THE LEVER OF RICHES

Technological Creativity and Economic Progress

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CHAPTER TEN

The Industrial Revolution: Britain and Europe

As we have seen, after 1750 the Industrial Revolution was initially concentrated primarily in Britain. Explaining Britain’s headstart on its Continental neighbors has been a popular pastime among economic historians for many decades now, though a consensus has failed to emerge. In some global sense, the question may seem relatively unimportant compared to the much larger question of why such a deep gap opened between Europe and most of the rest of the world in the same period. Nevertheless, the variance within the West, the “successful” part of’ the world, remains puzzling as well. The difficulty is that during the British Industrial Revolution there were changes in many aspects of the economy that were not technological in nature, and it is impossible to disentangle demographic change, urbanization, enclosures, wars, social and commercial policy, and so on from technological changes and then compare the outcome with what happened on the Continent. In what follows, I shall confine myself to the questions of why Britain managed, for about a century, to generate and diffuse superior production techniques at a faster rate than the Continent, and serve as a model that all European nations wished to emulate and how and why it eventually lost its leadership in technology.

Technological success depended on both the presence of positive elements and on the absence of’ negative ones. Among the positive factors, the generation of technological ideas and the ability to implement them seem a natural enough point from which to start. The generation of’ ideas, as we have seen, was often an international effort. The British, to be sure, were prominent in providing technologically revolutionary ideas: there can hardly be any question that most of the truly crucial inventions in the period were made by Britons. Yet Britain’s relative role in invention was smaller than its corresponding role in implementation. Many important inventions that can be attributed to Continental inventors found their successful implementation in Britain. Such names as Berthollet, Leblanc, de Vaucanson, Robert, Appert, de Girard, Jacquard, Argand, LeBon, Heilmann, and Fourneyron deserve it place in the Inventors' Hall of Fame next to Newcomen, Arkwright, Watt, Cort, and their colleagues. In the eighteenth century, Britain did not have much of a reputation for being particularly original or inventive. Daniel Defoe remarked in 1728 that the English perfected other people's ideas. A Swiss calico printer, jean Ryhiner, wrote in a treatise on his trade in 1766 that "[the English] cannot boast of many inventions but only of having perfected the inventions of others … for a thing to be perfect it must be invented in France and worked out in England" (cited by Wadsworth and Mann, 1931, p. 413). Much later, in 1829, John Farey, an engineer, told a Parliamentary committee that "the prevailing talent of English and Scotch people is to apply new ideas to use and to bring such applications to perfection, but they do not imagine as much as foreigners" (cited in Musson, 1975b, p. 81). Invention was not equivalent to technological change. More was needed.

One crucial difference between Britain and the Continent that helped Britain to establish its head start was its endowment of skilled labor at the onset of the Industrial Revolution. In his Industry and Trade, Alfred Marshall (1919, pp. 62-63) observed that the Englishman had access to a great variety of highly skilled artisans, with a growing stock of tools capable of work more exact than the work of the human hand. "Thus every experiment cost him less, and was executed more quickly … than it could have been anywhere else. When at last success had been fully achieved, the new contrivance could be manufactured more cheaply and … applied in production on a scale far greater than in any other country." In other words, by the middle of the eighteenth century, Britain had at its disposal a large number of' technicians and craftsmen who could carry out the mundane but indispensable construction details of the "new contrivances." These skills rested on an informal and antiquated system of apprenticeship and on-the-job training; they had little to do with schooling. If England led the rest of the world in the Industrial Revolution, it was despite, not because of her formal education sys- tern. In this, Scotland was different, as its schools were far superior to England's. In England the dissemination of technical knowledge took place through informal lectures, scientific societies, and technical literature.

