles, the technical problems were on the whole less complex than in the chemical industry or in power engineering, but even there, as Jacob (2007) shows, mechanical science found its way soon enough to the shopfloor with important consequences for productivity and efficiency. Moreover, France too had skilled artisans, yet for decades it seemed unable to build the steam engines and develop the iron-processing improvements that Britain did on its own. Not all artisans were friendly and conducive to technological progress, as Hilaire-Pérez points out. The armourers' resistance to Honoré Blanc and interchangeable parts in musket making helped derail a potentially promising advance. The Lyon weavers' resistance to the Jacquard loom failed, but only after the innovators were given military protection.

3. The first Industrial Revolution: A new approach

The absence of long-term growth in most societies is thus clearly overdetermined. The real miracle is not that these Malthusian societies grew so slowly, but that they were, in the end, replaced by a society in which rapid growth became the norm. At the core stood something I have called the Industrial Enlightenment (Mokyr, 2002). The Industrial Enlightenment was an attempt to carry out Bacon's dream that useful knowledge would become "a rich storehouse, for the Glory of the Creator and relief of Man's estate" (Bacon, 1996, p. 143). In the *New Organon* Bacon explained what became almost axiomatic to his followers in the eighteenth century: "If Man endeavor to establish and extend the power and dominion of the human race itself over the universe, his ambition…is without doubt a wholesome thing and . . .noble… Now the empire of man over things depends wholly on the arts and sciences. For we cannot command Nature except by obeying her" (aphorism 129, cited in Bacon, 1999, p. 147).

The influence of Bacon on subsequent generations was enormous. Clearly, he had expressed a sentiment that was already in the air at his time, but by expressing it with precision and impeccable logical reasoning, he became, with Adam Smith, Karl Marx, and John Maynard Keynes, one of those intellectuals whose thinking affected actual economic outcomes. The so-called invisible college that formed in England after his death (and which included such notables as Christopher Wren, Robert Boyle, and Robert Moray) was formalized into the Royal Society, whose declared purpose it was to increase useful knowledge, and to build bridges between formal science and the actual practical applications of the "useful arts." The great experimentalist Robert Boyle expanded the ideas of the Master, pointing out that Lord Verulam (Bacon) had made a distinction between "luciferous" (enlightening) and "fructiferous" (useful) experiments, but that in fact the one led to the other. "There is scarce any physical truth which is not, as it were, teeming with profitable inventions and may not by human skill and industry be made the fruitful mother of diverse things" (Boyle, 1744, vol. 3, p. 155). The Royal Society was explicitly patterned after Bacon's Solomon's House. The Royal Society started off with boundless enthusiasm for practical technical matters. "The business and design of the Royal Society is to improve the knowledge of natural things, and all useful Arts, Manufactures, Mechanic practices, Engines, and Inventions by Experiments" (Lyons, 1944, p. 41). Robert Hooke added in his preface to his *Micrographia* that [the Fellows of the Royal Society] "have one advantage peculiar to themselves, that very many of their number are men of converse and traffick, which is a good omen that their attempts will bring philosophy from words to action, seeing men of business have had so great a share in their first foundation."

The Royal Society eventually lost interest in practical knowledge, but the spirit of Bacon lived on in many other organizations that came to the fore in eighteenth-century Britain. Thus the Society of Arts, founded by William Shipley in 1754, viewed its purpose as follows "Whereas the Riches, Honour, Strength and Prosperity of a Nation depend in a great Measure on Knowledge and Improvement of useful Arts, Manufactures, Etc... several [persons], being fully sensible that due Encouragements and Rewards are greatly conducive to excite a Spirit of Emulation and Industry have resolved to form [the Society of Arts] for such Productions, Inventions or Improvements as shall tend to the employing of the Poor and the Increase of Trade." The second half of the eighteenth century witnessed a veritable explosion of formal societies and academies dedicated to combine natural philosophy with the "useful arts," by bringing together entrepreneurs and industrialists with scientists and philosophers. In 1799, two paradigmatic figures of the Industrial Enlightenment, Sir Joseph Banks and Benjamin Thompson (Count Rumford), founded the Royal Institution, devoted to research and charged with providing public lectures of scientific and technological issues. In the first decade of the nineteenth century, these lectures were dominated by the towering figure of Humphry Davy, in many ways a classic figure of the Industrial Enlightenment.

Did all this lead to the Industrial Revolution? The paradoxical point is that for most of the eighteenth century, the Baconian program had but meager results to report. Many (though not all) of the central inventions of the Industrial Revolution, above all in textiles, had little to do with advances in science or propositional knowledge more widely defined. While the debate between those who feel that modern science played a pivotal role in the Industrial Revolution and those who do not is still ongoing, it is more than the hackneyed discussion whether a glass is half-full or half-empty. The glass started from almost empty and slowly filled in the century and half after 1750. The argument is thus in large part about the *rate* at which this glass filled.

Moreover, the exact delineation of what part of Bacon's luciferous knowledge was supposed to stimulate and enhance the "useful arts" should be defined with some care. Galileo, Newton, Descartes, and Huygens represented a rigorous and analytical science, but in the eighteenth century much of natural philosophy consisted of the three Cs: counting, cataloguing, and classifying. By describing in detail natural phenomena they did not really understand (including technological practices), experimentalists and natural historians provided a huge information base. To be sure, scientists and science (not quite the same thing) had a few spectacular successes in developing new production techniques, above all the chlorine bleaching technique, Leblanc's soda-making process, the lightning rod, and the mining safety lamp. However, the majority of the path-breaking innovations we associate with the Industrial Revolution did not depend much on this knowledge. It did broaden the epistemic base of some techniques that had been in use for centuries, explaining—in part—why the things that were known to work actually did so, paving the road for even more significant advances to come.

The Malthusian and epistemic constraints were broken not only because propositional knowledge got better at informing technology, but also because there was feedback from improved technology into more knowledge that created the virtuous circles that broke the negative feedbacks of preindustrial society. This mechanism, stressed by Rosenberg (1976, 1982) and de Solla Price (1984), has not been fully recognized by economic historians and is worth stressing. Improved technology, broadly defined, made better science possible. While the discovery of the moons of Jupiter thanks to the early telescopes is common knowledge, the phenomenon is wide and broad. The great advances made by Lavoisier and his pupils in debunking phlogiston chemistry were made possible by the equipment manufactured by his colleague Laplace, who was as skilled an instrument maker as he was brilliant a mathematician. The invention of the first battery-like device that produced a steady flow of direct current at a constant voltage, Alessandro Volta's pile of 1800, made it possible to separate elements in the newly proposed chemistry filled in the details of the landscape whose rough contours had been outlined by Lavoisier and his students. Volta's invention made it possible to separate elements in the newly proposed chemistry filled in the details of the landscape whose rough contours had been outlined by Lavoisier and his students. As Humphry Davy, perhaps the most accomplished practitioner of the new electrochemistry put it, Volta's pile acted as an "alarm bell to experimenters in every part of Europe" (cited by Brock, 1992, p. 147).

Improved instruments and research tools thus played important roles in a range of "Enlightenment projects" that might be seen as technological improvements with poetic license. One such improvement was the use of geodesic instruments for surveying. Jesse Ramsden designed a famous theodolite that was employed in the Ordnance Survey of Britain, commenced in 1791. A comparable tool, the repeating circle, was designed by the French instrument-maker Jean-Charles Borda in 1775, and was used in the famed project in which the French tried to establish with precision the length of the meridian. Time, too, was measured with increasing accuracy, which was as necessary for precise laboratory experiments as it was for the solution to the stubborn problem of determining longitude at sea, one of the age of Enlightenment's proudest successes. Experimental engineering also made methodological advances. John Smeaton was one of the first to realize that improvements in technological systems can be tested only by varying components one at a time holding all others constant (Farey, 1827, p. 168). Smeaton's improvements to the water mill and steam engine increased efficiency substantially even if his inventions were not quite as spectacular as those of James Watt. Much experimental work was carried out in the more progressive early factories, often on the shopfloor.

The new technology created factories (Mokyr, 2001). Factories were many things, one of them the repositories of useful knowledge, the sites where techniques were executed through a growing process of specialization. But they were also places in which experimentation, in the best traditions of the Baconian Enlightenment, took place. Of course, only a minority of the great mills carried out such experimentation, but they were the ones that counted. Some of the more famous early mill owners were deeply involved in experimentation. James Watt and Josiah Wedgwood, led the pack, but other such as textile manufacturers Benjamin Gott, John Marshall, and George Lee followed a similar course. They were often in touch with the best scientific minds of their day, but there were limits on what could be learned. The best-practice propositional knowledge of the time was inadequate to guide the industrialists in their technical choices. When the exact natural processes underlying a technique are poorly understood, the best way to advance through systematic trial and error. James Watt wrote in 1794 that even in mechanics theory was inadequate and thus experiment was the only answer. "When one thing does not do, let us try another" (cited by Stewart, 2007, p. 172). Experiments, once the realm of gentlemen scientists, had by the late eighteenth century become a shopfloor activity. In such systems, progress tends to be piecemeal and cumulative rather than revolutionary, yet without such microinventions, the process of innovation would have ground to a halt. Macroinventions and microinventions are inherently complementary, but their capacity to stimulate one another was itself improving in an age that believed deeply in improvement and was learning how to bring it about.

Just as important, technological bottlenecks and issues set the agenda for scientists, just as Bacon and his followers had suggested, and many of them set their minds to solve real-world problems. Among them were the greatest minds of the scientific Enlightenment. Leonhard Euler was concerned with ship design, lenses, the buckling of beams, and (with his less famous son Johann) contributed a great deal to theoretical hydraulics. The great Lavoisier worked on assorted applied problems as a young man, including the chemistry of gypsum and the problems of street lighting. Gottfried Wilhelm Leibniz, William Cullen, Joseph Black, Benjamin Franklin, Gaspar Monge, Joseph Priestley, Humphry Davy, Claude Berthollet, Tobern Bergman, Count Rumford, and Johann Tobias Mayer were among the many first-rate scientific minds who unabashedly devoted some of their efforts to solve mundane problems of technology: how to design calculating machines, how to make better and cheaper steel, increase agricultural productivity and improve livestock, how to build better pumps and mills, how to determine longitude at sea, how to heat and light homes and cities safer and better, how to prevent smallpox, and similar questions.

Of the many examples one could elaborate upon here, the career of René Réaumur (1683–1757) is telling as the epitome of the Enlightenment ideals. Although one of the most recognized scientists of his day (he was a distinguished mathematician and president of the French Académie Royale), his reputation today has been eclipsed by others. Yet in his day he worked on a variety of problems concerning the nature of iron and steel (he was first to suggest the chemical properties of steel), on problems of porcelain and glazing; he showed the feasibility of glass fibers and suggested that paper could be made from wood; carried out a huge research program on entomology and farm pests, egg incubation, and worked on meteorology and temperature measurement (hence the now defunct temperature scale still named after him).

Part of the problem with understanding the Industrial Revolution is the literature's focus on textile industries, which is quite understandable given the central importance of the technological revolution in cotton. Yet as Temin (1997) has argued, the Industrial Revolution was spread over many industries and sectors and technological progress spread to many sectors even if these constituted at first a small part of the British economy. What was unique in the second half of the eighteenth century was not the advances in one industry or another, but the push for progress on a wide front. We tend to be biased in our thinking toward the cases in which success was attainable, such as cotton textiles, steam, iron, and engineering.

Yet there was a similar "push" for improvement in a range of other goods and services, where progress was slower or even barely existent at first simply because nature offered more resistance, that is, the problems were harder.

This resistance is especially notable in agriculture and medicine. The reason economic historians do not speak much about an agricultural revolution anymore is that many of the problems in increasing productivity in farming were beyond the scientific capabilities of the time. But this was not for lack of trying. What is striking about them is the increasingly tight connections agricultural innovators sought with natural philosophers. Arthur Young himself sought the help of the leading British scientist of the 1780s, Joseph Priestley, in preparing his experiments. Many leading scientists were deeply interested in farming. The eminent chemist Humphry Davy was commissioned to give a series of lectures on soil chemistry resulting in his *Elements of Agricultural Chemistry* (published in 1813), which became the standard text until replaced by Von Liebig's work in 1840. The creative Scottish chemist Archibald Cochrane, the ninth earl of Dundonald, published in 1795 a treatise entitled *Shewing the Intimate Connection that Subsists between Agriculture and Chemistry*. Most of these writings were empirical or instructional in nature. Davy had to admit that the field was "still in its infancy" (p. 4), although he realized that it was scarcely possible to do any investigations in agriculture without depending on chemistry. At the time he was writing, the work in organic chemistry carried out in Giessen and which eventually unleashed the agricultural revolution that the Baconian program had promised was another half-century in the future. The same was true mutatis mutandis for medicine. Physicians and public health officials in the eighteenth century launched a massive assault on the main diseases ravaging the population of the day, and while, much like in farming, they scored a few local victories, the main objectives—understanding the nature of infectious diseases—were beyond them.

