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 But do they have historical content?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 serious scientific endeavor and eventually allowed Pasteur, Koch, and their disciples to refute spontaneous generation and to establish the germ theory, a topic I return to below. The germ theory was one of the most revolutionary changes in useful knowledge in human history and mapped into a large number of new techniques in medicine, both preventive and clinical. The speed and intensity of this interaction took place was still slow, but it was accelerating, and by the close of the eighteenth century it had become self-sustaining. In our time, new instrumentation has been an underestimated and unsung hero of advances in useful knowledge (Rosenberg, 1994).

A third way in which technology "fed back" into propositional knowledge was through the rhetoric of technology: techniques are not "true" or "false." Either they work or they do not, and thus they confirm or refute the propositional knowledge that serves as their epistemic base. **Q** -knowledge has varying degrees of tightness, depending on the degree to which the available evidence squares with the rhetorical conventions for acceptance. Laboratory technology transforms conjecture and hypothesis into an accepted fact, ready to go into textbooks and to be utilized by engineers, physicians, or farmers. But a piece of propositional knowledge can be also be tested simply by verifying that the techniques based on it actually work. Wedgwood felt that his experiments in the pottery actually tested the theories of his friend Joseph Priestley, and professional chemists, including Lavoisier, asked him for advice. During the nineteenth century, the general confidence in the **Q** -knowledge generated was reinforced by the undeniable fact that the techniques based on it worked. Thus, once biologists discovered that insects could be the vectors of pathogenic micro- parasites, insect-fighting techniques gained wide acceptance. The success of these techniques in eradicating yellow fever and malaria was the best confirmation of the hypotheses about the transmission mechanisms of the disease and helped earn them wide support.

Had it not been for the cascading interaction between **Q** -knowledge and A-knowledge, the finiteness of the epistemic base would at some point have imposed a binding constraint on the expansion of the book of blueprints, as it had done in the past. Without a widening epistemic base, the continuous development of techniques will eventually run into diminishing returns simply because the natural phenomena can be understood only partially, and arguably only superficially. It is, of course, not easy to say precisely where the point of diminishing returns occurs. Complicating matters is that even when techniques rest on a fixed epistemic base, they can be recombined into compound techniques, and thus technological creativity can continue expanding even when the epistemic base was fixed—provided potential inventors have sufficiently inexpensive access to the catalog of techniques in use. All the same, if the epistemic base does not expand, technological progress will eventually slow down. Once the Q and ***X*** sets are subject to sufficient positive feedback, however, there is no way to predict the economic system's dynamics, and it may well diverge from its original state forever.[38]

That growing access to a common knowledge base was a catalyst in technological progress in the second Industrial Revolution cannot be proven rigorously, but a fair amount of historical evidence can be amassed to support it. An example is the simultaneity of many major inventions. The more a new technique depends on an epistemic base that is in the common domain and accessible to many inventors at low cost, the more likely it is that more than one inventor will hit upon it at about the same time. As useful knowledge became increasingly accessible and universal, it is hardly surprising that many of the inventions of the period were made independently by multiple inventors who beat one another to the patent office door sometimes by a matter of days.[39] Some scholars have suggested that the second Industrial Revolution rested as much on industry-based science as on the more common concept of science-based industry, implying feedback from ***X*** to Q (Konig, 1996).

As already noted, the *kind* of knowledge that was admissible as the basis for techniques and the mechanisms by which propositional knowledge could be verified and tightened also changed after 1830. An important element of the second Industrial Revolution was the growing recognition and admissibility of statistical evidence to establish natural regularities. Although the use of statistics has eighteenth-century origins, the growing legitimacy of statistical data as a source of useful knowledge can be traced back to the work of Adolphe Quetelet, Edwin Chadwick, William Farr, Villerme, and their colleagues in the 1820s and 1830s.[40] After 1815 statistics flourished, statistical societies were founded everywhere, and governments all over the West started to collect more or less orderly statistical censuses and other types of data. This kind of empirical methodology led to important breakthroughs in clinical medicine, such as the doubts regarding the efficacy of bloodletting therapy spearheaded by the statistical research of C. A. Louis and the discoveries that cholera and typhus are transmitted through water (Lilienfeld, 1978; La Berge, 1992). Statistical evidence (“data”) was a new investigative tool that made persuasion possible even if the underlying mechanisms were poorly understood. Natural regularities could be “tightened” by showing that they occurred in the majority of cases, even if there were unexplained outliers and the knowledge was “shallow” in the sense that the mechanisms accounting for the regularities were unknown. This approach led to an expansion of the epistemic base of public health. Villerme, Chadwick, and others showed that poverty was associated with higher morbidity and mortality (Hodgkinson, 1968; Mokyr, 1996). From there it was a natural step to techniques that prevented diseases from breaking out and reduced mortality long before effective cures had been found. Statistics was also used in the study of agriculture and the determinants of productivity, most famously at John Bennet Lawes's experimental farm at Rothamsted.

Beyond that, again, was the further level of interaction and feedback between human knowledge and the institutional environment in which it operates. Had institutional feedback been negative, as it had been before 1750, technological progress would have been short-lived. The economies that were most successful in the second Industrial Revolution were those in which the connections were the most efficient. The institutions that created these bridges are well understood: universities, polytechnic schools, publicly funded research institutes, museums, agricultural research stations, research departments in large financial institutions. Improved access to useful knowledge took many forms: cheap and widely diffused publications disseminated it. Technical subjects penetrated school curricula in every country in the West (although Britain, the leader in the first Industrial Revolution, lost its momentum in the last decades of the Victorian era). All over the Western world, textbooks, professional journals, technical encyclopedias, and engineering manuals appeared in every field and made it easier to “look things up.” The professionalization of experts meant that anyone who needed some piece of useful knowledge could find someone who knew, or who knew who knew. The learned journal first appeared in the 1660s and by the late eighteenth century had become one of the main vehicles by which **Q** -knowledge became accessible, if perhaps through the intermediation of experts who could decode the jargon. Review articles that summarized and abstracted the learned papers began appearing, an obvious example of an access-cost reduction.