Britain had been fortunate. In the late seventeenth century it had taken the lead in clock- and watchmaking. France, its closest com- pe(itor, had been "crippled by the exodus of some of' its best practitioners fleeing it wave of' anti-Protestant bigotry" (Landes, 1983, p. 219). By contrast, Britain welcomed men of technical ability whatever their religious persuasions. The mechanical skills of clockmakers became one of the cornerstones of the new industrial tech- nology.s Another industry that produced skilled artisans was the shipping sector, with its demand for accurate and well-made instruments. British shipping grew enormously in the eighteenth century, and naval instruments were a chief output of men such as Harrison, Smeaton, and Ramsden. A third industry that helped to prepare the skills and dexterity necessary for the Industrial Revolution was mining. Pumps and transport equipment were crucial to mining, and both the steam engine and the iron rail were built first for use in the mines. By the end of the seventeenth (entury, British mining and metallurgical technology was still "between it hunched and it hundred and fifty years behind the best-practice techniques of the Continent" (Hollister-Short, 1976, p. 160). By 1760, it was at the forefront of Europe in these areas, giving it it technological advantage that has been fully recognized by historians only recently.; The net result of Britain's tradition in high-tech industry was that it could rely on engineers such as Wilkinson, New(omen, and Smeaton to help build and improve machines conceived by others.' Other countries, of course, had some engineers of distinction. But most of' these, such as the Swede Christopher Polhent, the Austrian Joseph Karl bell, and the Frenchman .Jacques de Vaucanson, were relatively isolated.' In Britain, the number of' engineers and mechanics was sufficiently large to allow interaction with each other, through lecturing, spying, copying, and improving. The famed Manchester Literary and Philosophical Society and the Birmingham Lunar Society were but two of the many mechanisms via which technical ideas and information were exchanged in Britain. Interaction among engineers, scientists, and businessmen created a total that was larger than the sum of its individual components. Technological change and the creation of new information are processes that do not obey the laws of arithmetic.

Britain did not have a significant scientific advantage that would explain its technological leadership. In view of the modest role that scientific progress played in technological progress, this observation is hardly surprising. One historian of science (Kuhn, 1977, p. 143) has even gone so far as to describe Britain as "generally backward" in the century around the Industrial Revolution, and concludes that science must have been unimportant in the technological changes of the time. Such a view, as we have seen, is somewhat oversimplified. Perhaps a better way to approach the role of science in explaining British leadership is to recognize that Britain did not necessarily have "more" science than other countries, but it did have a different kind of science. As Kuhn notes, the traditional view that British science was predominantly experimental and mechanical, whereas French science was largely mathematical and deductive seems to have withstood the test of time (ibid., p. 137). In the early stages of the Industrial Revolution, there was an advantage in having a science that was applied and down-to-earth, and a scientific community that maintained close ties with engineers and manufacturers. In Britain, as Jacob (1988) has recently stressed, scientists were not in opposition to the political status quo, nor its servants. Unlike the Continent, where scientists and philosopher either worked against the political establishment or were employed by it, British scientists and engineers worked together with commercially minded persons, who were more interested in money than in matters political or military. In this respect, Britain's advantage seems self-evident. Yet such an advantage was inevitably ephemeral, as the natural principles on which British technology rested were being uncovered during the nineteenth century. Indeed, Cyril Stanley Smith (1981, p. 36) has suggested that the successes of Britain in metallurgical technology (which had little to do with scientific insights) forced Continental countries to try to discover the science behind the practice in order to beat Britain eventually at her own game.

The formation of human capital in Britain before and during the Industrial Revolution depended on a rather unique social environment. By 1750, Britain already had a “middle class” of sorts, that is, people who were literate and well fed, and came from commercial or artisanal backgrounds. This class supplied most of’ the founders of large industrial undertakings in Britain (Crouzet, 1985), and there is no doubt that most of the creative technical minds also came largely from this class. The supply of creativity was channeled into industrial activities, in large part because of’ the lack of alternatives. Government and military services careers were closed to nonconformists, as they were, for all practical purposes, to anyone not born into a wealthy British family. Members of Parliament and army officers had to buy into their offices and maintain expensive lifestyles. The professional civil service was small, and the imperial bureaucracy was still embryonic in 1800. Moreover, by being exclusive it forced talented men born below it to search for the only key that could open the doors of politics, public schools, and landed estates: money. As far as the social elite is concerned, the landowning elite, which controlled political power before 1850, contributed little to the Industrial Revolution in terms of technology or entrepreneurship. It (lid not, however, resist it.