The central conclusion to take home about the first Industrial Revolution is that its historical importance as the fountainhead of modern economic growth was not so much in the transformations in cotton and steam that occurred between 1760 and 1800, but in the ability of the Western economies to sustain technological progress and somehow managed to avoid the negative feedbacks and hard constraints that had prevented a similar breakthrough after the great macroinventions of the fifteenth century (iron casting, printing, and three-masted shipping, among others). While much of the action in the first 40 years of *Sturm und Drang* of the Industrial Revolution took place in Britain, this was clearly a multinational effort. French, German, North American, and Italian knowledge, as well as that emanating from the Low Countries and Scandinavia were all more or less freely shared in the "Republic of Letters," an international "invisible college" of men and (a few) women of science who shared their knowledge through correspondence and publications and (more rarely) personal contact and travel. This community had already emerged in the sixteenth century (Collins, 1998, pp. 523–569), and by the eighteenth century it had extended to mechanical and technical knowledge (Darnton, 2003; Daston, 1991).

Such a collaboration between scholars and engineers was necessary, because it took the ingenuity and intelligence of people beyond the British boundaries to create the growing knowledge base that was the big difference between the Industrial Revolution and earlier "efflorescences." Contemporaries were aware of that, and while Britain's scientists and mathematicians at times made contributions of substance (one thinks of the work of Priestley, Hale, Cavendish, Black, Faraday, and many others), it is also quite clear that they were quick and ready to adopt and adapt new ideas wherever they came from. John Farey, an eminent engineer, testified in 1829 before a Parliamentary committee 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" (Great Britain, 1829, p. 153). He provided a long list of such inventions, not entirely accurate, but also omitting some of the most important ones. The Industrial Revolution was a collaborative effort of most of the Western economies, and the British may have had a comparative advantage in competence and microinventions and thus exported skilled craftsmen and mechanics (laws on the books prohibiting such movements notwithstanding), but they imported many of the best ideas.

Precisely because they could draw on a much larger knowledge base than what was produced in Britain alone, British engineers and inventors were able to keep the wheels of innovation turning. This was especially true in chemistry, in which the British, by their own admission, fell behind their European counterparts, such as Lavoisier and his student Claude Berthollet, Berthollet's student J.-L. Gay-Lussac, and many others. What it also meant, however, that Britain's advantage as "the first Industrial Nation" was inherently ephemeral, and the much-discussed British decline in the second half was little more than an equilibrating process, in which the technological capabilities of the other Western nations roughly caught up with Britain, even if differences in national styles and nuances can be readily discerned.

4. The transition to modern growth, 1830–1880

The economies of the West, by 1830, had more or less committed to progress and economic development. The political economy here is fairly complex. On the one hand, the 1815 restoration had reinstated conservative regimes throughout Europe. Yet the impact of the Enlightenment could not be undone. The influence of liberal political economy, the Enlightenment's proudest offspring, soon became too powerful to ignore as the reactionary regimes learned the hard way in 1830 and again in 1848. Moreover, nations were aware of the impact of economic performance on military and political power, and as a consequence increasingly reformed their economy and supported the creation and dissemination of useful knowledge in its various forms.

The most spectacular development of this period in economic history was the growth in transport technology. The railroad was almost exclusively a British invention, and was led by British engineers. Following the development of the high-pressure engine in the first years of the nineteenth century, it at first relied little on formal scientific breakthroughs. The technological history of the railroad is typical of a "hybrid" technology. It combined a number of elements, the most important of which were the flat rail and the high-pressure steam engine. The use of wooden tracks to minimize the friction created by pulling heavy cargoes on wheeled vehicles can be tracked down to the early middle ages, and were quite widely used by British mines in the late eighteenth century. At Coalbrookdale, a cast iron cover was used to reinforce wooden rails in 1767. By the first decade of the nineteenth century, decades before the first successful locomotives, Britain was estimated to have 300 miles of (horse-drawn) railway track (Bagwell, 1974, p. 90). The first "general-purpose" railroad was the Surrey horse-drawn iron railway completed in 1805, built by William Jessop, one of Britain's prime engineers and John Smeaton's star pupil. While no financial success, it indicated what this form of transport could do.

The high-pressure steam engine was a logical extension of the machines of the eighteenth century but its progress was slow, in part because of the deliberate resistance of James Watt and in part because they were difficult to build and unlike low-pressure engines prone to explosions. Its lighter weight made it, however, ideal for transportation purposes. The possibilities of this engine were explored in the first years of the century by Richard Trevithick, and Arthur Woolf, but brought to perfection by a remarkable engineer, George Stephenson, a man of no formal training, barely literate, yet with unfailing technical intuition. The first use of steam power was the Stockton and Darlington railroad (mixed horse and steam power) in 1825. The conventional start of the railway age, however, is taken as the opening of the Liverpool–Manchester route in 1830, and the triumph of Stephenson's famed *Rocket* in the Rainhill competition.

The railroad was the ultimate achievement of British engineering competence. British technicians often laid the foundations of railroad construction and rolling stock design elsewhere. The first locomotives put in service in France were built by Murray and Jackson of Leeds and Bury of Liverpool and even the famed French engineer Marc Séguin purchased engines from Stephenson's shop in Newcastle "to be used as models by French builders" (Daumas and Gille, 1979, pp. 348, 366). It was mostly designed and built by people with little or no formal education, but who had mastered a profound if informal understanding of what did and did not work through a combination of natural talent and access to the right masters.

It is striking how strong the connection was between the railways and the mining sector. Many of the railroad pioneers came from a mining background. The first models were built by Richard Trevithick, whose education was in the Cornish mines, mostly provided by his own father and uncle (Burton, 2000, p. 28). George Stephenson had even less informal education, and both he and William Hedley, the designer of an intermediate proto-model of the locomotive known as "puffing Billy" was trained in the mining sector. Another railroad pioneer, Timothy Hackworth, similarly, was apprenticed to his father (a blacksmith) and he too worked at a colliery. Even when advances were made by non-Englishmen, such as Séguin's fire-tube boiler design, it was made not by a formally trained polytechnician but by a self-made engineer, ignorant of advanced mathematics. The technical problems in the railroad were often hard and perplexing, but they were still mostly of the kind that could be overcome with the traditional empiricist engineering skills that had stood British mining and manufacturing in such good service during the Industrial Revolution. It was, however, not a promising strategy for future technological advances.

The same was true for mechanical engineering. The period after 1815 in Britain was a period of major consolidation, and with it came a huge drive toward the rationalization of manufacturing. As in other industries, Britain was well served by the high skills and broad practical knowledge of its mechanical engineers, in an age in which dexterity and experience could still substitute for a formal training in mathematics and physics. Mechanical engineering, as MacLeod and Nuvolari (2007a) stress, was a core activity of the Industrial Revolution, generating a disproportional share of innovations. The operators of lathes and cutting machines learned to make power-driven machinery that could then be applied in other industries by workers with fewer skills than themselves. Much of this equipment was becoming standardized. The key was special-purpose tools; much like the division of labor, mass production required a specialization in the design of machine tools. Presses, drills, pumps, cranes, and many other forms of mechanical equipment were produced in large series. The idea of a high degree of accuracy, both in measurement and in manufacturing, which had become increasingly prominent in the eighteenth century, was finally becoming operationalized.

Manchester, close to the best customers of many of these machines, became a center of this industry competing with London's. Perhaps the paradigmatic examples of a British engineer in this tradition were Henry Maudslay (in London) and his one-time apprentice Joseph Whitworth (who moved back to Manchester), who helped modernize mechanical production by standardizing screw threads and thus laid a foundation of modern mass production through the modularity of parts. The influence of the machine-tool industry on the advance of manufactures, in the admittedly somewhat biased opinion of one of its leaders, had been comparable to that of the steam engine (Nasmyth, 1841, p. 397). They did so by replacing the human hand in holding the tools of cutting metal by "mechanical contrivances," thereby achieving an accuracy hitherto unimaginable, using far less-skilled labor.

Over the long haul, the emergence of these prosaic devices proved to be one of the most radical innovations of all time. Mass production, based on large batch manufacture of perfectly identical and hence interchangeable parts, has turned out to be one of the unsung heroes of technological history. Less sudden than cotton, less dramatic that steam, less spectacular than gaslighting, mass production was just as much a child of the first Industrial Revolution as cotton and steam and one of the chief causes of how a set of localized technological advances after 1760 turned into a cascade of economic progress. The famous Portsmouth block-making machines, devised by Henry Maudslay and Marc Brunel around 1801 (a project directed by Samuel Bentham, Jeremy's brother) to produce wooden gears and pulleys for the British Navy, were automatic. In their close coordination and fine division of labor they resembled a modern mass-production process, in which a strongly interdependent labor force of 10 workers produced a larger and far more homogeneous output than the traditional technique that had employed more than 10 times as many. As Musson (1975) and others have argued, the widespread belief that Britain fell behind in this area of technology and eventually ceded mass production to the United States, is simply inaccurate. By 1841, a Parliamentary committee could proudly report that the implements after 1820 were "some of the finest inventions of the age" and that by their means the machinery produced by these tools is better as well as cheaper "tools have introduced a revolution in machinery and tool-making" (Great Britain, 1841, p. vii).

The railroad and mechanical engineering notwithstanding, after 1830 the ever-widening epistemic basis of technology was becoming a central factor in technological progress. This process was far from balanced, much less linear and even. But in a number of industries, the importance of scientific understanding became too important to ignore. Inventors did not need to be schooled themselves; it was often sufficient for them to have access to others who were. In iron and steel for instance, the accumulation of useful knowledge played a role in the development of the work of James Neilson. Neilson's "hot blast" was perfected in 1829 and reduced the fuel consumption of blast furnaces by two-thirds. Neilson was not a trained scientist but a practicing and experienced engineer, and his invention was the result of trial and error far more than of logical inference. Yet he was inspired and informed by the courses in chemistry he took in Glasgow, where he learned of the work of the French chemist Gay-Lussac on the expansion of gases he utilized in his invention (Clow and Clow, 1952, p. 354). In steel, a famous paper by Berthollet, Monge, and Vandermonde "Mémoire sur le fer considéré dans ses différents états métalliques" published in France in 1786 explaining the scientific nature of steel may have been above the heads of British steelmakers. The immediate impact of the paper was not large. It was "incomprehensible except to those who already knew how to make steel" (Harris, 1998, p. 220).

But five years later, the British chemist and physician Thomas Beddoes published a paper that relied on it and by 1820 the paper was well known enough to make it into an article in the *Repertory of Arts, Manufactures and Agriculture* (Boussingault, 1821, p. 369), who noted that idea had been adopted by all chemists who have turned their attention to the subject. Further work by scientists, such as Michael Faraday's on the crystalline nature of wootz steel (high-quality steel made directly from ores), increased the understanding of the characteristics of ferrous materials. As Smith (1964, p. 174) noted, "with carbon understood, Bessemer found control of his process easy, though its invention was not a deduction from theory, as the Martins' probably was."

Similar developments can be discerned in some less well-known sectors. In the cement industry, an article in *Rees's Encyclopedia* in 1819 described in detail the chemical processes involved in the hardening of cement, a description deemed "remarkably acute" by a modern expert (Halstead, 1961–1962, p. 43). To be sure, the full explanation of cement's hydraulicity was not put forward until the 1850s, but this was an area on which the new chemistry had a lot to say. The same was true in a different area of chemistry: fatty acids, the raw materials used in candles and soap. Michel Eugène Chevreul, the director of dyeing at the *Manufacture des Gobelins*, who discovered their nature, turned the manufacture of soap and candles from an art into a science. His discovery of stearine served as the basis of improved candles that burned longer and more brightly, with little smoke or smell. The real cost of candle light is estimated to have declined from £15,000 per million lumens-hour in 1760 to below £4000 in constant prices in the 1820s (Fouquet and Pearson, 2006, p. 153). Interestingly enough, Chevreul did not succeed in manufacturing artificial dyes, despite his obvious interest in them.

We should not exaggerate the immediate impact of the Lavoisier revolution in chemistry on industrial practices. Certainly, the full impact of scientific chemistry such as it was on industry did not begin to be felt until 1820 (Daumas, 1979, p. 564), and some modern historians have expressed skepticism whether Lavoisier and his pupils really established a "modern chemistry." Much of the new science remained quite untight—experts still disagreed about basic topics such as the atomic structure of matter and the nature of heat. Some scholars feel that "early nineteenth-century chemists did not regard their practice as having been reformed decisively. They were still in the process of reforming it" (Bowler and Morus, 2005, p. 76). This, of course, is an extreme view; no matter what the underlying philosophy, the establishment of chemical elements and the relations between them, the notation proposed by Berzelius, and the discoveries made by Dalton, Berthollet, Davy, Gay-Lussac, and others did establish new concepts, a new language, and a new set of laboratory tools. The growth of the epistemic base of existing technology made a steady expansion of useful knowledge possible.

In the 1830s, furthermore, the many decades of research in electricity started to see their first payoff: the research of scientists such as Oersted and Joseph Henry led to the development of the electrical telegraph, a breakthrough of truly momentous economic and social consequences later in the nineteenth century. It was a truly international effort. Oersted was Danish and Henry an American, but the research involved Germans and Frenchmen too. All the same, it was two Englishmen, Charles Wheatstone and William Cooke who turned an experiment into an enterprise. It took another decade to convince business interests and bureaucrats that this was indeed a useful technique, but in 1846 Cooke founded the Electric Telegraph Company, and installed 4000 miles of cable in its first 6 years. The first successful submarine cable was laid by Thomas Crampton's Company between Dover and Calais in 1851, and became a technological triumph that lasted 37 years. By 1857, most British cities were linked, and an operating line to the Continent had been established. In telegraph, as elsewhere, the give-and-take between scientists and inventors in the nineteenth century was complex. Before the telegraph could become truly functional, the physics of transmission of electric impulses had to be understood. Physicists, and above all William Thomson (later Lord Kelvin), made fundamental contributions to the technology. Thomson invented a special galvanometer, and a technique of sending short reverse pulses immediately following the main pulse, to sharpen the signal (Headrick, 1989, pp. 215–218).