The driving force behind progress was not just that more was known, but also that institutions and culture collaborated to create better and cheaper access to the knowledge base. Technology in the nineteenth century co-evolved with the new institutions of industrial capitalism. Institutional evolution in many ways followed its own dynamic. For instance, the repeal of the Bubble Act in 1825 was in large part the result of a power struggle between parties that believed they stood to gain from it (Harris, 2000). The creation of modern management ran into endless difficulties as documented in the late Sidney Pollard's still unsurpassed classic (Pollard, 1965). Yet on balance the feedback from technology to institutions was positive. Rent-seeking and unproductive behavior never disappeared in any human society, but in the years after 1815 in the West they were more and more subjugated by a free-market liberal ideology that provided incentives for entrepreneurial behavior which enhanced efficiency and productivity on a wide front. It is characteristic of competitive industrial capitalism as it emerged in those decades to spend effort and resources on microinventions and to make the new useful knowledge work (Baumol, 2002).

The co-evolution of technological knowledge and institutions during the second Industrial Revolution has been noticed before. Nelson (1994) has pointed to a classic example, namely the growth of the large American business corporation in the closing decades of the nineteenth century, which evolved jointly with the high-throughput technology of mass production and continuous flow. In their pathbreaking book, Fox and Guagnini (1999) have pointed to the growth of practically-minded research laboratories in academic communities, which increasingly cooperated and interacted successfully with industrial establishments to create an evergrowing stream of technological adaptations and microinventions. Many other examples can be cited, such as the miraculous expansion of the British capital market which emerged jointly with the capital-hungry early railroads and the changes in municipal management resulting from the growing realization of the impact of sanitation on public health (Cain and Rotella, 2001). But co-evolution did not always quickly produce the desired results. British engineering found it difficult to train engineers using best- practice Q- knowledge, and the connections between science and engineering remained looser and weaker than elsewhere. In 1870 a panel appointed by the Institute of Civil Engineers concluded that “the education of an Engineer is effected by…a simple course of apprenticeship to a practicing engineer.. .it is not the custom in England to consider *theoretical* knowledge as absolutely essential” (cited by Buchanan, 1985, p. 225). A few individuals, above all William Rankine at Glasgow, argued forcefully for more bridges between theory and practice, but significantly he dropped his membership in the Institute of Civil Engineers. Only in the late nineteenth century did engineering become a respected discipline in British universities.

Elsewhere in Europe, the emergence of universities and technical colleges that combined research and teaching, thus simultaneously increasing the size of Q and reducing access costs, advanced rapidly. An especially good and persuasive example is provided by Murmann (1998), who describes the co-evolution of technology and institutions in the chemical industry in imperial Germany, where the new technology of dyes, explosives, and fertilizers emerged in constant interaction with the growth of research and development facilities, institutes of higher education, and large industrial corporations with a knack for industrial research.[41] Institutions, then, remained a major determinant of access costs. To understand the mapping from **Q** to **A,,** we need to ask who talked to whom and who read what. Yet the German example illustrates that progress in this area was halting and complex; it needs to be treated with caution as a causal factor in explaining systematic differences between nations. The famed *technische Hochschulen,* the German equivalent of the French *polytechniques,* had lower social prestige than the universities and were not allowed to award engineering diplomas and doctorates till 1899. The same is true for the practical, technically oriented *Realschulen* which had lower standing than the more classically inclined *Gymnasien.* Universities conducted a great deal of research, but it goes too far to state that what they did was a *deliberate* application of science to business problems. James (1990, p. Ill) argues that Germany's "staggering supremacy" was not due to scientists looking for applicable results but came about "because her scientists experimented widely without any end in mind and then discovered that they could apply their new information." This seems a little overstated, but all the same we should be cautious in attributing too much intent and directionality in the growth of **Q** -knowledge. Much of it was in part random, and it was the selection process that gave it its technological significance. In that respect, the evolutionary nature of the growth in useful knowledge is reaffirmed.

A Third Industrial Revolution?

The half-century or so that followed the beginning of World War I is odd in at least three respects. First, it was a period of major political and economic upheavals that affected growth and productivity in many of the leading industrial countries, although in different ways. Second, as DeLong (2000) has recently reminded us, notwithstanding these disruptions, the twentieth century was a period of unprecedented growth. Third, much of this growth was technological in origin, yet true macroinventions were scarce in the period between 1914 and 1950 in comparison with the preceding decades. While science and useful knowledge in general kept expanding at an exponential pace, this era actually produced few radical new departures. Instead, a continuous flow of microinventions was the driving force behind much of the economic growth in the period 1914-73. The striking phenomenon here is that it took a very long time for these microinventions to start running into diminishing returns, and their effects on the productivity and thus on the standard of living were pervasive and ubiquitous. The main cause for the persistence and sustainability of technological progress was the widening of the epistemic base of techniques *already in existence* (some of them, admittedly, barely) in 1914, which created continuous opportunities for economic expansion and productivity growth.[42] When that base was narrow, as it was in pharmaceutics and synthetic materials, progress was halting and depended on serendipity. When that base was wider, as it was in mechanical engineering, electricity, and metallurgy, progress was relentless and continuous.

For many years, then, technological progress in the twentieth century followed the trajectories established in the years before 1914. In automobiles, chemicals, energy supply, industrial engineering, food processing, telephony and wireless communications, and synthetic materials, the developments after 1914 should be regarded as primarily *micro-* inventions. Microinventions tend to be the result of directed and well-organized searches for new knowledge, what the twentieth century has increasingly termed R&D.

Perhaps the most important development of the twentieth century is the change in the nature of the process of invention with the emergence of corporate, university, and government-sponsored R&D, what Mowery and Rosenberg (1998) have called the "institutionalization of innovation."[43]Whether individual independent inventors would eventually be made redundant by this development has been the subject of a long and inconclusive debate (Jewkes, Sawers, and Stillerman, 1969). A fair description of what happened in the twentieth century is that technology and the institutions on which it depended continued to co-evolve in the way I described above. In some industries, technological change may well have favored in-house research, particularly in the chemical and automotive industries, where large-scale facilities were all but indispensable. Yet the relation changed as the nature of technology and the environmental parameters changed. The twentieth century was the one century in which both the nature and the speed of technological progress were actively determined by politics. Governments invested in and encouraged research for strategic reasons.[44] Defense accounted for the lion's share of federal R&D in the United States, and the federal government financed a substantial proportion of R&D. In other countries, governments and other coordinating agencies were equally important. Much of the history of technology in the twentieth century can be described as a continuous search for the right "mix" of private and public efforts in R&D. The fundamental dilemma is well known to any economist: the private sector systematically underinvests in R&D because of the appropriability problems in the market for propositional knowledge. Government agencies, in both market and command economies, have done a poor job of picking winners, however, and have only haphazardly contributed to civilian techniques.