One development that may help explain the timing and location of’ the Industrial Revolution concerns the attitudes of the educated and literate elite toward technological change. MacLeod (1988, ch. 11) has recently argued that there was no linear progression from the Baconian notion of’ technological progress as a means of increasing wealth to the Industrial Revolution. In the late seventeenth century, in her view, attitudes toward inventions regressed, becoming more abstract and detached, and a concern for unemployment coupled with a sense of’ British inferiority emerges from the writings of economists and philosophers. Technological progress plays a much more modest role in the writings of’ Hume and Smith than it did in those of Bacon and Boyle. By 1776, however, the tide was turning again, and Smith’s lack of enthusiasm for inventions was exceptional for his time. MacLeod interprets her evidence to mean that writers were influenced by the success of technology and the need to protect it against its detractors and enemies. The relationship was, however, more complex. Values and attitudes toward invention could and did differ greatly across time and space, as we have seen repeatedly. The causal chain ran as much from attitudes to achievements as it did in the opposite direction. Margaret Jacob (1988) has explicitly argued for this mechanism, namely that the Baconian ideas of progress were increasingly accepted by the British educated elite and constituted an essential precondition for the success of' the Industrial Revolution. Moreover, she shows how other countries lagged behind in accepting these notions, thus providing a plausible explanation of British pre-eminence.

Yet advantages in human capital are fragile. With some exceptions, Britain's early inventors tended to be "tinkerers" without much formal technical schooling, whose genius lay primarily in their mechanical ingenuity. As it happened, most of the devices invented between 1750 and 1830 tended to be a type in which mechanically talented amateurs could excel. In many cases British inventors appear simply to have been lucky, although, as Pasteur once remarked, Fortune favors the prepared mind. The cotton, iron, and machine tool industries during the Industrial Revolution lent themselves to technological advances that did not require much scientific understanding of the physical processes involved. When, after 1850, deeper scientific analysis was needed, German and French inventors gradually took the lead, and the breakthroughs in chemistry and material science tended to be more concentrated on the Continent. Bessemer, Perkin, and Gilchrist-Thomas notwithstanding, the "amateur" stage in the history of technology was coming to an end by 1850. But Britain rode the wave high while it lasted.'

Another factor in Britain's head start in technology at the beginning of the Industrial Revolution was that Britain alone among the large European economies constituted a comparatively unified market in which goods and people moved easily. Compared to the European Continent, Britain had excellent internal transportation. Coastal shipping, canals, and roads provided it with a network unequalled by any Continental nation, with the possible exception of the Netherlands. Transport in Britain was itself becoming a specialists' occupation, run by professionals who increased efficiency, speed, and reliability (Szostak, 1986). Moreover, Britain was politically unified and cohesive. No tolls were charged on rivers and no tariffs were levied when crossing man-made lines (unlike France, for example, where before the Revolution internal tariffs were levied on goods moving within the country). As the technology of building roads and canals improved in the eighteenth century, Britain became an integrated market system.

Why did market integration matter to technological progress? Market size affected both the generation and the diffusion of new knowledge. In 1769, Matthew Bonbon wrote to his partner,]allies Watt, "It is not worth my while to manufacture [your engine] for three counties only; but I find it very well worth my while to make it for all the world" (cited by Scherer 1984, p. 13). Some minimum level of demand was necessary to cover the fixed costs of development and construction. In very small and segmented markets insufficient demand may have impeded the diffusion of certain innovations that involved fixed costs. "I he whole world" was perhaps an exaggeration; in the eighteenth century the British market was large enough to cover the costs of invention. Adam Smith, too, thought that market size and integration were crucial. Smith regarded technological progress as a consequence of specialization. Specialization depended on the division of labor and thus on the extent of the market. If workers concentrate every day on a particular task, they are much more likely to find "easier and readier methods of' performing their own particular work." As evidence, Smith argued that "a great part of' the machines made use of' in those manufactures in which labour is most subdivided were originally the inventions of common workmen."7 The Master's authority notwithstanding, it is far from obvious that a fine division of labor and a high degree of intrafirm specialization are conducive to learning by doing or to the generation of new techniques.'