In steam technology, the books of John Farey and François-Marie Pambour in the 1820s and 1830s summarized the best-practice knowledge of their time, but they were still clearly thinking of steam engines as propelled by the steam rather than heat engines. Oddly enough, it fell to an engineer to suggest for the first time the true nature of the steam engine, namely Sadi Carnot's 1825 *Reflexions*. It took a few decades for the insights to sink in. As one scholar has sighed, "The application of Carnot's explicitly stated results could have been of assistance in some of the problems with which the engineers were wrestling such as the merits of fluids other than water as the working medium or a quantitative estimate of the benefits derived from using high pressure engines. Certainly, the use of Carnot's theory would have, at the very least, prevented many engineers from spending time on hopeless projects" (Kerker, 1960, p. 258).

The transnational and semi-cooperative nature of Western useful knowledge, revived after 1815, was a direct continuation of the Enlightenment *Republica Litteraria*. The development of thermodynamics is another good example of this feature. The 1825 breakthrough paper by Carnot was published by his compatriot Emile Clapeyron in France, but remained unknown in France. It was translated into English in 1837 and into German in 1843, and thus in a position to influence James Joule and William Thomson in Britain and Hermann von Helmholtz and Rudolf Clausius in Germany (Cardwell, 1971, 1972). A young Scottish engineer named William Rankine, more than anyone else, made the new science of thermodynamics part of practical engineering. Rankine insisted that engineering knowledge must have its roots in scientific principles. His style was to state a general problem, solve it if he could, and only then to treat the special cases encountered in practice. Yet his work remained deeply empirical at heart. Much as had been the case for much of the Baconian program, where no general principles were yet accessible, he was much like a "natural historian of an artefactual world," provisionally collecting the empirical regularities and data of engineering with the ultimate intention of subsuming them under scientific law in the best of Baconian traditions (Marsden, 2004).

It is hard to know, exactly, how much the subsequent development of engines owed precisely to Carnot or Rankine specifically, but clearly thermodynamics formed the basis for the continued improvement of engines in the ensuing decades. The Glaswegian engineer John Elder, who receives most of the credit for building the compound marine steam engines that made the final victory of steam over sail possible, worked closely with Rankine and his quadruple compound engine made long sea voyages on steam-driven ships an economic reality (Day and McNeil, 1996, p. 237). As Smith (1990, p. 329) has noted, in Britain the great engineering firms of Manchester and Glasgow required more than just trial-and-error methods to resolve issues of economy and engine efficiency. Rankine's *Manual of the Steam Engine* published in 1859 made thermodynamics accessible to engineers, and the new steam engines made explicit use of the Carnot principle that the efficiency of a steam engine depends on the temperature range over which the engine operates. Rankine has been judged to have developed "a new relationship between science and technology" (Channell, 1982, p. 42).

This is not to say that good, old-fashioned intuition and practical skills were right away relegated to a secondary role. Thus, the famed American Corliss engine was built by a man with little formal education

(1848) and before the revolution of thermodynamics was widely disseminated. It was based on the idea of a shuttle-type valve which gave the engine an automatic variable cutoff capability, which brought a huge improvement in the efficiency with which the engine exploited the expansive power of steam and saved a third of the fuel costs, as well as delivered a much more smooth and responsive delivery of power. It was of central importance in cotton spinning where achievement of higher and constant speeds was central to productivity improvement (Rosenberg and Trajtenberg, 2004, p. 74).

Perhaps, the best way to summarize the kind of useful knowledge that served Britain best in the first half of the nineteenth century was the concept of "mechanical science," almost an oxymoron in our own time (Jacob, 2007; Marsden and Smith, 2005, p. 145). Within the hierarchy of useful knowledge, it was low in the pecking order. The British Association for the Advancement of Science, established in 1831 relegated it to its Section G, founded a few years later, as a bridge between the theoretical sections such as Section A (mathematics and physics) and practical engineers. It was an applied area, and throughout the period attracted some of Britain's most illustrious engineers such as William Fairbairn and the naval architect and engineer John Scott Russell. It provided respectability to the area that, as it seems to us now, Britain was best at, namely to use empirical methods and competence to apply ideas from science to practical engineering issues. Yet the BAAS was not a narrow, national organization, and it made serious efforts to bring foreign scientists to its meetings (Morrell and Thackray, 1981, pp. 372–386). It, too, was a product of the institutions of the eighteenth-century Enlightenment.

5. The second Industrial Revolution

By 1860, the Western world had experienced a revolution in textiles, materials, transportation, and energy. Yet daily life had been affected but little for most of the populations, except that travel had become faster and cheaper, people were wearing cotton clothes, and a number of large industrial towns had sprung up, such as Manchester and Glasgow in Britain, St. Etienne and Mulhouse in France, Ghent and Liège in Belgium, Essen in the Ruhr, and a few budding centers elsewhere. It is quite possible to imagine a counterfactual world in which innovation would have fizzled out at that stage, a world of steam and large cotton mills, of wrought iron and hybrid ships (sailing ships with auxiliary steam engines), of homes illuminated by gas and communications confined to telegraph lines, and in which growth would have slowed down and settled on a set of dominant designs vintage 1860. Such a world would have been different in some visible ways from the world of 1800, but not nearly as spectacularly different as the world of 1860 turned out to differ from that of 1914. The wave of innovations that occurred roughly between those two dates was more radical and spectacular in its technical and conceptual advances than perhaps any era in human history. The period 1859–1873 has been characterized as one of the most fruitful and dense in innovations in history (Mowery and Rosenberg, 1989, pp. 22–23). Vaclav Smil has gone further and characterized this period as a whole as the most revolutionary and innovative in history. It is hard to precisely quantify and test such statements, of course, but almost every new technique developed during the first half of the twentieth century, and many beyond, originated during the period commonly identified as the second Industrial Revolution.

The impact of cheap steel has been hard to overestimate, simply because no other material remotely competitive with it could be made at that time. Steel had been known since the middle ages and before, but its high cost prohibited its use in all but the most demanding uses. Benjamin Huntsman, a Sheffield clockmaker, perfected in 1740 the so-called crucible process, which made it possible to make high-quality steel in reasonable quantities. Huntsman used coke and reverberatory ovens to generate sufficiently high temperatures to enable him to heat blister steel (an uneven material obtained by heating bar iron with layers of charcoal for long periods) to its melting point. In this way, he produced a crucible (or cast) steel that was soon in high demand. Huntsman's process was superior not only in that it produced a more homogeneous product (important in a product such as steel, which consisted of about 2% carbon mixed in with the iron) but also removed impurities better because it created higher temperatures. His product remained too expensive for many industrial uses, however, and attempts to make steel not only good but also cheap, had to wait until the second half of the nineteenth century. Nevertheless, Huntsman's process, one of the early path-breaking inventions of the eighteenth century, is worth mentioning as an important advance. Steel was essential in the production of machine parts, cutting tools, instruments, springs, and anything else that needed a material that was resilient and durable. Crucible steel may have been one critical catalyst to innovation that economic historians have tended to overlook. The quality of crucible steel was such that it was produced in considerable quantities in Sheffield long after the nineteenth-century methods of producing cheap bulk steel had been introduced. Huntsman worked in a world of tacit knowledge, of an instinctive feel for what worked based on experience and intuition, data-driven rather than based on a scientific analysis. As noted, by the 1820s and 1830s, the chemical nature of steel as an alloy of pure iron small quantities of carbon was known, and it is hard to envisage the subsequent advances in steelmaking without it. The two breakthroughs, Bessemer's converter (1856) and the Siemens–Martin process (1865), happened fairly close to one another. Neither of them was built from scratch on purely theoretical reasoning (Bessemer admitted to being surprised by his success), but neither of them would have developed further without the support of an epistemic base that made it possible. At first, Bessemer steel was of very poor quality, but then a trained British metallurgist, Robert Mushet, discovered that the addition of *spiegeleisen*, an alloy of carbon, manganese, and iron, into the molten iron as a recarburizer solved the problem. Scientists such as Henry Clifton Sorby turned new tools (microscopes) on the question of the nature of steel and should be regarded as the founder of what we call today metallography.

Chemistry also helped straighten out problems in both techniques, including the removal of phosphorus from ores, which spoiled the quality of steel. The leader of Britain's Cleveland steel district was Isaac Lowthian Bell, himself a distinguished scientist, who pleaded incessantly for a greater emphasis on science in British steel industry. "The way in which he combined business and science was unusual in Victorian Britain: nevertheless, his abilities as chemist, mineralogist, and metallurgist challenge the view that the economy at that time was run only by empiricists" (Tweedale, 2004). Britain's concern with losing its technological leadership here was to a great deal misplaced. German iron and steel remained dependent on British innovations, and the first Kaiser Wilhelm Institute for Iron and Steel Research was established only in 1917 (Weber, 2003, p. 340). Apart from the Siemens–Martin process, most of the major breakthroughs such as stainless steel came from Britain.

The Bessemer and Siemens–Martin processes produced bulk steel at rapidly falling prices, and were able to use all ores after the Gilchrist-Thomas basic Bessemer process (1878). High-quality steel continued for a long time to be produced in Sheffield using the old crucible technique. However, the steel revolution was brought about by lower prices, not by a novel product. Cheap steel soon found many applications beyond its original spring-and-dagger demand; by 1880 buildings, ships, and railroad tracks were increasingly made out of steel. Steel allowed economies of scale in areas that had until then run into serious constraints: much larger ships and taller buildings. It revolutionized international trade, urban locational patterns, and warfare. It became the fundamental material from which machines, weapons, and implements were made, as well as the tools that made them. The conclusion that cheap steel "created" modern industrial society would be oversimplified and sound like technological determinism. But without it, the morphology of the modern economy would have been dramatically different.

Iron and steel were informed by science, but it remained primarily science of an empirical, descriptive sort. In chemistry, a wider epistemic base turned out to be essential, even if there, too, a full understanding of the principles involved coevolved with the exploitation of new techniques, many of them derived through trial and error. The development of organic chemistry in the late 1820s by two Germans, Friedrich Wöhler and Justus von Liebig, must count as a revolution equal to (and complementing) the insights of Lavoisier and his followers four decades earlier. The novelty was not one compound or another, but the fundamental realization that four elements (oxygen, carbon, nitrogen, and hydrogen) could combine together in almost infinitely many different ways, to produce millions of different compounds (Brock, 1992, p. 201), and that organic compounds could be created through man-made techniques and not just by some mysterious "vital force." Again, this was an international and collaborative effort taking place in the European Republic of Science. Liebig studied in Paris with Gay-Lussac, and Wöhler in Stockholm with Berzelius. The critical insight that soil fertility depended in great measure on nitrogen content was due to a French chemist, Jean-Baptiste Boussingault and two British experimentalists, John Bennet Lawes and Joseph Henry Gilbert. Organic chemistry opened the door for manufacturing in major areas which are often regarded as a core of the second Industrial Revolution: artificial dyes, fertilizers, explosives, and pharmaceutics.

And yet, even here, science went hand in hand with serendipity and patient trial-and-error experimentation. The famous tale of William Perkin, much like the young would-be king Saul, setting out to find one thing and discovering another has often been told. The 18-year-old Perkin searched for a chemical process to produce artificial quinine. While pursuing this work, he accidentally discovered in 1856 aniline purple, or as it became known, mauveine, which replaced the natural dye mauve. The discovery set in motion what was to become the modern chemical industry. Perkin, however, was trained by the German von Hofmann, who was teaching at the Royal College of Chemistry at the time, and his initial work was inspired and instigated by him. Three years later a French chemist, Emanuel Verguin, discovered aniline red, or magenta, as it came to be known. In 1869, after years of hard work, a group of German chemists synthesized alizarin, the red dye previously produced from madder roots, beating Perkin to the patent office by one day. The discovery of alizarin in Britain marked the end of a series of brilliant but unsystematic inventions, whereas in Germany it marked the beginning of a process in which the Germans established their hegemony in chemical discovery (Haber, 1958, p. 83). German chemists succeeded in developing indigotin (synthetic indigo, perfected in 1897) and a series of other dyes. Outside artificial dyes, the most noteworthy discoveries were soda-making, revolutionized by the Belgian Ernest Solvay in the 1860s and explosives, where dynamite, discovered by Alfred Nobel, was used in the construction of tunnels, roads, oil wells, and quarries. If ever there was a labor-saving invention, this was it.

The alleged German advantage in chemicals was based on the scientific lead they had enjoyed since the path-breaking work in Giessen and Göttingen in the 1820s and 1830s. At a range of German universities, chemists slowly unraveled the mysteries of organic compounds. The most famous breakthrough was that of August Kekulé at Bonn, who realized that organic chemistry was the study of carbon compounds and suggested the structure of the benzene compound. But most German chemistry consisted of normal science, cumulative advances by men such as Heinrich Caro (chief researcher at BASF) and Adolf von Baeyer (Professor of Chemistry at Strasbourg and Munich) that added up to a better understanding leading to a flow of innovations that created an industry. British and French contemporaries bewailed the rise of Germany as the chemical giant of the time, but the knowledge on which chemical technology was based was, like all Western science, an open-source endeavor. The techniques themselves, of course, were not, and patent protection was increasingly a factor in this industry, as R&D was costly and often slow. German patent protection was more effective than the British laws, in large part because the 1877 law was shaped by the manufacturers (Murmann and Landau, 1998, pp. 41–42). Germany became the dominant producer of artificial dyes, accounting for as much as 85–90% of the world market.