Despite the widely held belief that the twentieth century was qualitatively different from anything that came before (DeLong, 2000), much of the technology that deluged consumers with new and improved products and that accounted for unprecedented growth in total factor productivity was around—if in somewhat preliminary form—in 1914. As noted, the number of epochal macroinventions in the 1914-50 period was comparatively small. Nuclear power, of course, would rank at the top of those. It demonstrates that the minimum epistemic base for some technologies had become very extensive. Although quantum mechanics and nuclear physics were without doubt major expansions of the set of propositional knowledge, and the use of nuclear power a true discontinuity, nuclear power did not lead to the usual pattern of diffusion and microinventions. Improvements in the technique continued, but the costs of nuclear fission reactors in its fast breeder or thermal versions never quite became sufficiently low to drive out fossil fuels, and the safety and disposal problems have remained hard to solve.[45] More than any technology since the Industrial Revolution, nuclear power generation has become a target of political opposition (a topic I return to below). Nuclear fusion, which has the potential to produce limitless energy at low prices, has so far failed to become a reality except in hydrogen bombs. One might say that the minimum epistemic base required for handling materials at exceedingly high temperatures was not attained.

Quantum physics was less objectionable, perhaps because it was difficult to understand and its applications were less intrusive, at least at first. Much of the modern information and communication technology is in some way dependent on epistemic bases that belong to quantum physics. Tegmark and Wheeler reckon, perhaps somewhat heroically, that today an "estimated 30 percent of U.S. GNP is based on inventions made possible by quantum mechanics" including all microprocessors, lasers, and magnetic resonance imaging (2001, p. 69).

The other major macroinvention in the first half of the twentieth century was antibiotics (Kingston, 2000). It too followed a rather unusual path, but for quite different reasons. The minimum epistemic base for antibiotics to work was the knowledge that specific bacteria existed and that they caused diseases. Without the germ theory, Alexander Fleming's discovery of penicillin would not have taken place, since he would never have realized that his molds killed bacteria. Yet Fleming's discovery that certain molds were bactericidal and could be deployed in combating infectious disease was famously accidental. Fortune favored the prepared minds of Howard Florey and Ernst Chain, who purified and made possible the mass production of penicillin. Once the knowledge that antibiotics are feasible had been added to propositional knowledge, the development of other antibiotics followed. The epistemic base was still rather narrow: it is fair to say that no one had a very good idea precisely how antibiotics affected the germs they kill. Even the structure of the penicillin molecule was not fully understood until 1949. The way in which substances such as penicillin kill bacteria has been elucidated only in recent years leading to the possibility of replacing side chains of the molecule and thus overcoming bacterial resistance (Nicolaou and Boddy, 2001). Much work in pharmaceutics, even in the twenty-first century, still follows some systematic and computerized "try every bottle on the shelf' algorithm. The difference from other technologies was that antibiotics, much like insecticides, are subject to a negative feedback mechanism (the mutation of living species makes them immune to harmful substances), which after a while weakens their effectiveness. As a result, it is conceivable that the gains in the war against infectious diseases were temporary and that in the end humankind won a battle but not the war.

There were, of course, other major breakthroughs in the post-1914 decades. One thinks, for example, of the jet engine, catalytic cracking, and the emergence of man-made fibers and substances such as nylon. Many of these were, however, improvements upon *existing* techniques rather than totally new techniques.[46] These improvements and extensions (many of them, of course, major) became possible thanks to the continuous widening of the propositional knowledge on which they rested, but also because "modern science" made this knowledge tighter. Experimental and statistical methods to establish natural regularities and "causes" became more sophisticated, and new propositional knowledge, after being subjected to rigorous tests and critiques, when it became consensual, became the basis of searches for new prescriptive knowledge.

Perhaps the most discontinuous breakthroughs in the 1920s came in physiology. One of those was the discovery of insulin in 1922 and its extraction from animal pancreases, which made the treatment of diabetes possible. Another was the growing realization that trace elements (called vitamins in 1920) played a major role in preventing diseases that were recognized as caused by nutritional deficiency. The propositional knowledge about nutrition mapped directly into techniques employed by households in preparing food for their families, as well as by the food industry, which fortified products such as margarine with trace elements to ensure adequate intake.

Much of the progress in the first half of the twentieth century consisted of "hybrid" inventions, which combined components that had been worked out before 1914. The principles of the use of electrical power to run engines, activate vacuum tubes, and heat objects could be combined into radios, dishwashers, vacuum cleaners, fans, and virtually every other household appliance. Other pre-1914 inventions formed the basis of much industrial development until 1950 and beyond. The internal combustion engine and its cousin, the diesel engine—both up and running by 1914— eventually replaced steam as the main source of power.

The story of the chemical industry is a bit more complex (see Arora, Landau, and Rosenberg, 1998). Much of the chemical science underlying the synthetic materials industry was simply not around in 1914. A few synthetics such as celluloid and Bakelite were developed on a very narrow epistemic base.[47] Even so, some true macroinventions predate 1914.[48] Yet the advance of this industry into large-scale manufacturing of mass produced commodities such as nylon and polyester had to await the establishment of its epistemic base by Hermann Staudinger, who discovered the chemical structure of large polymers in the 1920s. The subsequent development of new materials depended crucially on this advance. The boundaries of chemicals expanded enormously in the inter- war years, into synthetic alcohol and fuels, paints, petrochemical organic feed stocks, new pharmaceuticals, and photographic materials (Murmann and Landau, 1998, p. 47). Yet the "golden age" of petrochemicals started only in 1945. The same dynamic holds for aerodynamics, where the epistemic base kept expanding as a response to technical successes, but which served as a further input into their design. The Wright brothers flew in 1903, a year before Ludwig Prandtl, the great theorist of aerodynamics, became a professor in Gottingen.[49] Only in 1918 did Prandtl publish his magisterial work on how wings could be scientifically rather than empirically designed and the lift and drag precisely calculated (Constant, 1980, p. 105; Vincenti, 1990, pp. 120-25). Even after Prandtl, not all advances in airplane design were neatly based on their epistemic base and derived from first principles, and the ancient method of trial and error was still widely used in the search for the best use of flush riveting in holding together the body of the plane or the best way to design landing gear (Vincenti, 1990, pp. 170-99; Vincenti, 2000).[50]

Much of the productivity increase in the twentieth century was the result of the perfection of production techniques and process innovation. Again, the roots of many of these ideas had been around in 1914, but the scale of organization and accuracy of detail continued to grow. These led to a continuous transformation in organizational methods, most obviously in mass production in manufacturing techniques but eventually in services and agriculture as well. For better or for worse, these changes have become known as "the American system of manufacturing" (actually their historical roots were complex), and their dissemination to the rest of the industrialized world was inevitable. It is perhaps a matter of semantics whether we think of these changes as "technological" or "organizational." What matters is that they co-evolved with the ability of the capital goods industry to produce the tools and machinery that made their deployment practical, relying on an ever-growing epistemic base of materials and mechanical engineering.

