Chapter 3

The Industrial Revolution and Beyond

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

—John Nicholson (1826)

Introduction

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

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 But do they have historical content?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

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

The First Industrial Revolution

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

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

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

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

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

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

This qualification does not invalidate the argument that the interaction between propositional knowledge and techniques was the driving force behind technological expansion, only that we are missing most of the action if we concentrate our efforts on formal science. Two stereotypic cartoons—the one of an ignorant amateur "tinkerer" who stumbled into great inventions through a combination of inspired intuition and sheer luck, the other of the methodical, well-informed scientist whose rigorous papers inform applied scientists and engineers of the exploitable natural regularities—are ahistorical. In between, there was a semidirected, groping, bumbling process of trial and error by clever, dexterous professionals with a vague but gradually clearer notion of the processes at work.[1] They enjoyed occasional but increasingly frequent successes, squeezing a messy, poorly defined blob of useful knowledge, some of it formal and codified, some of it propositional knowledge passed on orally in the form of "this works and this does not" (in Q), that mapped into "here is how you do this" (in A,).[2] Instructions, not ideas, make things work. The early application of techniques were often based on the vaguest of ideas. Operating a technique led to a better and better notion of *why* something worked and from there to how to make it work more efficiently or how to make it do something else. Watching a machine work or a telegraph signal pass without knowing why it does so serves as an irritant to a mind trained in science. In this sense, technology works as a "focusing device," to use Rosenberg's (1976) term, for the growth of **Q** -knowledge.

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

All the same, the technological changes that occurred in western Europe between 1760 and 1800 heralded a new age in the generation of new prescriptive knowledge. It was slowly becoming less random and serendipitous. As a result, the 1820s witnessed another "wave" of inventions and conceptual breakthroughs, which, while perhaps not as spectacular and pathbreaking as the classic inventions of the "*annus mirabilis*, "created a second wind that prevented the process from slowing down and petering out. These microinventions, which extended and consolidated earlier advances were possible because they could rely on an ever-widening epistemic base and much of its widening was the result of deliberate searches. The advances in epistemic bases seem modest when compared with what was to follow and hence have not been much noticed. Yet besides the great advances associated with Lavoisier and his followers, there were myriad advances in the physics of heat, the understanding of the location of mineral deposits, mechanics, electric current, hydraulics, and soil management.

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

We could say, then, that the process of innovation was gradually becoming "less Darwinian" in the sense that the mutations in useful knowledge were becoming less random and more directed. Many areas in Q-knowledge that had previously been informal, artisanal, and thus limited as epistemic bases, were increasingly infused with the methods of science. To a large extent, this change was endogenous and a function of industrial needs. Yet oddly, much of the systematic expansion of **Q** -knowledge was carried out in France and Germany, especially after the continent recovered from the social and political upheavals of the revolutionary period. After 1820, some of the important inventions were less the result of serendipity than of concentrated efforts by informed engineers, chemists, and machinists. Some of the ideas generated in this period, however, were not realized until after 1860, marking the beginning of the second Industrial Revolution.

The Second Industrial Revolution

It is part of accepted wisdom that the techniques that came into being after 1860 were the result of applied science, which had made enormous advances in the first two-thirds of the nineteenth century.[6] In some industries this is surely true: one can hardly imagine the advances in the chemical industry after 1860 without the advances in organic chemistry that followed von Liebig and Wohler's work in the 1820s and 1830s. The industrial R&D lab, the greatest innovation of the time in the technology of generating technology, made its entrance in the 1860s in the German chemical industry.[7] Indeed, some techniques that emerged as a result of the new **Q** -knowledge were instrumental in expanding useful knowledge even further. The two types of knowledge, propositional and prescriptive, kept reinforcing each other. The invention that may have heralded the second Industrial Revolution, William Perkin's aniline purple (or mauve) process in 1856, was largely a matter of good fortune, although it happened to a prepared mind. But it set in motion a process that brought industrial and academic chemists ever closer together, culminating in the discovery in 1869 of alizarin dyes (by the Germans Carl Graebe and Carl Liebermann). The pivotal breakthrough in the propositional knowledge set was the identification of the structure of the benzene molecule by the German chemist August von Kekule in 1865, after which the search for synthetic dyes became simpler and faster. Benzene had been known for a few decades, so the discovery of the chemical structure is a paradigmatic example of a broadening of the epistemic base of an existing technique. The result was a continuous stream of innovations which, instead of slowing down as it might have a century earlier, gathered force to become a veritable torrent as chemists focused on the problem and gradually worked out the chemistry of synthetic dyes (Fox and Guagnini, 1999, p. 34). Yet as always there was more continuity than is often allowed for. Invention by trial and error, luck, and instinct was not replaced entirely by a more complete understanding of the natural processes at work. Moreover, while the importance of the specialized sector of R&D in some industries was large, Fox and Guagnini rightly insist that the laboratory remained the tip of an iceberg, most of which was still rooted in practice, experience, and serendipity.