The German advantage in chemicals in the second Industrial Revolution was, in that respect, comparable to the British advantage in the early cotton industry. Although it made many of the advances itself, its chemists and its chemical knowledge were internationally mobile. If Germany had any advantage that was hard for other countries to replicate it was *competence*. Its polytechnic universities produced a steady stream of well-trained and able midlevel chemists, who were able to implement and execute the new processes, and in the process introduce the stream of microinventions and adaptations that accounted for most gains in productivity and the successful new products. Unlike the early cotton industry, however, the chemical industry required a "scientifically literate workforce" as Murmann (2003, p. 56) has put it, and the German higher education was far better in producing this resource. Such advantages, much like the early British advantage in the eighteenth-century techniques, were inherently ephemeral, and Germany's much-feared industrial superiority in chemicals dissipated after World War I.

Just before the War German chemists produced one of the most spectacular innovations of all times. To be sure, as Vaclav Smil has noted in his brilliant book on the topic (Smil, 2001), major discoveries rarely arise *de novo*, and what seems to us a breakthrough was only the last step in a long intellectual journey. Yet the ability to synthesize ammonia (NH_3) from the atmosphere at reasonable cost, the Haber–Bosch process in 1912, must be counted as one of the most momentous breakthroughs in history. The logic is one of social savings, popularized in the railroad literature of the 1960s. A counterfactual world without nitrates would have been a world in which World War I might have been considerably shorter, but also one in which a human race of 6 billions would have been doomed to a Malthusian disaster: Smil (2001, p. 160) estimates that only half of the current world population could have been fed without nitrogen fertilizers and that with diets that would have been considerably more vegetarian-based.

The story of the invention is clearly another combination of scientific understanding of the process, yet never sufficient to dispense of a large amount of experimental work, trial and error, and innumerable dead alleys and the frantic search in Alvin Mittasch's (Fritz Haber's assistant at BASF) lab for a catalyst that would work well ended up involving 20,000 runs of 4000 different substances, clearly an example of an old-fashioned "try-every-bottle-on-the-shelf" scientific method. Yet in chemistry, much like in other fields, science and formal training prepared the minds that Fortune favored.

This was equally true in electricity, the other spectacular advance of the age of the second Industrial Revolution. Electricity had fascinated many of the best minds of the eighteenth century, and the early nineteenth century, but despite growing understanding of how to generate and control electrical power through the work of, among others, Ampère and Faraday, economically significant applications beyond the telegraph were difficult to bring about for many decades. From the day Faraday and Hippolyte Pixii built the first dynamos (1831), a multiple of scientists and engineers were occupied in a research effort to tame this phenomenon, which promised so much.

Research in electricity shared the three characteristics of nineteenth-century technological change. First, it was multinational, carried out within a community of scholars that had little interest in national identity but only cared about pressing forward. Second, the epistemic base of the techniques that were being developed was emerging more or less hand in hand with the techniques themselves. Formal mathematics was used successfully next to experiments, and the two reinforced one another. It is a field in which multiple discovery was common, simply because access to the best-practice propositional knowledge was available to all participants. International exhibitions and a rapidly growing periodical literature in electrical engineering were central to the easy and cheap access to knowledge. It was also an area in which patenting was common, in part because the costs of experimentation were often high but above all because it was believed that the economic possibilities were indeed promising. The classic multipurpose technology, electricity, could transform production, transportation, and consumption, as many foresaw.

The innovation that made it all possible came in the late 1860s, when the principle of self-excitation could be applied to generate electricity on a large scale. Many could make a claim to being the discoverer of the dynamoelectric generator (as Werner Siemens called it), more than all perhaps the Englishmen Samuel Alfred Varley and Henry Wilde, but Zénobe Théophile Gramme, a Belgian working in Paris, built the first practical generator in 1870. From there, on a cascade of innovations took place, in which more famous names such as Tesla and Edison were able to build devices that could take advantage of the new form of energy. The impact of electricity on both firms and households was profound above all because it allowed energy to be consumed in infinitesimal quantities at constant cost.

Much like the railway and the telegraph before it, electric power involved network externalities, and the possibilities for coordination failures were many—until the present day different currents, frequencies, and even electrical outlets are still not standardized, as the annoyed traveler knows all too well. The mother of all standardization issues was the "battle of the systems" between AC and DC currents, fought in the 1880s, eventually won by Westinghouse and the AC people in 1890. An electric polyphase motor using alternating current was built by the Croatian-born American Nikola Tesla in 1889, and improved subsequently by Westinghouse. Of equal importance was the transformer originally invented by the Frenchman Lucien Gaulard and his British partner John D. Gibbs and later improved by the American William Stanley who worked for Westinghouse (Hughes, 1983, pp. 86–92; Smil, 2005, pp. 68–74). Tesla's polyphase motor and the Gaulard–Gibbs transformer solved the technical problems of alternating current and made it clearly preferable to direct current, which could not overcome the problem of uneconomical transmission. But electricity also required a great deal of systems building, it was "technology not of concentration but of distribution" (Friedel, 2007, p. 458). It required close cooperation between three kinds of experts: pure scientists and mathematicians, practical inventors without necessarily much theoretical knowledge but with a good "feel" for what worked, and entrepreneurs and organizers such as Emil Rathenau and Samuel Insull.

The impact of electricity on industrial productivity was relatively slow in coming, but there can be little doubt that its consumption transformed society. The story of lighting has been told many times (Bowers, 1998), but the impact of streetcars on daily life and the pattern of urbanization was just as dramatic. In the household, within about 15 year, electricity showed how technology could change cooking, heating, entertainment, cleaning, and the cooling of food and the environment in ways that had never been possible. Social savings logic can be applied to any of those advances, but the problem is that they came in a cluster and interacted with one another. Moreover, because it was a democratic form of energy, electricity allowed the survival of small-scale units who could draw the energy they needed from the networks. In an age in which most technological developments were scale-augmenting and pointed to large size, this development pulled in the other direction.

The development of the internal combustion engine shared some characteristics with steel and electricity, but not its social savings aspect. The world would have managed easily without internal combustion for many decades. External combustion, that is to say, steam engines, were being constantly improved, and much of what was done by gasoline-burning engines could have been carried out by ever more efficient and lighter steam cars. There is no reason why steam-driven tractors, while never quite successful, would not have been perfected to the point where they would have been adopted more generally (although one wonders if engines could have ever been built light enough to fly airplanes). But the internal combustion engine outperformed steam for a variety of uses, and in the long-run doomed steam power. It, too, was an international effort, the first internal combustion engine built by a Belgian, Jean-Etienne Lenoir, and the first theoretical paper pointing out the advantages of a four-stroke engine written by a Frenchman, Alphonse Beau de Rochas. Yet most of the critical components of what we would recognize today as "automobile technology" were developed by Germans, above all Nicolaus August Otto who developed the practical four-stroke engine. Otto was anything but a trained scientist. He was an inspired amateur, without formal technical training. Initially, he saw the four-stroke engine as a makeshift solution to the problem of achieving a high enough compression and only later was his four-stroke principle, which is still the heart of most automobile engines, acclaimed as a brilliant breakthrough (Bryant, 1967, pp. 650–657). Among the other pioneers were Wilhelm Maybach, a Daimler engineer, who invented the modern float-feed carburetor, and finally Gottfried Daimler and Karl Benz who put it all together. Other technical improvements added around 1900 included the radiator, the differential, the crank starter, the steering wheel, pneumatic tires, and pedal-brake control.

Interestingly enough, the French and the Americans adopted these techniques faster than the Germans ever did, and by 1914 they had far more automobiles per person than in Germany. While the four-stroke engine thus had a complex parenthood, its competitor was a one-man production. Rudolf Diesel was a trained engineer, a good specimen of the "new inventor," trained in science, a "rational" engineer, in search of efficiency above all else. Rather than tinkering and tweaking, Diesel started from first thermodynamic principles He began searching for an engine that incorporated the theoretical Carnot cycle, in which maximum efficiency is obtained by isothermal expansion so that no energy is wasted, and a cheap, crude fuel can be used to boot (originally Diesel used coal dust in his engines). Isothermal expansion turned out to be impossible in practice, and the central feature of Diesel engines today has remained compression-induced combustion, which Diesel had at first considered to be incidental (Bryant, 1969), which created a more efficient if more dirty and noisy engines. These Diesel engines powered German submarines during the First World War, and in the following decades gradually replaced steam engines on ships and locomotives and Otto-type engines on trucks, a classic example of the long-run coexistence of two competing techniques.

Changes in ship design were equally dramatic. As happened in power technology, the push to improve and augment efficiency led to a simultaneous advance of both the old and the new techniques. Despite major improvements in sailing ships in the years 1815–60 culminating in the famous clipper ships, wind power as a propulsive force at sea was eventually relegated to niches in sports and leisure boats. First, the materials of which ships were made changed. In the nineteenth-century shipbuilders like Isambard K. Brunel built ships out of iron. The ultimate technological (if not economic) achievement here was the vast *Great Eastern*, completed in 1859 by Brunel. The ship was six times larger than the largest ship built before and the largest ship built in the nineteenth century. Since the maximum speed of a ship increases with its water line, and iron and steel ships could be made much larger than wooden ships, ships grew bigger, more powerful, and faster at unprecedented rates.

To those advances two critical inventions should be added. One was the screw propellor, another example of multiple invention. The propellor's optimal design was a difficult problem, and it took many years until the most efficient propellors emerged after which the clumsy paddle wheels (which still helped move the *Great Eastern*) disappeared. The nature of technological change at this time is illustrated with a little anecdote: in 1837 a British engineer, Francis Pettit Smith launched a steam ship with a screw propellor made out of wood; in one of the trials half of it broke off. It was noted with amazement that this accident actually *increased* the speed of the vessel (Spratt, 1958, p. 147). The propellor had to move at very high speeds, which required complex and heavy gearing. The reinvention of the steam turbine was critical here (it had first been identified by Hero of Alexandria and mentioned repeatedly in earlier technological writings). It was first suggested in its modern form by the Swede Gustav de Laval (who had intended it to be used in butter and cream production) and Charles Parsons in 1884. Its subsequent improvement led to a revolution at sea: the rotary motion of the turbine could develop enormous speed (the prototype that Parsons built in 1884 ran at 18,000 rpm and had to be geared down), was far more efficient, faster, cleaner, and quieter, than the old reciprocating marine steam engines, and their adoption after 1900, when most of the bugs had been removed, was led by naval ships. Parsons, even more than Diesel, personified the second Industrial Revolution. The first turbine was built simply because "thermodynamics told him that it could be done" (Smil, 2005, p. 16). His steam turbine supplied power to both fast moving ships and electrical generators, both of which depended on high speed power. Like Diesel, Parsons was a trained scientist, with 5 years of mathematics under his belt (at Cambridge), then was trained as an apprentice at various engineering firms. His realization that to make a turbine work well the whole expansion of the steam must be subdivided into a number of stages, so that only comparatively moderate velocities have to be dealt with, still forms the basis of all efficient turbine design. At the famous grand Naval review in celebration of Queen Victoria's 60th anniversary in 1897, his ship the *Turbinia* developed speeds never seen before and ran circles around the naval vessels trying to catch up with it, to the delight of the bigwigs present. It was masterful engineering combined with brilliant public relations. Six years later, the new *Dreadnoughts* adopted direct-drive turbines, as did the gigantic passenger ships built before World War I.

While the typical ship of 1815 was not much different from the vessels of 1650, by 1910 both merchant ships and men-of-war (to say nothing of submarines) had little in common with their steam-operated hybrid predecessors half a century earlier. The result was a sharp decline in transportation costs. In the first half of the nineteenth-century freight rates fell by 0.88% a year, which reflected mostly improvements in sailing ships. The decline after 1850 accelerated to 1.5% a year, rates that are all the more impressive in view of persistently rising labor costs. Despite some organizational improvements, there can be little doubt that the decline in transatlantic freight rates was the result of technological improvements (Harley, 1988).

The drive toward improvement in the second Industrial Revolution affected consumers directly in many ways that had never been anticipated let alone experienced. One effect of the new technology was improved diets. Part of the reason was, of course, improved transportation, which allowed far cheaper agricultural imports from nations with a comparative advantage in food production to reach Europe. European farmers responded by specializing in high-end product lines. Dairy products, fresh meat, and fruits and vegetables became increasingly available. These products, too, were exposed to world competition. The efficient method of preserving beef in transit was by deep freezing it at about 14 °F. In 1876, the French engineer Charles Tellier built the first refrigerated ship, the *Frigorifique*, which sailed from Buenos Aires to France with a load of frozen beef. By the 1880s, beef, mutton, and lamb from South America and Australia were supplying European dinner tables.