The modernization of techniques can be broken down into several elements. The first is *routinization,* which made production processes interchangeable. Assembly, welding, painting, and packing all became increasingly similar for different products, a development with obvious implications for the specificity of human capital and skills. Another component was *modularization*, meaning that parts were identical up to a high level of tolerance and thus fully interchangeable. The advantages of modularization had been understood since Christopher Polhem enunciated them in the early eighteenth century, but the precision engineering that made it possible on an almost universal scale required machine tools that became available only in the twentieth century.[51] Modularization was closely related to *standardization*, making all products of a particular type conform to a uniform standard. Standardization, much like modularization, helped not just during the production stage of output but also in the maintenance of durable equipment. Whoever could repair one Model T could repair *any* Model T. It was also essential to mass marketing through catalogs and price lists. Mass production also entailed *acceleration* through continuous flow production. Continuous flow, in which the employer could determine the speed of each worker, could take place in production that involved assembly or disassembly (as in the stockyards), as well as for continuous physical and chemical processes (grain milling, refining).[52] Finally, in some applications there was a trend toward *miniaturization* (space-saving) such as in the design of smaller motors and steadily less clumsy microelectronics culminating in modern nanoelectronics.

Parallel with changes in the organization of production was the growing specialization of labor. Trends in specialization are complex: the routinization of production, as Marx already pointed out, was fundamentally de-skilling, and production employed undifferentiated homogeneous labor to perform simple tasks on machines that were increasingly user-friendly in the sense that they were easy to operate. Yet the division of labor became more and more refined in the twentieth century and led to a myriad of highly specialized occupations and tasks. The advantages of the division of labor and specialization have been commented on ever since Adam Smith wrote *The Wealth of Nations*.

Along with nuclear power and antibiotics, the most spectacular macroinvention of the twentieth century was the semiconductor.[53]Although all three emerged in the 1940s, electronics is the only area in which the continuous feedback between prescriptive and propositional knowledge, as well as recombination with other inventions led to a sustained and continuous growth that to date shows no evidence of slowing down and is believed by many to herald a “new economy.” Helpman and Trajtenberg (1998) have pointed to the semiconductor's unusual properties as an innovation: its ability to recombine with other techniques, its complementarity with downstream innovations, and its consequent pervasiveness in many applications, meriting the term general purpose technology (GPT). There have been few comparable macroinventions since the emergence of electricity in the late nineteenth century. A large cluster of separate inventions emerged, with an unusual propensity to recombine with one another and to create synergistic innovations that vastly exceeded the capabilities of individual components. Around 1955, vacuum tubes were replaced by the junction transistors invented by William B. Shockley a few years earlier.[54] In the 1980s and 1990s, such hybrid machines combined high-speed integrated circuits and then microprocessors with lasers, fiber optics, satellites, software technology, and new breakthroughs in material science and electronics that made high-density RAM storage possible. The so-called ICT (information and communication technology) revolution is not identical to the computer and was not implied by it, and many of the debates on the impact of "the computer" on productivity in the 1990s for that reason miss the point. Mainframe computers in the 1950s and 1960s and even the early personal computer (at first little more than a glorified typewriter and calculator) were not really a revolutionary general purpose technology, their many uses notwithstanding.

It always seems rash and imprudent when historians analyze contemporary events as if they occurred sufficiently long ago to be analyzed with some perspective. But the arguments made above suggest that the cluster of innovations around semiconductors and their applications will be viewed by future historians as a macroinvention; they represent the kind of discontinuity that separates one era from another, much like the two previous Industrial Revolutions. For a true technological watershed to take place, there has to be more than a GPT such as steam power or electricity or chemical engineering (Rosenberg, 1998a). There has to be a profound change in the generation and deployment of knowledge. The significance of the information revolution is not that we can read on a screen things that we previously read in the newspaper or looked up in the library, but that marginal access costs to codified knowledge of every kind have declined dramatically. The hugely improved communications, the decline in storage and access costs to knowledge, may turn out to be a pivotal event.

The significance of ICT is not just its direct impact on productivity but that it is a *knowledge technology and* thus affects every other technique in use precisely because it affects the level of access costs, which, as I argued in chapter 1, is one of the critical properties of Ω. Given the huge dimensions that the set of propositional knowledge attained in the twentieth century (and its continuing exponential growth), ever-increasing specialization and narrow-based expertise are inevitable. The existence of search engines that allow an individual to find some known piece of propositional knowledge at low cost becomes critical, but other technologies to sort and assess the information to prevent overload are becoming essential. Indeed, it must be true that if useful knowledge had grown at the rate it did without changes in the technology of access, diminishing returns would have set in due to the difficulty in information management. After all, there is one immutable fixed factor: the human cranium. Although the flexibility of the human mind is remarkable, it remains true that the segment of total social knowledge that each person possesses is declining proportionally (even if it increases in total terms) over time. Specialization is the only way to deal with the current size of useful knowledge. An increasingly fine division of knowledge requires better and better access relations between people, and between individuals and storage devices. The Internet may seem to be the culmination of this process, but in fact access has been improving for decades in the form of computer-based information such as library catalogs, databases, and online access devices such as Medline. As some—if by no means all—of the people who carry out technological instructions (let alone those who write new ones) need access to more and more useful knowledge, the means by which they can find, access, sort, evaluate, and filter this knowledge is crucial.

That aspect of information technology holds the key to the future of technological creativity in our time. The uniqueness of the late twentieth century is that this body has become vast and depends on access-cost- reducing technology, without which it could never have advanced as fast as it did. The Internet and its "search engines"are but one element of this information revolution. Equally important is the institutional element: the establishment of social conventions of rhetoric and acceptability, coupled with growing professionalization and the formalization of expertise. The resource cost learning something is not the only variable that determines how easy access to knowledge is; there is also the matter of the reliability of the information.