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

Perhaps the paradigmatic invention of the second Industrial Revolution, the Bessemer steelmaking process of 1856, was made by a man who by his own admission had "very limited knowledge of iron metallurgy."[9] Henry Bessemer's knowledge was so limited that the typical Bessemer blast, in his own words, was "a revelation to me, as I had in no way anticipated such results" (Carr and Taplin, 1962, p. 19). All the same, the growth of the epistemic base in the preceding half-century was pivotal to the development of the process. Bessemer knew enough chemistry to realize that his process had succeeded and similar experiments by others had failed because the pig iron he had used was, by accident, singularly free of phosphorus. By adding carbon at the right time, he would get the correct mixture of carbon and iron—that is, steel. He did not know enough, however, to come up with a technique that would rid the iron of phosphorus; the so-called basic process that solved this problem was discovered twenty years later.[10] Moreover, the epistemic base at the time was much larger than Bessemer's knowledge. This was demonstrated when an experienced metallurgist named Robert Mushet, showed that Bessemer steel contained excess oxygen, a problem that could be remedied by adding a decarburizer consisting of a mixture of manganese, carbon, and iron. The Bessemer and related microinventions led, in the words of Donald Cardwell (1994, p. 292), to “the establishment of metallurgy as a study on the border of science and technology.” In the years following Bessemer and Mushet's work, the Siemens Martin steelmaking process was perfected, and Henry Clifton Sorby discovered the changes in crystals in iron upon hardening and related the trace quantities of carbon and other constituents to the qualities and hardness of steel (Higham, 1963, p. 129).[11]

Energy utilization followed a comparable pattern. Engines in the sense we would recognize today—that is, devices that convert heat to work in a controlled way—had existed since the first Newcomen engines, but the physics underlying their operation and governing their efficiency was not properly understood. Good mechanical intuition coupled to a sound experimental method was, up to a point, a good substitute for formal science and helped James Watt to transform a crude and clumsy contraption into a universal source of industrial power. In the first decades of the nineteenth century Richard Trevithick, Arthur Woolf, and their followers created the more compact high-pressure engine, which a few decades later revolutionized transportation. But the epistemic base that could help analyze and explain the efficiency of such engines did not exist.[12] John Farey, the best expositor of the mechanical details of the steam engine, still regarded the steam engine in 1827 as a vapor-pressure engine rather than a heat engine. The same is true for one of the most influential treatises on steam, Francois Marie Pambour's 1837 *Theorie de la machine a vapeur,* which became a standard work and was translated into German and English. It was written for an audience of engineers and foremen, but it required considerable mathematical sophistication (Kroes, 1992).[13] Perhaps typical of the division of labor between Britain and France, the first enunciation of the principles at work here—efficiency was a function of the differences in temperature—was laid out by a French engineer, Sadi Carnot, in 1824, after he observed the differences in efficiency between a high-pressure Woolf engine and an older model.[14] The next big step was made by an Englishman, James P. Joule, who showed the conversion rates from work to heat and back.[15] Joule's work and that of Carnot were then reconciled by a German, R. J. E. Clausius (the discoverer of entropy), and by 1850 a new branch of science dubbed “thermodynamics” by William Thomson (later Lord Kelvin) had emerged (Cardwell, 1971, 1994).[16]

Yet this expansion of the epistemic base on which the practice of steam engines rested would have mattered little had it not led to applications in engineering. Old engines were made better and new ones were created. William Rankine, the author of *Manual of the Steam Engine* (1859), made thermodynamics accessible to engineers, and Scottish steam engines made good use of the Carnot principle that the efficiency of a steam engine depends on the temperature range over which the engine operates.[17] Rankine developed a new relationship between science and technology (Channell, 1982, p. 42). He distinguished between three kinds of knowledge: purely scientific, purely practical, and the application of sound theory to good practice (Smith and Wise, 1989, p. 660).