Of special interest to the historian interested in economic welfare is the development of food preparation and preservation. Much human suffering has been caused over the ages by nutritional deficiencies and by the unwitting consumption of spoiled foods. Food canning had been invented as early as 1795, but because the process was not understood, the food was overprocessed and tasted poorly. Canned food was already consumed at the Battle of Waterloo, played an important role in provisioning the armies in the American Civil War, and led to more consumption of vegetables, fruit, and meat in the rapidly growing cities. Only when Louis Pasteur's path-breaking discoveries showed why canning worked and the epistemic base of food canning widened in the late nineteenth century, did it become clear that the optimal cooking temperature was about 240 °F and quality improved noticeably. Other food preservation techniques were also coming into use. Gail Borden invented condensed milk powder in the 1850s and helped win the Civil War for the Union and made a fortune in the process. By the end of the century his dehydration idea was also successfully applied to eggs and soups.

In terms of economic welfare, it is hard to argue that any technological development can match the impact of the dramatic improvements in health that took place during the second Industrial Revolution. The statistical evidence from demography seems to bear this out without any question. Between 1870 and 1914 infant mortality in the West declined by about 50%: in France, which was fairly typical, the rate fell from 201 per thousand in 1870 to 111 in 1914. In Germany the corresponding numbers were 298 and 164. Life expectancy at birth increased accordingly, in Britain it went from about 40 to 50 years. This decline, it has been argued, was in part simply due to rising incomes: as people enjoyed higher incomes, they could buy more and better food, live in less congested and better heated dwellings, own better clothes, and had access to running water, sewage, and medical care.

But there was more. The eighteenth century had made a huge effort to fight the many scourges that afflicted people, to the point that some scholars have called the age "a medical enlightenment" (Porter, 1982). Before 1850, the results were disappointing but not altogether absent. Over the entire period, medical progress followed a strange and unbalanced path. It was especially significant in preventive measures. The main advances of this period were the discovery that fresh fruits and vegetables could prevent scurvy, the use of cinchona bark (quinine) to fight off the symptoms of malaria, the prescription of foxglove (now known as digitalis) as a treatment for edemas (first recommended by Dr. William Withering, a member of the Lunar Society, in 1785), the consumption of cod liver to prevent rickets, and above all the miraculous vaccination against smallpox discovered by Edward Jenner in 1796. Jenner's discovery, in many ways, epitomizes the huge changes that had occurred in Europe in the preceding century, which made the application of new useful knowledge an effective tool in improving the material conditions of life. By that time, statistics and probability calculations were already becoming part and parcel of scientific discourse, and Jenner's discovery had to be verified by more systematic minds. Yet on the whole, medical progress was constrained by the narrow epistemic base of the medical profession, and especially the failure to understand the nature of infectious diseases, including their etiologies and modes of transmission.

Clinical treatment made but little progress, and most advances were through the abandonment of useless or harmful practices such as bleeding, purging, and obsessive ventilation. Medical practices before 1914 improved only in isolated areas, such as obstetrics, surgery, and better diagnostic tools like stethoscopes, and had only local effect. The main route to progress in this area before 1860 was through the careful collection of data on the occurrence of diseases and the search for empirical regularities, without much understanding of the mechanisms involved. The development of statistical methods to test for the efficacy of curative technology owed most to Pierre C.A. Louis who developed a "numerical method" for evaluating therapy and in about 1840 provided statistical proof that bloodletting was useless, leading to the gradual demise of this technique (Hudson, 1983, p. 206). A few years later, Ignaz Semmelweis observed on the basis of significant difference in the mortality rate that postnatal puerperal fever was caused by contaminated hands and could be reduced by delivery-room doctors and attendants washing their hands in antiseptic solution. In Britain, the use of statistics in the nineteenth century was heavily relied on by William Farr, superintendent of the statistical department of the Registrar General (Eyler, 1979). After 1850, the use of statistics in public health became almost a rage: between 1853 and 1862 a quarter of all papers read at the Statistical Society of London were on public health and vital statistics (Wohl, 1983, p. 145). The most famous triumph of the "empirical" approach to preventive medicine was the discovery of the water-borne sources of cholera in 1854 by John Snow and William Farr through the quantitative analysis of the addresses of the deceased. At about the same time, William Budd demonstrated the contagious nature of typhoid fever and its mode of transmission and successfully stamped out a typhoid epidemic in Bristol.

The epistemic base of medical care was rapidly augmented, thanks to the sudden growth in the understanding in the nature of infectious disease due to the work of Pasteur, Koch, and their associates. Within a few decades, the medical profession managed to work out a more or less complete theory of infectious disease in which many of the causative agents were identified and their modes of transmission established. The main impact that the new bacteriology had was again in preventive medicine, both public and private. The advances in public medicine in separating drinking water from sewage and preventing other epidemics have been well documented (Szreter, 1988).

Households, too, increasingly realized that by following certain simple "recipes" that involved minor redeployments of resources, they could reduce the incidence of infectious disease. Germs could not be seen, but they could be fought by simple household techniques, available at relatively low cost. Once water was established as a carrier of certain diseases, people began to realize the importance of filtering, boiling, and later chlorination. When insects were identified as a carrier of malaria and yellow fever, a war against insects erupted. Food-borne diseases could be reduced by proper cooking, cleaning, and preservation. All this had to be taught and the teaching took time. Many mistakes were made, wrong turns made, causal mechanisms misidentified, and false recommendations made. Yet when all is said and done, the effects of this technological revolution on human welfare are the most unequivocal: the sharp declines in mortality and morbidity rates in this period speak for themselves.

6. A suggested interpretation

The explosion of modern technology and the concomitant economic modernization has been the subject of a huge multidisciplinary literature, and will continue to fascinate scholars as one of the central issues in long-term analysis. Technological creativity seems to be a uniform and ubiquitous feature of the human species, and yet just once in history has it led to a sea change comparable to a phase transition in physics or the rise of *Homo sapiens sapiens* in evolutionary biology. The Industrial Revolution and the subsequent developments did not just raise the *level* of technological capabilities; they changed the entire dynamics of how innovation comes about and the speeds of both invention and diffusion. For much of human history, innovation had been primarily a byproduct of normal economic activity, punctuated by a periodical flashing insight that produced a macroinvention, such as water mills or the printing press. But sustained and continuous innovation resulting from systematic R&D carried out by professional experts was simply unheard of until the Industrial Revolution.

To create the new dynamic, a lot of things had to come together. This is precisely what happened in the West in the eighteenth century. The Baconian program of the eighteenth century that led into the Industrial Revolution came on top of the heritage of the Renaissance and the Scientific Revolutions of the seventeenth century. To thrive beyond occasional flashes, innovation needed a society with an urban sector and a middle class that produced a level of national income that was sufficiently above subsistence to sustain a class of people whom we would call "professionals"—merchants, engineers, scientists, artists, and professors. A nation that consisted primarily of peasants struggling to survive and soldiers and priests keeping them in check was not likely to create a flow of innovations, although even the European early middle ages, mistakenly dubbed a "dark age," was still capable of creating some remarkable innovations.

But generating a few bursts of technological advances was one thing, creating a world in which sustained progress becomes the rule rather than the exception was another. What happened is that in the slightly amorphous region known as the "West" the dynamic of innovation began to change in the eighteenth century. The notion that uncovering nature's secrets and understanding its regularities and laws were the key to economic progress ripened slowly in the minds of a growing number of influential scientists and *philosophes* in the eighteenth century. In the 1760s, without having as yet much of sense of what was in store, Joseph Priestley reflected in purely Baconian terms on the history of knowledge that it is here that "we see the human understanding to its greatest advantage…increasing its own powers by acquiring to itself the powers of nature…whereby the security and happiness of mankind are daily improved" (Priestley, 1769, p. iv).

Beyond the gradual expansion of useful knowledge surveyed above, what made the success of the West possible was a set of institutional developments. The new institutional economics has concentrated on constraints on the executive, to make sure that government enforced the rules but did not abuse them. Secure property rights, and limits on the predatory behavior of people in power are seen as the taproot of economic growth (North, 1990, 1995). The historical problem is, of course, that such favorable institutions explain first and foremost the kind of Smithian growth in which the expansion of commerce, credit, and more labor mobility were the main propulsive forces. But the exact connection between institutional change and the rate of innovation seems worth exploring, precisely because the Industrial Revolution marked the end of the old regime in which economic expansion was driven by commerce and the beginning of a new Schumpeterian world of innovation.

The growth of useful knowledge occurred in an institutional context that has been called "a market for ideas" (Mokyr, 2007). The market for ideas is not a real market in the literal sense, but it is a useful metaphor. In it, people with ideas and beliefs tried to sell them to others, acquiring influence and through it prestige. Just as commodity markets can be judged by their efficiency if they, for instance, observe the law of one price, we can define yardsticks for the efficiency of a market for ideas. Three criteria should be emphasized here: *consensus*, *contestability*, and *cumulativeness*.

Markets for ideas can be assessed as to whether there is a built-in tendency to converge to a consensus. Knowledge can be characterized as *tight* when it is held by a wide consensus and with high confidence, in which case it is more likely to lead to applications. Much of the knowledge in the areas crucial to modern economic growth in chemistry, biology, medicine, and physics, and which is held with a reasonably high degree of tightness in modern society, was the subject of heated debates in the seventeenth and eighteenth centuries, the resolution of which was sometimes difficult. Consensus was achieved when there was a widely accepted set of criteria by which hypotheses are accepted or rejected and when the selection environment was relatively stringent, so that there was no room for what is known as "occasionalism." In other words, laws of nature were viewed as firm and there was little interest in miracles or magic. In a sense tightness is self-referential, that is, there has to be consensus about how to achieve consensus. An efficient market for ideas has widely-accepted rhetorical tools by which it assesses experiments, observation, and logical analysis. In the eighteenth century, the assessment of experimental data, mathematical logic, and improved observation tools to bear on deciding what was right matured, even if the rhetorical tools were often social as well as epistemological (Shapin, 1994).

Contestability was political in nature, implying limits on intellectual authority, and is the flip side of consensus. It is the equivalent of the notion of "free entry" in markets. Free entry in preindustrial societies was often blocked by reactionary political forces. The notions of "heresy" and "black magic" were still raised against such eminent scientists such as Jan Van Helmond and Giambattista Della Porta as late as the seventeenth century. Physics and metaphysics were still too closely bound up to be free of coercion, by either religious or secular authorities. Between the execution of Jan Hus in 1415 and the expulsion of the Huguenots in 1685, a great deal of senseless violence and suppression thwarted the contestability of new ideas. By the eighteenth century, such coercion was increasingly abandoned, although the political tensions engendered by the French Revolution and the subsequent wars brought it back for a few decades.

Cumulativeness means an effective means of passing knowledge from generation to generation. Knowledge resides in people's minds and is thus subject to depreciation. Without some mechanism that preserved knowledge and made it available in the future, each generation would have to reinvent a few wheels, and worse, some important knowledge might have been lost. Cumulativeness thus depended on the efficacy of the institutions in charge of passing knowledge from generation to generation, and their technological support in knowledge-storage devices such as books and artifacts (Lipsey et al., 2005,

p. 260). Codifiable knowledge was accumulated through the publication of books and periodicals storing useful knowledge. Here, too, the eighteenth century represented a change in degree more than in essence, but degree is everything in these matters. The age of Enlightenment took a special delight in compiling books that summarized existing knowledge, added sophisticated and detailed drawings that elaborated the operation of technical devices, and placed these books in public libraries. The growth of scientific books and periodicals in the eighteenth century was impressive. An analysis of the topics of the books published in the eighteenth century presented shows that the proportion books published on "Science, Technology and Medicine" increased from 5.5% of the total in 1701–1710 to 9% in 1790–1799. As the absolute number of books published in the British Isles tripled over this period, this implies a quintupling of the total number of such books (Mokyr, 2009).

The growth of technical books, dictionaries, compendia, and encyclopedias were a typical eighteenth-century phenomenon. An example is Thomas Croker's three-volume *Complete Dictionary* published in 1764–1766, which explicitly promised to its readers that in it the "the whole circle of human learning is explained and the difficulties in the acquisition of every Art, whether liberal or mechanical, are removed in the most easy and familiar manner." These works were perhaps the prototype of a device meant to organize useful knowledge efficiently: weak on history and biography, strong on brewing, candle-making, and dyeing. They contained hundreds of engravings, cross-references, and an index. These books and journals circulated widely and the growth of libraries made access to them easier and easier.

Yet cumulativeness could become an encumbrance if it degenerated into orthodoxy, and therefore the third component of efficient knowledge markets, contestability, is critical. No social system of knowledge can work without some notion of authority, but in a well-functioning market for ideas there should be no sacred cows and no belief should be beyond challenge. Market theory teaches us that free entry creates on the whole a more salutary outcome than a monopolist. Hence, it was the combination of cumulativeness with contestability that created the unique environment for the rapid growth of useful knowledge.

The cumulativeness of tacit knowledge operated through different channels, and depended on both formal and informal intergenerational transmission mechanisms. Universities had existed in Europe since the middle ages, and not all of them were concerned with useful knowledge. In the eighteenth century, Oxford and Cambridge had little impact in this regard, but the Scottish Universities taught many useful topics and trained many of the key figures in the Industrial Revolution. But artisanal skills and that mixture of intuition and experience that may best be called a technological *savoir faire* were accumulated and passed on from generation to generation by means of personal relationships, usually father–son or master–apprentice.