Declining access costs are instrumental in the rapid diffusion of new techniques, not just because they cannot be employed before their existence is known, but also because in many cases each user has idiosyncratic needs and uses and has to adapt the technique to his or her specific conditions. This is surely true for agriculture, but it holds with equal force in the service industries and manufacturing. Someone executing a technique whose instructions were written elsewhere needs a way of answering specific questions that arise while actually implementing the technique, and these questions can often be answered using rapid and cheap communications.

Furthermore, falling access costs have stimulated technological progress through another phenomenon, technological hybrids and recombinations (what one might call technological compounds). If we consider each technique in ***X*** to be a “unit” of analysis, these units can interact with other units to produce entirely new entities. Most modern devices represent such compound bundles of knowledge, often scores or even hundreds of them.[55]

The notion that existing techniques can recombine into new ones is not novel (Weitzman, 1996), but in our framework it has deeper significance. It means that techniques can not only incorporate other techniques whole (which we might call “hybrids”) but also import subsets of their instructions and their epistemic bases and combine these with their own (which would more properly be thought of as a recombination).[56] Hybrids and recombinations are not quite the same: there is a conceptual difference between joining together an internal combustion engine, a propeller, and a glider to make an airplane, and the application of mechanical knowledge underlying bicycle repairs in solving the specific problems that occur in airplane construction.[57] Either way, however, better access to knowledge not only will make it more likely that best-practice techniques are widely employed, but will also generate the emergence of such compound innovations.

But what, exactly, does “better access” mean? Even scientific knowledge in the public domain needs to be found, interpreted by specialists, and reprocessed for use. In recent years, economists have returned to Michael Polanyi's juxtaposition of tacit vs. codified knowledge (Cowan and Foray, 1997). Modern technology may be more codified and is thus more accessible by normal channels. In any event, even in the twenty-first century there is still a great deal of tacit knowledge that cannot be readily acquired from storage devices and can be accessed only by hiring the people who possess it. Nevertheless, modern ICT makes it easier to find the people who possess that tacit knowledge, and hire them, if possible, on an ad hoc basis. Technical consultants and subcontractors with “just-in-time expertise” have become pervasive. One reason, I suggest, is that modern ICT makes it easier to track down where this knowledge can be found (or, one step removed, easier to track down *who knowsvthzxt* this knowledge can be found, and so on).

Modern information technology has also produced new tools for conducting research, and thus an immensely powerful positive feedback effect from prescriptive to propositional knowledge. As I have argued repeatedly, a great deal of knowledge still consists of cataloging phenomena of great underlying complexity rather than coming to grips with their underlying mechanisms. Invention remains a pragmatic and empirical process of informed and systematic experiments, and looking what works. The process of drug discovery, although not as dependent on serendipity and intuition as it was in the age of Hoffman and Ehrlich, still often relies on "brute force" rather than on strategy. Molecular structures of proteins are so complex that the old and crude methods of search-and-see-what- works are still in place, albeit in a highly sophisticated form. Databases on genes, proteins, and their mind-boggling interactions require computer memories measured in petabytes (billions of megabytes). Molecular biology has expanded our knowledge of the natural world, and the modern pharmaceutic R&D based on it may well be called "guided discovery/' but it still represents a streamlined version of a traditional empirical discovery technique. Computers likewise have become indispensable in engineering. In the past, the difficulty of solving differential equations limited the application of theoretical models to engineering. A clever physicist, it has been said, is somebody who can rearrange the parameters of an insoluble equation so that it does not have to be solved. Computer simulation can evade that difficulty and help us see relations in the absence of exact closed- form solutions and may represent the ultimate example of Bacon's "vexing" of nature.[58] In recent years simulation models have been extended to include the effects of chemical compounds on human bodies. It is easy to see how the mutual reinforcement of computers and their epistemic base can produce a virtuous circle that spirals uncontrollably away from its basin of attraction. Such instability is the hallmark of Kuznets's vision of the role of "useful knowledge" in economic growth. Yet it would be as futile to search directly for these effects of ICT on national income statistics as it would be to search for the effects of the *Encyclopedie* on eighteenth-century French economic growth.

Useful Knowledge and Growth

The productivity and growth implications of revolutions in knowledge are at the core of much of the literature in the economics of technological change and productivity measurement. Oddly, however, economistshave not gotten into the "black box" of knowledge evolution in the past (with a few notable exceptions such as F. M. Scherer, Richard Nelson, and Nathan Rosenberg). Instead, total productivity measures generally take technological progress as exogenous. Models of endogenous growth have attempted to open these black boxes, but have just found another black box inside. The analysis of human knowledge as defined here takes a small step toward understanding what is inside this black box. As has been argued by many analysts in the evolutionary epistemology school (e.g., Plotkin, 1993; Wuketits, 1990) as well as by evolutionary psychologists (Nelson and Nelson, 2002), human knowledge can be and needs to be analyzed as part of a larger evolutionary paradigm. This effort was started in economics by Nelson and Winter in 1982, but so far has been little applied to economic history, where its marginal product seems particularly high.

The interaction between propositional and prescriptive knowledge grew stronger in the nineteenth century. It created a positive feedback mechanism that had never existed before, not among the scientists of the Hellenistic world, not among the engineers of Song China, and not even in seventeenth-century Europe. In that sense, Kuznets's insight is fully vindicated. The useful knowledge as it emerged in the decades after 1850 was truly *social* but the “society” in question was international—though not global. Societies that could overcome their own reluctance and the inertia of their institutions could “join the club,” if at considerable cost. Japan and Russia, in very different manners, made that decision.

The economic history of knowledge suggests that an emphasis on aggregate output figures and their analysis in terms of productivity growth may be of limited use in understanding rapid growth over long periods. The full *economic* impact of some of the most significant inventions in the past two centuries would be almost entirely missed in that way. One reason for that has been restated by DeLong (2000). Income and productivity measurement cannot deal very well with the appearance of entirely new products. The Laspeyre index of income measures a basket from some year in the past and asks how much it would cost today; that is, comparing the current standard of living with that at some point in the past asks essentially how much *our* income would have bought then. But the whole point of technological progress is not just that goods can be made more cheaply. If that were all that was going on, such indices would measure progress accurately. In fact, new consumer goods not even dreamed of in an earlier age are making direct welfare comparisons otiose. In that regard we see a progression from the first to the second Industrial Revolution and even more into the twentieth century. The Industrial Revolution in the early nineteenth century created few new consumer goods, and consumption baskets in 1830 were not radically different from those in 1760. This was no longer the case in 1914, and by the end of the century new goods that satisfied needs hitherto unsuspected (Walkman radios, Internet service providers) or needs that simply could not have been satisfied earlier (laser vision-correction surgery) keep emerging at an accelerating pace. Traditional measures underestimate the rate of progress and do so at a rate that grows over time.

