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 But do they have historical content?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