To achieve consensus, contestability, and cumulativeness, the intellectual and technological communities that produced useful knowledge needed to be integrated and closely knit. Knowledge had to be distributed and shared, so that it could be compared to existing notions, tested, vetted, and accepted, rejected, or left as undecided. Once absorbed and accepted, it could form the basis of new techniques of production. Integration of that nature required, above all, a freedom from coercion and repression by interest groups with a stake in the intellectual status quo. Yet the main historical phenomenon that made the improvement of these features of useful knowledge possible was the sharp decline in *access costs* (Mokyr, 2005). Access costs are the cost incurred by anyone seeking knowledge from another person or storage device. Access costs consisted of physical costs, affected by such technological advances as the printing press, cheaper paper, postal services, cheaper personal transportation, and of institutional changes such as the development of schools and universities, and the establishment of academies and scientific societies. It was also strongly affected by the emergence of open science and the decline of secrecy in the generation of new useful knowledge (Eamon, 1994).

The decline in access costs had momentous consequences for the characteristics of useful knowledge. It increased the tightness of much knowledge because it became understood that any experiment could be replicated and any theorem's proof thoroughly checked simply because others could easily access any result of interest. Potentially productive ideas were first made accessible to other intellectuals, who could peer-review and criticize them. If found to be acceptable by the rhetorical conventions of the time, they could be extended, recombined with other ideas, and applied. For nonexperts, this setup, at least in theory, increased the reliability of useful knowledge. People in the fields and the workshops might be more likely to make use of ideas that could be trusted because experts had presumably vetted them. In reality, for many decades, this idea remained more wishful thinking than reality, but just the shared ideal resulted in more trust and cooperation than there would have been in its absence.

What emerged in Europe in the century before the Industrial Revolution was an open-source system of knowledge creation, based on priority credit, in which the participants essentially placed their knowledge in the public domain, to be accessed by others, those who could verify it and those who could use it. This system rewarded its most successful participants through a signaling or reputation game, in which the most successful participants were rewarded with patronage and cushy jobs, pensions, or tenured positions in universities (David, 2004). No wonder that the late seventeenth century witnessed the beginnings of some of the fiercest priority fights between scientists.

The institutional context of access also requires consideration. Useful knowledge was organized, as it had to be, in formal and informal organizations. Informal organizations such as the invisible college that preceded the Royal Society or the Lunar Society of Birmingham a century later are justly famous. As noted, formal educational institutions played but a modest role in the growth of useful knowledge, and most of the leading engineers and inventors of the Industrial Revolution were self-taught or were educated privately. Many of the leading figures in the eighteenth century were still enjoying patronage employment, often through the national academies: Euler in St. Petersburg, Reaumur in Paris, and Aepinus in Berlin. Local scientific societies, founded in provincial towns, emerged everywhere in Enlightenment Europe. They were small-scale marketplaces for ideas, where knowledge was exchanged, lectures given, libraries utilized, and many conversations took place. They were a prime example of Habermas's "public sphere" but one that had momentous consequences for the economies in the long run. Scotland occupied a disproportionately large place in the evolution of these institutions. The flourishing of Scottish applied science and engineering in the eighteenth century have prompted some scholars to think of the Scottish tail wagging the English dog (Herman, 2001).

Access costs were, in part, supply-determined by the technology of communication and mobility. As Eisenstein (1979) has stressed, the invention of the printing press played a major role in the intellectual development of Europe, as did the improvements in shipping, navigation, and overall increase in the level of commerce and flow of people and objects after 1492. Less well-known but equally important was the improvement in the continent-wide flow of mail, thanks to the organizational abilities of de Tasso family, led by Francisco de Tasso (later known as Franz von Taxis) and his brothers who established regular postal services in Italy, Germany, and the Habsburg lands in the early sixteenth century. Their postal system covered much of the Continent by the middle of the sixteenth century and created one of the most durable business dynasties in history. Postal rates remained quite high, in part because they were a convenient revenue-raising device for the State. The establishment of the famous London penny post in 1683 and its gradual extension in the eighteenth century meant that by 1764 most of England and Wales received mail daily (Headrick, 2000, p. 187). Postal rates depended, in part, on the cost of internal transportation, and as roads were improved, canals dug, and carriages made faster and reliable, the effectiveness of internal communications increased greatly in the age of Enlightenment.

Consensus and contestability demanded new rhetorical tools. The centuries before the Industrial Revolution could be characterized by a growing irreverence toward to classical authorities and great canons that rules intellectual life in the later middle ages. The Age of Reformation brought significant changes. The iconoclastic physician Paracelsus (a contemporary of Martin Luther) delighted in ridiculing the great medical books, and the French philosopher Pierre de la Ramée wrote a dissertation that roughly translates as "everything Aristotle has taught is mistaken." Instead, consensus was to be attained by new criteria: mathematical logic, careful observation, and experimentation. When knowledge is untight, coercion can play an important role in deciding outcomes in the market for ideas. Part of the platform of the Enlightenment of the eighteenth century was to leave no stone unturned in its efforts to make knowledge tighter by confronting hypotheses with evidence and by allowing more and different evidence as admissible. In this effort, it failed more often than it succeeded before 1800, but the effort itself was significant. By the eighteenth century, these rhetorical rules had themselves become more or less incontestable, but everything else was continuously expected to be challenged.

Contestability, of course, depended on more than access costs, and it is here that Europe's unique position as a politically fragmented yet intellectually coherent region paid off handsomely (Mokyr, 2007). New knowledge had powerful enemies, both those with a strong stake in the status quo and those who feared that intellectual changes would upset carefully calibrated coalitions in an age in which physics and metaphysics were still closely related areas and religious affiliation had significant political ramifications. Yet the astonishing historical fact is that the reaction against innovation was on the whole unsuccessful, and that a mind set of toleration slowly pushed out bigotry and repression in the late seventeenth and eighteenth centuries. Of course, intolerance did not disappear completely, and there was always a risk associated with coming up with radical innovations, both in useful knowledge and in its applications. But it seems fair to say that by the time of the Industrial Revolution, such risks were significantly smaller that they had been in 1600.

How did this come about? It could be argued that in a highly fragmented world of independent political units, many of which were regionally decentralized, freedom and progress could take advantage of a massive coordination failure. Whereas Hus could still be burned through a treacherous alliance between the Pope and the Emperor, after Luther such cases were rare. Unless the reactionary forces resisting innovation could coordinate, it would be very difficult to quell innovation everywhere. Rebellious and unconventional thinkers could and did move around the Continent a great deal, and many intellectuals skillfully played one power against another. Among the many peripatetic intellects on the sixteenth and seventeenth centuries, those of Paracelsus, Comenius, and Descartes stand out (Mokyr, 2006). Moreover, the difficulties of coordination that plagued the conservative powers (even between those ostensibly on the same side, like the Catholic Bourbons and Habsburgs) meant that even if intellectual progress and the Enlightenment could successfully be suppressed in some areas (as it was, e.g., in southern Italy), it could always proceed elsewhere, and leave the repressive countries at a disadvantage.

The net result was that in the eighteenth century, coercion and repression were relegated to marginal roles in the market for ideas. Some Enlightenment figures such as Rousseau and Helvétius published controversial books and had to flee to more tolerant environments, but normally such events were fleeting, and they popped up back in their countries after a few years. It almost seems that after 1750 many of the formerly repressive regimes in Europe adopted a "if you can't beat them join them" attitude toward innovation. To be sure, when these so-called enlightened despots tried to reform their institutions in the 1770s and 1780s, they ran into a great deal of resistance (Scott, 1990). The triumph of Enlightenment forces was sealed by Napoleon's artillery, demonstrating that all innovation contains elements of violence and persuasion.

In any event, as long there were some tolerant environments in Europe, intellectual and technological innovation could not be suppressed effectively and nations that tried to crush novelties found themselves at a disadvantage relative to their neighbors. Enlightenment thinkers realized this well. Edward Gibbon wrote that "Europe is now divided into twelve powerful, though unequal, kingdoms, three respectable commonwealths, and a variety of smaller, though independent, states: the chances of royal and ministerial talents are multiplied, at least, with the number of its rulers... In peace, the progress of knowledge and industry is accelerated by the emulation of so many active rivals; in war, the European forces are exercised by temperate and undecisive contests." (Gibbon, 1789, vol. 3, p. 636). The contradiction between the cosmopolitan and pacifist elements in Enlightenment thought and the realization that political fragmentation and interstate rivalry could be beneficial for innovation because it created a more efficient market for ideas remained one of the unresolved issues of the time.

The eighteenth century saw a number of other fundamental changes in the way the market for ideas worked reach their final stage. One of those was the accommodation between religion and the search for useful knowledge. The Enlightenment cannot be characterized as a purely secular, much less an atheistic, movement. Especially in England, many of the leaders of what we think of as the Enlightened community were quite committed to their religious principles and communities. But religion was optimistic, with a faith in progress and a belief in the benefits of useful knowledge. Jacob (2000, p. 277) has argued that it provided the belief of a rational and enlightened God, "not Calvin's inscrutable and judgmental one." The point was not that religion was irrelevant or even secondary, but rather that the investigation of nature for material purposes was to proceed unencumbered by religion, wherever it may lead. Darwin might not have had it so easy had there been no Enlightenment.

Institutions, of course, mattered. Formal institutions, such as the tax and legal systems, have been widely credited for the economic success of modern Europe, but their connection with technological change is actually anything but transparent. In Britain, the connection of the state with the technological changes in the Industrial Revolution was rather tenuous. In a few instances the government initiated innovation. The best-known case was the Board of Longitude, established in 1714 after a naval disaster caused by faulty navigation. It inspired the perfection of Harrison's chronometer, one of the epochal innovations of the eighteenth century. Another was the Portsmouth dockyards, mentioned above. Demand for military supplies, especially the boring of cannon by John Wilkinson, was obviously a factor in the iron industry. Decades later Henry Bessemer, too, was prompted to his foray into steelmaking by his attempt to make ordnance for the military.

Intellectual property rights and their enforcement have been an important theme in the institutional analysis of innovation. Britain had a patent system that in principle was supposed to encourage and incentivize innovation, but its net effects are still much in dispute and probably were of secondary magnitude (MacLeod and Nuvolari, 2007b). Parliament voted pensions and prizes to a few inventors it deemed to have particularly valuable to society, such as smallpox vaccination, the power loom, and the mule. But in most of the areas where we think government may contribute a great deal to innovation, such as education, government-sponsored research, and investment in transport overhead, the British government did little. Continental governments were more interventionist and *dirigiste*, but even there the government was secondary to private enterprise.

Perhaps the most important thing that British institutions, and after 1815 much of the Western World, contributed to the progress of innovation was what they did *not* do: they did not expropriate the profits of innovators and entrepreneurs. While entrepreneurial activities in the Industrial Revolution were exceedingly risky, it was quite obvious to all that they were reasonably safe from predatory rulers who might have taxed away the rents produced by successful innovation. Britain in the eighteenth century was heavily taxed, but most of the revenues came from excise taxes on middle-class goods such as sugar, tobacco, alcoholic beverages, candles, and so on. Successful industrialists used their gains to purchase country estates, and their children moved into the highest circles. Money bought not only comfort and beauty, but also social prestige (Perkin, 1969, p. 85). If money could be made by innovating, as became increasingly the case, the hope for social advancement created the most powerful incentive of all.

It is worth stressing that there was nothing inexorable about this outcome. It is easy to imagine the survival of short-sighted, bellicose, autocratic regimes, guided by militant mercantilism. To win conflicts over the distribution of resources and the gains from trade, they slaughtered the geese that lay the golden eggs by taxing the wealth of innovators and entrepreneurs or by allowing others (such as tax farmers) to redistribute wealth away from them. Arguably, the Napoleonic wars moved Britain in that direction and perhaps briefly threatened the progress of innovation by threatening personal freedoms. Fortunately, the regime remained committed to innovation and never wavered in its support for entrepreneurs and industrialists at the cutting edge of the Industrial Revolution.

Innovation needed venture capital, and eighteenth-century investors, it seems, were highly risk-averse. Formal capital markets typically invested in government securities and a few public projects such as canals and turnpikes (later railways). Yet oddly, there is not that much evidence that fixed capital goods, embodying the new technology, were especially difficult to accumulate and that their high cost constituted a serious bottleneck on the growth of the early industrializing economies. Economists have been prone to look at the roots of accumulation through the prism of perfect capital markets, summarized by “the” rate of interest. Yet nothing of the sort existed in Britain or elsewhere. Governments and certain public overhead projects such as canals and turnpikes, as well as mortgage borrowers could indeed access capital markets, but innovators were usually excluded from them and needed to rely on their own resources except for short-term credit. These resources constituted, first and foremost, ploughed-back profits, as has been pointed out many times (Cottrell, 1980; Crouzet, 1972). But beyond that, entrepreneurs had access to private informal networks that supplied them with credit on the basis of personal relations and trust. These private networks, often established between members of local associations, freemason lodges, or churches, allowed businessmen to diversify their portfolios by investing in the projects of their relatives, coreligionists, or acquaintances (Pearson and Richardson, 2001). The existence of these networks, dubbed the “associational society” by one historian (Clark, 2000), was another facilitating institutional element of the Industrial Revolution. These networks, of course, imposed *informal* institutions, rules by which people behaved although they were not enforced by third-party organizations such as courts. But they allowed the creation of partnership relationships between innovators and businessmen based on trust, both of whom were expected to behave like “gentlemen.” This meant above all that they professed not to be so greedy as to engage in opportunistic behavior. Concerns about reputation assured that the bulk of industrialists, merchants, bankers, professionals, skilled workers, and substantial farmers kept their word and paid their debts.