Moreover, goods become different, and they improve in ways that are very difficult to quantify.[59] Some aspects are difficult to quantify: reduced wear and tear, ease of repair and maintenance, and improved user- friendliness come to mind.[60] It has also been pointed out repeatedly that increased diversity and choice by themselves represent welfare improvements, and that modern technology makes mass customization possible by allowing customers to “design” their own final product from modular components (Cox and Aim, 1998).

[1]**The discovery of jasper by Josiah Wedgwood was based by experimenting on 10,000 trial pieces. McKendrick assesses that “every conceivable mixture was tried, every possible combination tested” (1973, p. 286). Yet Wedgwood instinctively felt that science would streamline this costly process, and if it were not materialized in his lifetime it would be the wave of the future.**

[2]**The way this came about was best described by the French chemist Claude Berthollet: “we are frequently able to explain the circumstances of an operation [that is, technique], which we owe entirely to blind practice, improved by the trials of many ages; we separate from it everything superfluous; we simplify what is complicated; and we employ analogy in transferring to one process what was useful in another. But there are still a great number of facts which we cannot explain, and which elude all theory. We must**

then content ourselves with detailing the processes of the art; not attempting idle explanations, but waiting till experience throws greater light upon the subject" (Berthollet, 1791).

[3]**John R. Harris (1988) has pointed out that the switch from charcoal to coal-based fuels in the iron industry in the second half of the eighteenth century is believed by some to be the first such transition whereas in fact it was "virtually the last." Industries such as soapboiling, brewing, and glassmaking had switched to coal centuries earlier, and home-heating (the largest use for fuel) had become dependent on coal in medieval times.**

[4]**The famous Portsmouth block-making machines, devised by Henry Maudslay together with Marc Brunei around 1801 to produce wooden gears and pulleys for the British Navy, were automatic, and in their close coordination and fine division of labor resembled a modern mass-production process, in which a labor force of ten workers produced a larger and far more homogeneous output than the traditional technique that had employed more than ten times as many (Cooper, 1984). For an early application of the idea of interchangeability in France's musket-making industry, see Alder (1997). The opus classicus on the role of machine tools in the emergence of precision engineering is Rosenberg (1976). The continuous-flow process of the early mechanical spinning mills is emphasized by Chapman (1974).**

[5]**Neilson's breakthrough, which reduced the fuel consumption of blast furnaces by two- thirds, 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 (Clow and Clow, 1952, p. 354).**

[6]**Mowery and Rosenberg (1989, p. 22) maintain that if one had to choose any fifteen-year period on the basis of the density of scientific breakthroughs, it would be hard to beat the decade and a half after 1859.**

[7]**The first "research lab" is traditionally dated to 1868, when Heinrich Caro founded such a facility at BASF in Ludwigshafen.**

[8]**A more detailed survey can be found in Mokyr (1999), available in English on the website http://www.faculty.econ.northwestern.edu/faculty/mokyr/.**

[9]**This example is also used by Arora and Gambardella (1994).**

[10]**Bessemer's later life demonstrates the hazards of inventing with a narrow epistemic base. He lost a large amount of money in building the Bessemer steamship, which would have built-in stabilizers around its saloon to prevent seasickness, from which he suffered severely, and with which he became obsessed.**

[11]**Sorby's work is a classic example of the expansion of the epistemic base of existing technology: he discovered how the known properties of iron and steel were caused by the crystal structures of the metal which changed under high temperatures (C. S. Smith, 1960, pp. 181-84). Yet the economically most important advance in applied metallurgy after the breakthroughs of Bessemer and Siemens Martin around 1860 was the development of the Gilchrist-Thomas process in 1878 to remove phosphorus from the**

materials used to make Bessemer steel. Its inventor, Sidney Thomas, was an amateur chemist who was inspired by a course in chemistry at Birkbeck College, where he had heard a lecturer say that whoever eliminated phosphorus from the Bessemer process would make a fortune (Carr and Taplin, 1962, p. 98).

[12]**An interesting example of an invention supported by a narrow epistemic base was the Stirling air engine, patented in 1816 by a Scottish clergyman, Robert Stirling. In principle the machine could be optimized thermodynamically, since it uses a closed regenerative cycle-though that principle was not fully grasped till the middle of the nineteenth century. The Stirling engine is still believed to be a piece of dormant useful knowledge that might be resuscitated under the right circumstances. See for instance http://www.sesusa.org/.**

[13]**As late as 1878, Robert Thurston could write of Pambour's book "The work is far too abstruse for the general reader, and is even difficult reading for many accomplished engineers. It is excellent beyond praise, however, as a treatise on the thermodynamics of heat engines" (1878, ch. VII).**

[14]**Sadi Carnot, Reflexions sur la puissance motrice du feu ([1824], 1986). In his introduction, Robert Fox points out that French technology was widely regarded to be behind British in all matters of power engineering, yet French engineering was distinctly more theoretical than British; and a flurry of interest in the theory of heat engines. It is interesting to note that Carnot's now famous book was wholly ignored in France and found its way second-hand and through translation into England, where there was considerably more interest in his work by the builders of gigantic steam engines such as William Fairbairn in Manchester and Robert Napier in Glasgow (Crosbie Smith, 1990, p. 329). Carnot's work was incomplete and initially contained little of help to engineers, but it was rediscovered by William Thomson (Lord Kelvin) in the 1840s.**

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

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

[17]**Rankine did more than anyone in his time to bridge the gap between science and engineering by writing four textbooks that made the findings of the new science available to engineers. His Manual of Applied Mechanics went through twenty-one editions**

between 1858 and 1921, and the Manual of the Steam Engine through seventeen editions between 1859 and 1908 (Caidwell, 1994, pp. 335, 529).