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

A third example of the widening of the epistemic base of technology leading to the emergence and then continuous improvement of techniques is the telegraph. Many eighteenth-century scientists, such as the great French physicist Charles-Augustin de Coulomb, believed that magnetism and electricity were unrelated. But in 1819 a Danish physicist, Hans Oersted, brought a compass needle near a wire through which a current was passing. It forced the needle to point at a right angle to the current. Electricity and magnetism turned out to be related after all. Electro- magnetism, once discovered, was turned into a legitimate field of inquiry by the work of William Sturgeon, Michael Faraday, and above all Joseph Henry. Their work in turn created the epistemic base for the work of Wheatstone, Cooke's partner, as well as that of Samuel Morse. The first successful submarine cable was laid by Thomas Crampton's Company between Dover and Calais in 1851, a technological triumph that lasted thirty-seven years. The idea of using electrical current on a magnetized needle to transmit information at a speed much faster than anything previously possible was a classic macroinvention. Contemporaries praised the new invention as “this subjugation of nature and conversion of her powers to the use and will of man actually do, as Lord Bacon predicted it would, a thousand times more than what all the preternatural powers which men have dreamt of' (cited by Morus, 1998, p. 194).

The long-distance telegraph, however, required many subsequent microinventions. Submarine cables were a difficult technology to master. Signals were often weak and slow, and the messages distorted. Worse, cables were subject at first to intolerable wear and tear.[19] The techniques of insulating and armoring the cables properly had to be perfected, and the problem of capacitance (increasing distortion on long-distance cables) had to be overcome. Before the telegraph could become truly functional, the physics of transmission of electric impulses had to be understood. Again, the technique started off with a fairly narrow epistemic base, but the obvious economic and political importance of the invention placed the underlying **Q** -knowledge on the agenda. Developments in the techniques and the knowledge underlying it proceeded cheek by jowl. Physicists, and above all Kelvin, made fundamental contributions to the technology. Kelvin's was a classic example of a hybrid career, in which technology shaped science as much as it was supported by it (Kranakis, 1992; Smith and Wise, 1989). He worked out the principles governing the relation between the signal and the resistance, inductive capacity, and length, and computed the resistivity of copper and the inductive capacity of guttapercha, the insulating material. He also invented a special galvanometer, a siphon recorder (which automatically registered signals), and a technique of sending short reverse pulses immediately following the main pulse, to sharpen the signal (Wise, 1988; Headrick, 1989, pp. 215-18). These inventions were directly based on best-practice mathematical physics, and although the epistemic base was far from complete (Kelvin resisted Maxwell's electromagnetics and held on to the notion of ether believed to be the weightless medium for the transmission of electromagnetic waves), his contributions to submarine telegraphy and magnetic instruments were crucial (Smith and Wise, 1989, esp. chs. 19 and 22). In this close collaboration between science and technology, telegraphy was clearly a second- generation technology, in that wider epistemic bases made the process of invention faster and more efficient than trial-and-error methods.[20] Another example of a hybrid career was that of the physicist Hermann von Helmholtz, the inventor of the ophthalmoscope in 1851. Helmholtz possessed the necessary knowledge of both physics and physiology to complete this invention.

It would be a mistake to suppose that all new technology during the second Industrial Revolution required or could rest on broad epistemic bases. The complex relationship between propositional and prescriptive knowledge is illustrated by the profound difference between two path- breaking inventions of the period: aspirin (discovered in 1897) and electric generators (perfected between 1865 and 1880). Aspirin had a very narrow epistemic base. In 1763 a British clergyman, the Rev. Edmund Stone, drew attention to willow bark, which, he thought, would serve as a remedy against ague (malaria) because willows grew in damp places and God planted cures where diseases originated (Porter, 1997, p. 270). Not much was done with this “insight” until the 1820s, when chemists became once again interested in it. It was recognized that the active ingredient was salicin, and in 1835 Karl Lowig isolated salicylic acid. Although the chemical structure of these substances was known, they had little medical value because of severe side effects. These were eliminated when Felix Hoffman stumbled on the acetyl compound of salicylic acid, later known as aspirin, which was a true wonder drug: effective, without serious negative side effects, and cheap to produce. His employer, Bayer, hit the jackpot. Yet no one knew how and why aspirin did what it did. It was not until the 1970s that aspirin's physiological *modus operandi* became more evident. With this extension of the epistemic base of an existing technique, further adaptations were possible.[21] The epistemic base became wider, thus reducing the number of experiments and making the search a little bit more efficient. There was still a very long way to go. Paul Ehrlich's Salvarsan drug, which provided an effective treatment for syphilis (1910), was known as “Ehrlich's 606” in view of the fact that 605 earlier compounds had been tried and discarded. The same empirical and pragmatic methodology was followed even for the most epochal invention of the early twentieth century, Fritz Haber's ammonia-fixing process: despite a rapid widening of the epistemic base, too little was known about the underlying atomic structures of catalysts to design the optimal ones from first principles. Alwin Mittasch's laboratory at BASF had by 1922 tried no fewer than 4,000 different substances as catalysts (Smil, 2001, p. 96).