The typical entrepreneur in the Industrial Revolution, then, was hardly the ferocious, unscrupulous, merciless money grabber that some of the more sentimental accounts make him out to be. Far more important were “to be known and trusted in the locality” and to have “standing in the community” in addition to some form of property (Hudson, 1986, p. 262). Trust created successful partnerships between innovators and entrepreneurs. The classic association of Watt the engineer and Boulton the businessman is the standard example here. There were many others: John Marshall, the Leeds flaxspinner who could rely on his technical manager Michael Murray, and the great engineer Richard Roberts, notorious for having poor business management skills, who had able partners such as Thomas Sharpe and Benjamin Fothergill. Other famous teams were that of Cook and Wheatstone, one the businessman, the other the scientist, as were John Kay and Richard Arkwright, the railroad engineer George Stephenson and his partner and promoter Henry Booth, and the rubber pioneers Thomas Hancock and Charles Macintosh. Equally effective were the partnerships of William Woollett and his brother-in-law Jedediah Strutt, the inventors of the improved knitting frame that could produce ribbed stockings (1758), and that of James Hargreaves (inventor of the spinning jenny) and his employer Robert Peel.

The other mechanism through which informal institutions affected innovation was through training. Britain, as is well known, lagged behind other Continental economies in most areas of human capital formation. Apart from a few enclaves in which a useful education was provided, such as the Scottish universities and dissenting academies, Britain had no engineering schools during the Industrial Revolution, the first ones being established in the 1830s. Yet by all indications it had an advantage in the number and quality of its skilled artisans. These craftsmen provided Britain with the “competence” needed for the advances discussed earlier. In part, this advantage can be explained by geography. As a mining country, there clearly was a need to solve certain well-defined problems such as the design of better pumps. As a sea-faring nation, it needed carpenters, sailcloth makers, ropemakers, and the makers of navigational instruments. Britain also was fortunate to have a large clockmaking industry, many of them Huguenot refugees and their descendants. It had a relatively substantial middle class, people with the means to purchase consumer durables that required skills such as high-quality ceramics, musical instruments, watches, and fancy toys. In the century before the Industrial Revolution that middle-class demand expanded considerably (De Vries, 2008).

On the supply side, human capital in the forms of skilled craftsmen was created primarily through apprenticeships, in which adolescents were trained by accomplished craftsmen. The contract between master and pupil was notoriously incomplete, and lent itself to a great deal of opportunistic behavior (Humphries, 2003). On the Continent, these contracts were normally enforced and administered by guilds, which helped reproduce skills, but often crystallized existing technology. In Britain, craft guilds were weak, and by the eighteenth century did little to enforce apprenticeship relationships. Yet the institution survived and indeed lasted deep into the nineteenth century. The main reason was that the relationship was typically not established between strangers, but between neighbors, friends, business relations, and coreligionists. Mistreating one’s apprentice or cheating one’s master could bring long-term damage to reputations, on which credit and commerce depended. Information about such behavior was readily accessible in a nation of clubs, societies, and other associations, in which people networked and traded information.

Outside Britain, innovation had to rely on more powerful institutional friends. Continental Europe, as Gerschenkron famously pointed out, relied on large investment banks and government guarantees and subsidies to create the capital required by firms on the technological frontier. Different countries followed different recipes on the way to financing innovation, and it is clear that there was more than one way to skin this cat. In subsidizing research, too, the economies of the Continent faced more activist governments, which subsidized what they believed to be important research, from agricultural research stations in Saxony and Polytechnics in Prussia to the Kaiser Wilhelm Society for the promotion of sciences to the *Grandes Écoles* of France and the Pasteur Institute in Paris which, while in part established through private subscriptions, was under close government supervision. A typical Continental figure was Friedrich Althoff, the powerful undersecretary of the Prussian Ministry of Education who firmly established state control over the system of higher education in Germany between 1882 and 1907 (e.g., vom Brocke, 1991).

A venerable theory linking innovation to the economic environment is the one that relates the direction of innovation to pre-existing factor prices. The theory of induced innovation was famously applied to economic history by H.J. Habakkuk and has been the subject of a considerable literature in the 1960s and 1970s about the impact of high wages on the rate of technological change (Habakkuk, 1962; Ruttan, 2001). A recent attempt by Allen (2008) to revive this approach looks at the cost of labor relative to that of fossil energy, and postulates that labor-saving innovation in Britain was the direct result of the high cost of labor and the cheapness of coal. Coal-using machinery that saved labor made sense in such an economy. Innovation induced by factor prices seems a convincing story, as Ruttan and others have pointed out, when it comes to adoption and diffusion, but much less so when it comes to invention itself. What complicates matters, however, is that adoption and diffusion themselves often involve a great deal of local learning, and generate a flow of specific microinventions that may be crucial to ultimate effects on productivity.

There are both empirical and theoretical difficulties in the argument. One empirical difficulty is that coal was cheap near the mines, but much less so than in Cornwall and in London, where it had to be shipped in from a distance, yet Cornwall and London used steam engines and large amounts of coal. While the steam engine may appear the ultimate labor-saving machine, subsequent improvements were primarily aimed at saving fuel (i.e., capital). In its earliest forms, steam power often was intended to save horse- or water-power rather than labor. Coal mining itself, moreover, was highly labor intensive because until the introduction of compressed air in the late nineteenth century, there was no way to actually introduce labor-saving devices down the shaft. The most remarkable invention in deep-mining technology was Davy's mining lamp, a safety device that saved lives and prevented accidents but did not save labor costs. The other empirical difficulty is that most patentees, when asked the purpose of their invention, failed to mention the saving of labor (MacLeod, 1988, pp. 160–171). Interpreting this evidence is difficult not least because in eighteenth-century Britain, "labor saving" was still a fighting word for many militant artisans who feared that their employment would be jeopardized. Yet even after adjusting for this bias, the proportion of patents that can be classified as labor saving was about 21%.

The theoretical problems are not less. A rather obvious one is that high wages by themselves do not mean that labor was expensive and that labor costs were high. If labor productivity in Britain was higher simply because the quality of labor was higher, for instance because it was physically stronger and/or because it was more skilled, better motivated, or even better drilled and disciplined, then Britain's higher wages, stressed by Allen, would at least in part reflect not the high cost of labor but its quality. Some contemporaries had no qualms about this: Arthur Young, writing in the late 1780s, noted that "labour is generally in reality the cheapest where it is nominally the dearest" (Young, 1790, p. 311).

But the main argument against factor prices (or indeed any kind of initial endowment) affecting technological progress is that it often conflates the *rate* and the *direction* of technological change. The rate or intensity of innovation, much like a car's engine, determined the power of society's technological thrust, while endowments may have steered innovation into a particular direction. Resources are, in Rosenberg's (1976) terminology, a classic "focusing device" but they themselves do not determine the rate of innovation. A coal-intensive economy, given that the other factors facilitating technological creativity were present, may well direct its creativity in some way into coal-using techniques, but the large deposits of coal in, say, the Donetsk region of Ukraine or the Kemerovo region in Russia were not sufficient to create a coal-using technology until it had been developed elsewhere.

The fundamental difficulty with biased or induced innovation, then, is that it makes an inference from a static model about a dynamic setting. Economic theory suggests that factor prices determine technological choices from a given menu of techniques. It does not give us much insight on how the menu was written in the first place, and why some items are on it and others are not (Rosenberg, 1976, pp. 108–125). An ingenious attempt to link the two relies on learning-by-doing and localized innovation (David, 1975). The logic is that at first factor, prices dictate the technique chosen, and as the technique is being used, people acquire experience and make further innovations in the area of the technique being used, rather than in those that "exist" somewhere but are not actually implemented anywhere. This contrasts with the model suggested by Hansen and Prescott (2002), for example (and implied by other endogenous growth models), in which techniques that are "known" but not in use can experience an increase in productivity that switches producers to their use. What is not made explicit in these models is the role of the underlying epistemic base of the technological frontier. If the knowledge base permits developing techniques that do not currently exist but are feasible given the knowledge this society controls, such sudden switches triggered by factor prices or other stimuli may well induce technological change in a particular direction. But if a society does not know how to prospect for coal, how to dig the shafts, how to pump out the water, bring the coal to the surface and then transport it to users at a reasonable price, no amount of abundant coal—no matter how dear labor may be.

Were the great technological advances of this age the result of discrete quantum leaps in knowledge or of small incremental and cumulative microinventions? Putting the question in this form is a kin to asking if a bicycle moves thanks to it front or its rear wheel. The two types of processes were highly complementary. Historically, the path of innovation thus contained elements of both. At times, macroinventions occurred which switched some industries (and in the case of General-Purpose Technologies, entire sectors) onto a wholly new path. Such was the case, as we showed earlier, with sectors such as the chemical industry and electricity in the later nineteenth century. In many others, the technique in use was improved gradually through cumulative microinventions, through extensions and combinations with other techniques, as in textiles and iron. Such distinctions are not easy to make empirically because of the continuous spillovers between techniques and the pervasive effect of GPTs, and so it makes little sense to speak of "new-technology" sectors and "old-technology" sectors. In either case, what really counted was the underlying knowledge that created the technological opportunities and allowed the items on the technological menu to be written. To take advantage of them, other factors had to be available. A car with a powerful engine and flat tires or no coolant is of little use. Yet in the end, it is the engine that determines the car's power. The engine of growth in the economic history of the West was the international cooperative agenda for the accumulation of useful knowledge. It is in its dynamic that the key to economic growth is to be found.

References

Aghion, P., Durlauf, S. (Eds.), (2005). Handbook of Economic Growth, 2 vols. Elsevier, Amsterdam.

Allen, R.C. (2008). The British Industrial Revolution in Global Perspective. Unpublished manuscript, Nuffield College, Oxford University.

Bacon, F. (1996). In: Vickers, B. (Ed.), The Major Works. Oxford University Press, Oxford.

Bacon, F. (1999). In: Sargent, R.-M. (Ed.), Selected Philosophical Works. Hackett Publishing, Indianapolis.

Bagwell, P.S. (1974). The Transport Revolution from 1770. Barnes & Noble, New York, NY.

Berg, M. (2007). "The genesis of useful knowledge". History of Science 45 (Pt. 2, 148), 123–134 (June).

Boussingault, J.B. (1821). "On the presence of silicia platina and its presence in steel". Repertory of Arts, Manufactures, and Agriculture 39 (2nd series), 366–373.

Bowers, B. (1998). Lengthening the Day: A History of Lighting Technology. Oxford University Press, Oxford.

Bowler, P.J., Morus, I.R. (2005). Making Modern Science. University of Chicago Press, Chicago, IL.

Boyle, R. (1744). The Works of the Honourable Robert Boyle, (5 vols). A. Millar, London.

Britnell, R.H. (1996). The Commercialization of English Society, 1000–1500. Manchester University Press, Manchester.

Brock, W.H. (1992). The Norton History of Chemistry. W.W. Norton, New York, NY.

Bryant, L. (1967). "The beginnings of the internal combustion engine". In: Kranzberg, M., Pursell Jr., C.W. (Eds.), Technology in Western Civilization, vol. 1. Oxford University Press, New York, NY, pp. 648–663.

Bryant, L. (1969). "Rudolf Diesel and his rational engine". Scientific American 221, 108–117 (August).

Burton, A. (2000). Richard Trevithick: Giant of Steam. Aurum Press, London.

Cardwell, D. S. L. (1971). From Watt to Clausius: The Rise of Thermodynamics in the Early Industrial Age. Cornell University Press, Ithaca, NY.

Cardwell, D. S. L. (1972). Turning Points in Western Technology. Neale Watson/Science History Publications, New York, NY.

Channell, D.F. (1982). "The harmony of theory and practice: The engineering science of W.J.M. Rankine". Technology and Culture 23 (1), 39–52 (January).

Clark, P. (2000). British Clubs and Societies, 1580–1800: The Origins of an Associational World. Clarendon Press, Oxford.

Clark, G. (2007). Farewell to Alms: A Short Economic History of the World. Princeton University Press, Princeton, NJ.

Clow, A., Clow, N.L. (1952). The Chemical Revolution: A Contribution to Social Technology. Batchworth Press, London Reprinted in 1992, Gordon and Breach, New York, NY.

Collins, R. (1998). The Sociology of Philosophies: A Global Theory of Intellectual Change. Harvard University Press, Cambridge, MA.

Cottrell, P.L. (1980). Industrial Finance, 1830–1914. Methuen, London.

Crouzet, F. (1972). "Capital formation in Great Britain during the Industrial Revolution". In: Crouzet, F. (Ed.), Capital Formation in the Industrial Revolution. Methuen, London.

Darnton, R. (2003). "The unity of Europe". George Washington's False Teeth. W.W. Norton, New York, NY.

Daston, L. (1991). "The ideal and reality of the Republic of Letters in the Enlightenment". Science in Context 4 (2), 367–386.

Daumas, M. (1979). "The rise of the heavy chemical industry". In: Daumas, M. (Ed.), A History of Technology & Invention, vol. III. Crown, New York, NY.

Daumas, M., Gille, P. (1979). "Transportation and communications". In: Daumas, M. (Ed.), A History of Technology & Invention, vol. III. Crown, New York, NY.

David, P.A. (1975). Technical Choice, Innovation and Economic Growth. Cambridge University Press, New York, NY.