[18]**Otto vehemently denied having any knowledge of Beau de Rochas's work, and given its limited diffusion, most scholars find that claim plausible (L. Bryant, 1967, p. 656).**

[19]**Of the 17,700 kilometers of cable laid before 1861, only 4,800 kilometers were operational in that year—the rest were lost. The transatlantic cable, through which Queen Victoria and President James Buchanan famously exchanged messages in August 1858, ceased to work three months later. It was this failure that stimulated Kelvin to take up the problem of telegraphy, a good example of feedback from technology into the growth of Q-knowledge.**

[20]**After the success of the transatlantic cable in 1866, Kelvin pointed out that "abstract science has tended very much to accelerate the results, and to give the world the benefits of those results earlier than it could have had them if left…to try for them by repeated efforts and repeated failures" (cited by Smith and Wise, 1989, p. 683).**

[21]**The pathbreaking work was carried out by John Vane, Bengt Samuelsson, and Sune Bergstrom, who showed how aspirin inhibited the formation of prostaglandins. Following this insight, other analgesics and anti-inflammatory drugs such as acetaminophen and ibuprofen were developed (see Landau, Achilladelis, and Scriabine, 1999, pp. 246-51).**

[22]**The first working dynamo was constructed a year later by Hippolyte Pixii in Paris. Faraday himself oddly lost interest in the mechanical production of electricity soon thereafter.**

[23]**The physicist James Joule, who made seminal contributions to the underlying theory of energy, eventually lost his faith in the ability of electricity to fulfill its promise (Morus, 1998, p. 190).**

[24]**Oddly, few physicists understood what Joule argued or took the trouble to try, given that he was a professional brewer and an amateur scientist. Fortunately, young William Thomson was one of the few who realized its importance; he collaborated with Joule for many years.**

[25]**The self-excited electric generator was a case of simultaneous, independent invention by Werner von Siemens, Charles Wheatstone, C. F. Varley, and others. The first working generators were constructed in the early 1870s by Z. W. Gramme.**

[26]**The epistemic base of the Voltaic cell remained untight, as scientists were divided between chemical and anti-chemical ("contact") theories of what made the battery work (Kragh, 2000). Nelson and Rosenberg point out that Edison observed the flow of current across a gap between the hot filament and the wire in his lamp, without of course realizing that he was observing the motion of electrons—the existence of which was to be postulated twenty years later (1993, pp. 7-8).**

[27]**There were also serious costs associated with traditional methods of nitrogen fixing and preservation: the use of manure and nightsoil as fertilizer led to serious incidence of parasitic diseases, and some of the pulses grown to replace nitrogen were low-yielding**

and required extensive preparation and cooking before they could be eaten (Smil, 2001, pp. 36-37).

[28]**Alexander Gordon, a Scottish physician, had noted as early 1795 that puerperal fever might be connected to contaminated matter transmitted by physicians or midwives, and recommended the cleansing of hands. Holmes's 1843 paper cited Gordon's work.**

[29]**The story of Lister's discovery is well known: he heard of Pasteur's discovery by chance and was, in fact, not the first English doctor to note its significance. Pasteur's papers were read by a professor of chemistry, Thomas Anderson, a colleague of Lister's in Glasgow who brought them to his attention. He immediately realized that Pasteur's work provided a theoretical justification for his belief that treatment with carbolic acid reduced the chances of infection (Nuland, 1988, pp. 363-64). Lister's own techniques became quickly obsolete when antiseptic methods were replaced by asepsis, boiling and autoclaving instruments before their use. Yet these further improvements were made possible precisely because the epistemic base, by then, was wide enough.**

[30]**See especially Rosenberg (1982). At times, of course, engineering knowledge develops within the practice itself, and the practitioners who have gained knowledge from experience enrich those who try to enlarge the epistemic base by recounting what works "on the ground." For an interesting example of such a reverse flow of knowledge, see Konig (1996).**

[31]**Norton Wise (1988) rephrases Rosenberg's idea by formulating the concept of "mediating machines." The steam engine and the telegraph in different ways helped Kelvin to formulate his research program in investigating thermodynamics and electromagnetic theory.**

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

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

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

[35]**Davis notes that the "laws of stratigraphy as established by Smith had a universal application and his methods in this science are practiced today by coal and oil field geologists" (1942-43, p. 93).**

[36]**More often than not, these institutions were provincial specialized societies such as**

the Newcastle Literary and Philosophical Society (founded in 1793), dedicated to mining technology and geology (its name notwithstanding) (see Porter, 1973).

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

[38]**As evolutionary theorists such as Geerat Vermeij (1994) and system analysts such as Stuart Kauffman (1995) have pointed out, dual systems that interact in such a way can reach a critical point, at which they become dynamically unstable and start to diverge from an equilibrium.**

[39]**The phenomenon of independent simultaneous invention has often been interpreted as supporting the effect of demand conditions on the search for innovation, but obviously the ability of inventors to draw on similar bases in propositional knowledge provides a complementary explanation. Thus Frank Whittle developed the original jet engine based on knowledge of aerodynamics principles and new material science (which mapped into the making of alloys capable of withstanding very high temperatures). In parallel to the British team, Germans such as Hans von Ohain and Max Hahn came up with more or less the same mapping from the same body of knowledge. See Merton (1961) for a survey of the duplication-of-invention literature.**

[40]**For some insights in the emergence of the statistical method in post-1830 Europe, see especially Porter (1986) and Cullen (1975).**

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

[42]**Consider the following quote from a recent newspaper essay on the "new economy": "The computer, of course, is at its heart—but not as a miracle machine spinning a golden future comparable to the industrial leap forward that came in the late 19th and early 20th centuries. Then, the electric motor, the light bulb, the internal combustion engine, petroleum, natural gas and numerous new chemicals all came on the scene —rearranging the economy and making it vastly more productive. The electric motor alone made possible the factory assembly line and mass production." Note that no such "industrial leap" is identified for the post-1914 period (see Louis Uchitelle, "In a Productivity Surge, No Proof of a 'New Economy,"' New York Times, October 8, 2000).**

[43]**Here, too, there were clear-cut nineteenth century roots. The great German dye manufacturers and large U.S. corporations such as General Electric and Alcoa established the corporate research laboratory and the university as the prime loci where the technological frontier was pushed out, but the spread of this idea to the rest of the economy was slow and gradual.**

[44]**Mowery and Rosenberg (1998, p. 28) note the irony in the post-1945 view that the great research projects of World War II (the Manhattan Project, antibiotics, and synthetic rubber) demonstrated the capabilities of "Big R&D&" to enhance social**

welfare.

[45]The other great breakthrough of the last quarter of the twentieth century, biotechnology, has encountered similar problems, but for different reasons. Although the breakthroughs in this area may be as momentous as any technological advance since 1750, the genetic modification of crops, to say nothing of cloning, so far has not been able to gain the trust of large segments of the population.

[46]The definition of a macroinvention does not exclude the possibility that the ultimate form the technique takes results from a number of discontinuous complementary breakthroughs. The best example is the steam engine, which arguably was not complete until the reciprocal (double- acting) cylinder and the separate condenser were added by Watt. It seems a matter of preference whether one thinks of the jet engine and plastics in the same way.