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

The pioneers of the telegraph, Cooke and Wheatstone, patented the magneto in 1845. Joule had shown a few years earlier that the magneto converts mechanical energy into electricity (and not, as was believed until then, magnetism into electricity). The crucial implication of this insight was that the huge amount of mechanical power that the steam engines could create by that time was convertible into electrical energy.[24] Although not all the underlying physics had been worked out by 1865, Joule's work suggested how it could be done. A full generation after Faraday, the discovery of the principle of self-excitation in 1866-67 led to the construction of large generators in the early 1870s and eventually to the electrical revolution.[25] Electrical technology, much like organic chemistry, represents a new kind of Acknowledge that emerged in the nineteenth century, and in which the minimum epistemic base is much larger than ever before. Edison, no scientist himself, employed Francis Upton, a mathematical physicist, and Hermann Claudius, who had a Ph.D. in electrical engineering. Yet the *exact* physical processes that underlie the generation of electrical power were not really understood until much later.[26]

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

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

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

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

Where did the new knowledge that drove economic growth after 1850 come from? In a their pioneering study, Fox and Guagnini (1999) emphasize that in the second half of the nineteenth century engineers in many areas began to engage in “research and development” (the term is slightly anachronistic for the nineteenth century) that was less experimental and more directed.

Many advances were made simply because the limitations of the narrow epistemic bases of old technologies were shed and inventors increasingly had access to the propositional knowledge they needed. To be sure, many techniques still rested on very narrow epistemic bases. But in industry after industry, the knowledge base expanded, streamlining and accelerating the rate of technological progress. To return to the question posed in the previous chapters: why did this growth accelerate and accumulate rather than slow down and then fade out to settle in a new and somewhat higher state?

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

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

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

A less well known example of this feedback mechanism, but equally important to economic welfare, is the interaction between the techniques of food-canning and the evolution of bacteriology. The canning of food was invented in 1795, right in the middle of the Industrial Revolution, by a French confectioner named Nicolas Appert. He discovered that when he placed food in champagne bottles, corked them loosely, immersed them in boiling water, and then hammered the corks tight, the food was preserved for extended periods. Neither Appert nor his English emulators who perfected the preservation of food in tin-plated canisters in 1810 knew why and how this technique worked, because the definitive demonstration of the notion that microorganisms were responsible for putrefaction of food was still in the future. It is therefore a typical example of a technique with a narrow epistemic base. The canning of food led to a prolonged scientific debate about what caused food to spoil. In 1864, Frederick Crace Calvert, in a set of lectures given before the Society of Arts in London, maintained that the true sources of putrefaction were “sporules or germs of cryptogamic plants or animals,” using for his experiments cans of preserved food lent to him by Fortnum & Mason (Thorne, 1986, p. 142). The debate was not put to rest until Pasteur's work in the early 1860s. Pasteur knew of Appert's work, and eventually admitted that his work on the preservation of wine was only a new application of Appert's method. Be that as it may, his work on the impossibility of spontaneous generation clearly settled the question of why the technique worked. Only in the 1890s was it demonstrated that air was not the critical factor, because some bacteria did not need it. The epistemic base of food canning became wider, and with it, techniques improved: the optimal temperatures for the preservation of various foods with minimal damage to flavor and texture were worked out by two MIT scientists, Samuel Prescott and William Underwood.[32] The entire story demonstrates neatly how propositional and prescriptive knowledge can enrich each other.

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

Much of the progress in Q occurs through the agency of new research techniques, themselves often relatively minor advances in A,, such as the improvements in lens grinding in the late sixteenth century that led to the telescope, or the development of in vitro culture of micro-organisms (the Petri dish was invented in 1887 by R. J. Petri, an assistant of Koch's). Price feels that such advances in knowledge are “adventitious”(1984a, **p.** 112). Indeed, the widespread use of glass in lenses and instruments in the West was itself something coincidental, a “giant accident,” possibly a by-product of demand for wine and different construction technology (Macfarlane and Martin, 2002). It seems plausible that without access to this rather unique material, the development of propositional knowledge in the West would have taken a different course.

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

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

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

The invention of the modern compound microscope by Joseph J. Lister (father of the famous surgeon) in 1830 serves as another good example. Lister was an amateur optician, whose revolutionary method of grinding lenses greatly improved image resolution by eliminating spherical aberrations.[37] His invention changed microscopy from an amusing diversion to a