David, P.A. (2004). Patronage, Reputation, and Common Agency Contracting in the Scientific Revolution. Unpublished manuscript, Stanford University (August).

Day, L., McNeil, I. (Eds.), (1996). Biographical Dictionary of the History of Technology. Routledge, London.

de Solla Price, D.J. (1984). "Notes towards a philosophy of the science/technology interaction". In: Laudan, R. (Ed.), The Nature of Knowledge: Are Models of Scientific Change Relevant? Kluwer, Dordrecht.

De Vries, J. (2008). The Industrious Revolution: Consumer Behavior and the Household Economy, 1650 to the Present. Cambridge University Press, Cambridge (January).

Eamon, W. (1994). Science and the Secrets of Nature. Princeton University Press, Princeton, NJ.

Eisenstein, E. (1979). The Printing Press as an Agent of Change. Cambridge University Press, Cambridge.

Epstein, S.R. (1998). "Craft guilds, apprenticeship and technological change in pre-industrial Europe". Journal of Economic History 58 (3), 684–713 (September).

Epstein, S.R., Prak, M. (Eds.), (2008). Guilds, Innovation, and the European Economy, 1400–1800. Cambridge University Press, Cambridge.

Eyler, J.M. (1979). Victorian Social Medicine: The Ideas and Methods of William Farr. Johns Hopkins University Press, Baltimore, MD.

Farey, J. (1827). A Treatise on the Steam Engine, Historical, Practical and Descriptive. Longman, Rees, Orme, Brown, and Green, London.

Fouquet, R., Pearson, P. J. G. (2006). "Seven Centuries of Energy Services: The Price and Use of Light in the United Kingdom, 1300–2000". The Energy Journal 27 (1), 139–177.

Friedel, R. (2007). A Culture of Improvement: Technology and the Western Millennium. MIT Press, Cambridge, MA.

Galor, O., Weil, D. (2000). "Population, technology, and growth". American Economic Review 90 (4), 806–828 (September).

Gibbon, E. (1789). The History of the Decline and Fall of the Roman Empire (new ed.). A. Strahan and T. Cadell, London.

Great Britain. (1829). British Parliamentary Papers, vol. III (332), ("Select Committee on State of Law and Practice relative to Granting of Patents for Inventions").

Great Britain. (1841). British Parliamentary Papers, vol. VII (201), ("Select Committee on Operation of Laws affecting the Exportation of Machinery, first report").

Habakkuk, H.J. (1962). American and British Technology in the Nineteenth Century. Cambridge University Press, Cambridge.

Haber, L.F. (1958). The Chemical Industry during the Nineteenth Century. Clarendon Press, Oxford.

Halstead, P.E. (1961–1962). "The early history of Portland cement". Transactions of the Newcomen Society 34, 37–54.

Hansen, G.D., Prescott, E.C. (2002). "Malthus to Solow". American Economic Review 92 (4), 1205–1217 (September).

Harley, C.K. (1988). "Ocean freight rates and productivity 1740–1913: The primacy of mechanical invention reaffirmed". Journal of Economic History 48, 851–876 (December).

Harris, J.R. (1998). Industrial Espionage and Technology Transfer: Britain and France in the Eighteenth Century. Ashgate, Aldershot.

Headrick, D.R. (1989). The Invisible Weapon: Telecommunications and International Politics, 1851–1945. Oxford University Press, New York, NY.

Headrick, D.R. (2000). When Information Came of Age: Technologies of Knowledge in the Age of Reason and Revolution, 1700–1850. Oxford University Press, New York, NY.

Herman, A. (2001). How the Scots Invented the Modern World. Crown, New York, NY.

Hilaire-Pérez, L. (2007). "Technology as public culture". History of Science 45 (Pt. 2, 148), 135–153 (June).

Hudson, R.P. (1983). Disease and Its Control: The Shaping of Modern Thought. Greenwood Press, Westport, CT.

Hudson, P. (1986). The Genesis of Industrial Capital: A Study of West Riding Wool Textile Industry, c. 1750–1850. Cambridge University Press, Cambridge.

Hughes, T.P. (1983). Networks of Power: Electrification in Western Society, 1880–1930. Johns Hopkins Press, Baltimore, MD.

Humphries, J. (2003). "English apprenticeship: A neglected factor in the first Industrial Revolution". In: David, P.A., Thomas, M. (Eds.), The Economic Future in Historical Perspective. Oxford University Press, Oxford, pp. 73–102.

Jacob, M.C. (2000). "Commerce, industry, and the laws of Newtonian Science: Weber revisited and revised". Canadian Journal of History 35 (2), 275–292 (August).

Jacob, M.C. (2007). "Mechanical science of the shopfloor". History of Science 45 (2), 197–221 (June).

Kerker, M. (1960). "Sadi Carnot and the steam engine engineers". Isis 51 (3), 257–270 (September).

Lipsey, R.G., Carlaw, K.I., Bekar, C.T. (2005). Economic Transformations: General Purpose Technologies and Long-term Economic Growth. Oxford University Press, Oxford.

Lucas, R.E. (2002). Lectures on Economic Growth. Harvard University Press, Cambridge, MA.

Lyons, H.G. (1944). The Royal Society, 1660–1940, a History of Its Administration under Its Charters. Cambridge University Press, Cambridge.

MacLeod, C. (1988). Inventing the Industrial Revolution: The English Patent System, 1660–1880. Cambridge University Press, Cambridge.

MacLeod, C., Nuvolari, A. (2007a). "Glorious Times: The Emergence of Mechanical Engineering in Early Industrial Britain, c. 1700–1850". Unpublished manuscript.

MacLeod, C., Nuvolari, A. (2007b). "Inventive Activities, Patents, and Early Industrialization: A Synthesis of Research Issues". Unpublished manuscript.

Mantoux, P. (1928). The Industrial Revolution in the Eighteenth Century. Harper Torchbooks, New York, NY. Revised ed., 1961.

Marsden, B. (2004). Rankine, William John Macquorn (1820–1872). Oxford Dictionary of National Biography. Oxford University Press, Oxford.

Marsden, B., Smith, C. (2005). Engineering Empires: A Cultural History of Technology in Nineteenth-Century Britain. Palgrave MacMillan, Houndmills, Basingstoke.

Mokyr, J. (2001). "The rise and fall of the factory system: Technology, firms, and households since the Industrial Revolution". Carnegie–Rochester Conference Series on Public Policy, vol. 55, pp. 1–45 (December).

Mokyr, J. (2002). The Gifts of Athena: Historical Origins of the Knowledge Economy. Princeton University Press, Princeton, NJ.

Mokyr, J. (2005). "The intellectual origins of modern economic growth [Presidential address]". Journal of Economic History 65 (2), 285–351 (June).

Mokyr, J. (2006). "Mobility, creativity, and technological development: David Hume, Immanuel Kant and the economic development of Europe. Prepared for the session on "Creativity and the Economy"" In: Abel, G. (Ed.), Kolloquiumsband of the XX. Deutschen Kongresses für Philosophie, Berlin, German Association of Philosophy, Berlin, pp. 1131–1161.

Mokyr, J. (2007). "The market for ideas and the origins of economic growth in eighteenth century Europe". Tijdschrift voor Sociale en Economische Geschiedenis 4 (1), 3–38.

Mokyr, J. (2009). The Enlightened Economy. Yale University Press, London.

Mokyr, J., Voth, J. (2010). "Understanding growth in Europe, 1700–1870: Theory and evidence". In: Broadberry, S., O'Rourke, K. (Eds.), The New Cambridge Economic History of Europe, Volume 1, (in press).

Morrell, J., Thackray, A. (1981). Gentlemen of Science: Early Years of the British Association for the Advancement of Science. Oxford University Press, Oxford.

Mowery, D., Rosenberg, N. (1989). Technology and the Pursuit of Economic Growth. Cambridge University Press, Cambridge.

Murmann, J.P. (2003). Knowledge and Competitive Advantage. Cambridge University Press, Cambridge.

Murmann, J.P., Landau, R. (1998). "On the making of competitive advantage: The development of the chemical industries of Britain and Germany since 1850". In: Arora, A., Landau, R., Rosenberg, N. (Eds.), Chemicals and Long-term Economic Growth. John Wiley & Sons, New York, NY.

Musson, A.E. (1975). "Joseph Whitworth and the growth of mass-production engineering". Business History 17, 109–149 (July).

Nasmyth, J. (1841). Remarks on the introduction of the slide principle in tools and machines employed in the production of machinery Appendix B in Robertson Buchanan (3rd. ed., with additions by George Rennie). Practical Essays on Mill Work and Other Machinery, vol. 2. J. Weale, London.

North, D.C. (1990). Institutions, Institutional Change, and Economic Performance. Cambridge University Press, Cambridge.

North, D.C. (1995). Understanding the Process of Economic Change. Princeton University Press, Princeton, NJ.

Pearson, R., Richardson, D. (2001). "Business networking in the Industrial Revolution". Economic History Review 54 (4), 657–679.

Perkin, H.J. (1969). The Origins of Modern English Society, 1780–1880. Routledge & Kegan Paul, London.

Polanyi, K. (1944). The Great Transformation. Beacon Press., Boston, MA Reprinted in 1985.

Porter, R. (1982). "Was there a medical Enlightenment?" British Journal for Eighteenth-Century Studies 5, 49–63.

Priestley, J. (1769). The History and Present State of Electricity, with Original Experiments (second ed., corrected and enlarged). J. Dodsley, London.

Rosenberg, N. (1976). Perspectives on Technology. Cambridge University Press, Cambridge.

Rosenberg, N. (1982). "How exogenous is science?" Inside the Black Box: Technology and Economics. Cambridge University Press, Cambridge.

Rosenberg, N. (1996). "Uncertainty and technological change". In: Fuhrer, J.C., Little, J.S. (Eds.), Technology and Growth. Conference Series, no. 40. Federal Reserve Bank of Boston, Boston, MA, pp. 91–110.

Rosenberg, N., Trajtenberg, M. (2004). "A general-purpose technology at work: The Corliss steam engine in the late-nineteenth-century United States". The Journal of Economic History 64 (1), 61–99 (March).

Ruttan, V.W. (2001). Technology, Growth and Development: An Induced Innovation Perspective. Oxford University Press, New York, NY.

Scott, H.M. (Ed.), (1990). Enlightened Absolutism: Reform and Reformers in Later Eighteenth-Century Europe. Palgrave MacMillan, Houndmills, Basingstoke.

Shapin, S. (1994). The Social History of Truth. University of Chicago Press, Chicago, IL.

Smil, V. (2001). Enriching the Earth: Fritz Haber, Carl Bosch and the Transformation of World Food Production. MIT Press, Cambridge, MA.

Smil, V. (2005). Creating the Twentieth Century: Technical Innovations of 1867–1914 and Their Lasting Impact. Oxford University Press, Oxford.

Smith, A. (1757). Lectures on Jurisprudence. Clarendon Press, Oxford Reprinted in 1978.

Smith, A. (1776). Cannan, E. (Ed.), The Wealth of Nations. University of Chicago Press, Chicago, IL Reprinted in 1976.

Smith, C.S. (1964). "The discovery of carbon in steel". Technology and Culture 5 (2), 149–175 (Spring).

Smith, C. (1990). "Energy". In: Olby, R.C., Cantor, G.N., Christie, J. R. R., Hodge, M. J. S. (Eds.), Companion to the History of Science. Routledge, London.

Snooks, G. (1994). "The Industrial Revolution revisited". In: Snooks, G.D. (Ed.), Was the Industrial Revolution Necessary? Routledge, London.

Spratt, H.P. (1958). "The marine steam-engine". In: Singer, C., Holmyard, E.J. (Eds.), A History of Technology, vol. V, pp. 141–156.

Stewart, L. (2007). "Experimental spaces and the knowledge economy". History of Science 45 (148), 155–177 (June).

Szreter, S. (1988). "The importance of social intervention in Britain's mortality decline, c. 1850–1914: A re-interpretation of the role of public health". Social History of Medicine 1, 1–37.

Temin, P. (1997). "Two views of the British Industrial Revolution". Journal of Economic History 57 (1), 63–82 (March).

Toynbee, A. (1884). Toynbee's Industrial Revolution: A Reprint of Lectures on the Industrial Revolution. David & Charles, New York, NY Reprinted in 1969.

Tweedale, G. (2004). "Bell, Sir (Isaac) Lowthian, first baronet (1816–1904)". Oxford Dictionary of National Biography. Oxford University Press, Oxford.

vom Brocke, B. (1991). "Friedrich Althoff: A great figure in higher education policy in Germany". Minerva 29 (3), 269–283 (September).

Weber, M. (1923). General Economic History. Collier Books, New York, NY. Reprinted in 1961.

Weber, W. (2003). "Science, Technology, and Society in Germany from 1800 to the Present". In: Ogilvie, S., Overy, R. (Eds.), Germany: A New Social and Economic History, vol. III. Arnold, London.

Wells, H.G. (1923). Men Like Gods. Cassell, London.

Wohl, A.S. (1983). Endangered Lives: Public Health in Victorian Britain. Harvard University Press, Cambridge.

Wrigley, E.A. (2004). Poverty, Progress, and Population. Cambridge University Press, Cambridge.

Young, A. (1790). In: Maxwell, C. (Ed.), Travels in France during the Years 1787, 1788, and 1789. Cambridge University Press, Cambridge. Reprinted in 1929.