[47]Bakelite was patented in 1909 and manufactured on a commercial scale from 1910 on, but its chemical formula was not even established until 20 years later. Rosenberg also points out that pilot plants were necessary simply because no body of scientific knowledge could answer the necessary questions (1998b, p. 212).

[48]Of those, the technique to fix ammonia from the atmosphere perfected by Fritz Haber and his associates in 1909 must count as one of most momentous in modern history. Vaclav Smil (2001, p. xv) estimates that without the Haber-Bosch process, two fifths of the world's population might not have been around. Such counterfactuals are always somewhat hazardous without specifying the exact historical “rewrite,” but there can be no doubt that nitrates were the critical ingredient in both the fertilizer and the explosives industries and its fixation from the atmosphere had far-reaching consequences not only for agriculture but also for the prolongation of World War I. Thermal cracking, which separates the long-chain hydrocarbons of petroleum into smaller but more important ones such as gasoline, was first employed commercially in 1913 by Standard Oil researcher William Burton. Catalytic cracking was developed by Eugene Houdry in the 1920s and speeded up the process considerably.

[49]Much of the knowledge in aeronautics in the early days was experimental rather than theoretical, such as attempts to tabulate coefficients of lift and drag for each wing shape at each angle. The fundamentals were laid out by George Cayley in the early nineteenth century. The Wright brothers relied on the published work (especially of Otto Lilienthal) at the time to work out their own formulas, but they also ended up working closely with the leading aeronautical engineer of the time, Octave Chanute, who supplied them with advice right up to their pioneering flight at Kitty Hawk in 1903 (Crouch, 1989). It is clear, however, that the Wright brothers were avid consumers of engineering science and that their greatness lay in the mapping function. It might be added that the Q set they worked from was quite untight: in 1901 the astronomer and mathematician Simon Newcomb (the first American since Benjamin Franklin to be elected to the Institute of France) opined that flight carrying anything more than “an insect” would be impossible. He was joined in that verdict by the Navy's chief engineer, Admiral George Melville

(Kelly, 1943, pp. 116-17; Crouch, 1989, p. 137). Nor were the inventors themselves all that certain: in a widely quoted remark, Wilbur Wright in a despondent mood remarked to his brother that "not within a thousand years would men ever fly" (Kelly, 1943, p. 72).

[50]**The hardening process of aluminum, in which the metal hardens slowly over the week following heating and quenching, was discovered accidentally by Alfred Wilm in 1909 and eventually led to the use of aluminum in all aircraft construction. Metallurgists had a difficult time explaining the phenomenon of age hardening, and it took years until even a partial epistemic base had been uncovered (Alexander, 1978, p. 439).**

[51]**Hounshell notes that by 1913, when Ford initiated his line assembly techniques, the machine industry was capable—perhaps for the first time—of manufacturing machines that could turn out large amounts of consistently accurate work (1984, pp. 232-33).**

[52]**Von Tunzelmann (1995), who stresses the importance of time-saving technological changes, has identified at least four components of the speed of production: higher speed of operation, less down-time due to more reliable and easy-to-repair equipment, faster interprocess coordination, and faster intraprocess coordination.**

[53]**There are many excellent histories of the computer despite their obvious built-in obsolescence (see, for instance, Campbell-Kelly and Aspray, 1996).**

[54]**The transistor is a good example of the concepts employed here, as already noted in a classic paper by Nelson (1996). The epistemic base consisted of the natural regularity of the behavior of silicons as semiconducting materials, and the work of A. H. Wilson explained this in terms of quantum mechanics in 1931. Much of the theory, however, was not fully understood until Shockley wrote his 1949 book in which he showed how and why the junction transistor would work. As Nelson remarks, "the theory was the invention" (p. 170).**

[55]**The degree to which technology is "recombinant" can be approximated, however imperfectly, by citations to other patents and scientific literature in patent applications. Considerable research has gone into the topic of patent citations, and recent work shows that a fair number of citations refer to other patents that are not closely related. Unfortunately this information had to be attained from an ex post survey of the patentees, and thus the inference is from a small sample and for 1993 only. It is striking, however, that on a rank from 1 (unrelated) to 5 (closely related), 44 percent of the citations did not rank above 2. The data pertain to 1993 patents and therefore predate the Internet (see Jaffe, Trajtenberg, and Fogarty, 2000).**

[56]**Just as we can define "general purpose technology" as techniques that can readily hybridize with others (electric power being an obvious example), we can think of "general purpose knowledge" mapping into a large number of techniques and allowing them to recombine. I am indebted for this point to Richard G. Lipsey.**

[57]**Many techniques are particularly amenable to recombination. Historically in the West, watchmaking is probably the best example as a set of techniques with considerable spillovers of this kind. Watchmaking knowledge found its way into instruments and fine machinery of all kinds and some watchmakers made important inventions. The best-**

known inventors trained as clockmakers were Benjamin Huntsman, the originator of the crucible steel technique, and John Kay (not to be confused with the inventor of the flying shuttle of the same name), who helped Arkwright develop the water frame. Gunmaking played a somewhat similar role, such as when John Wilkinson's boring machines helped Watt build his cylinders. In a modern context, Nelson has pointed to the theory on which semiconductors were based as the source of better thermoelectric devices and the Bell solar battery (1996, p. 171).

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

[59]**DeLong (2000, p. 7) chooses a particularly felicitous example. In 1895 a copy of the *Encyclopedia Britannica* cost US $35, whereas today a print version costs $1,250, about one quarter in terms of labor costs. But a different good, the *Encyclopedia Britannica* on CD-ROM today costs only $50.00. How are we to compare the two? Assuming that in both cases the content reflects an equally exhaustive and reliable picture of the world, the CD-ROM has some major advantages besides cost: it is easier to store, and access to information is a bit faster and more convenient. It also includes more powerful imagery (through video clips) and audio. In short, readers in 1895 with a fast computer would have in all likelihood preferred the CD-ROM version.**

[60]**This point is insufficiently stressed in WilliamNordhaus's (1997) otherwise pathbreaking paper on the real cost of lighting and strengthens his conclusion that the gains to consumers are understated by standard measures. The true benefit from switching from candles or oil lamps to electric light was not just that electric light was cheaper, lumen per lumen. It is also that electric light was easier to switch on and off, minimized fire hazard, reduced flickering, did not create an offensive smell and smoke, and was easier to direct.**