Market integration has a more profound effect on the diffusion of new techniques. In a world of high production costs, inefficient and conservative producers are insulated from their more innovative competitors. A world of high transport costs is described by an economic model of' monopolistic competition. One of' the characteristics of such a model is that innovator and laggard can coexist side by side. In the region served by the innovator, lower production costs due to technological change meant a combination of higher profits for producers and lower prices for consumers. Nothing could force the laggards to follow suit, however, and the "survival of the cheapest" model so beloved by economists is short-circuited. High transport costs also made local oligopolies possible. A small number of firms in a market could facilitate conspiracies to stop new techniques, but as the market expanded and the number of firms with access to a given market increased, such "antitechnological cartels" became more difficult to organize and enforce without support from the authorities. In Britain, to a far greater extent than on the Continent, good transportation allowed competition to work, and the new technologies superseded the old sooner and faster than elsewhere. When diffusion lags occurred in Britain, they usually resulted from imperfections in the new techniques, rather than from entrepreneurial incompetence. Coke smelting and power weaving took decades to perfect, for example, but once their superiority was clear, the triumph of' these new techniques in Britain was as assured and swift as the triumphs of the mule and the puddling-and-rolling technique, which were perfected comparatively quickly.

All the same, unified markets and a high degree of commercialization were not sufficient conditions for technological progress. Both Manchu China and Imperial Rome serve as counterexamples. They were commercially. integrated economies in which Smithian growth was a substitute for technological progress. The Netherlands in the eighteenth and nineteenth centuries-the open economy par excellence, with a glorious tradition in shipping, highly developed commercial institutions, and it tradition of free trade-turned out to be singularly uncreative during the Industrial Revolution. It seems that Smithian growth served in many cases as a substitute for technologically driven growth, whereas in other cases it served as a stimulus and handmaiden of technological change. At this stage of knowledge it is not possible to specify the relationship between them more exactly. Nor is the nature of the relationship between competition and innovation clear. The Schumpeterian hypothesis argues that at some point less competition may actually be good for innovation. Although Britain's performance during the Industrial Revolution lends no support for this view, it remains to be seen whether the hypothesis can explain the post-1850 patterns.

Much has been made of the British political system as a cause of the Industrial Revolution. Perhaps the most distinguishing feature of Britain was that its government was one of, by, and for property owners. Economists have maintained that well-defined property rights were necessary to static efficiency. But what about technological change? The direct links between the British government and the rate of technological progress were few. Some scholars (McNeill, 1982) have maintained that government demand for military purposes led to innovation, but such effects were small. More important was the effect of patent laws on inventive activity. North (1981), in particular, argues that patents, which allowed the inventor to capture a larger part of the social benefits of his invention, were as important as a larger market. Here Britain led the Continent by a large margin. British patent law dates from 1624, whereas France did not have a similar law until 1791, and most other European countries established patent laws only in the early nineteenth century. The United States had a rather ineffective patent system from 1790, and the formal Patent Office was established only in 1836.

How decisive was the protection of the inventor's property rights by patents? Economic theory and contemporary empirical research suggest that the effect of a patent system on the rate of technological progress is ambiguous and differs from industry to industry (Kau- fer, 1989). The ex ante positive incentive effects on inventors have to be weighed against the ex post negative effects on the diffusion of new knowledge, which will slow down as a result of an inventor's monopoly. Moreover, technological progress may be hampered by the closing of avenues in the development of new ideas if a particular ingredient has been patented by someone else.`-‘ A monopoly position awarded as compensation for inventions might discourage further activity if it led to increased leisure consumption, or if the profits of additional invention had to be weighed against the possible loss of monopoly profits currently enjoyed (Kamien and Schwartz, 1982, pp. 29-30). Yet patent rights could also lead to further inventions if they were used to finance additional research, a substantial advantage when capital markets were leery of innovators.

Certainly some great inventors had no doubts about the importance of patent protection. James Watt wrote that he feared that “an engineer’s life without patent was not worthwhile,” and Bessemer believed that “the security offered by patent law to persons who expend large sums of money … in pursuing novel invention, results in many new and important improvements in our manufactures.” These statements may have been self-serving, coming from men who lived off patented inventions, and it is easy to find quotations from other major inventors indicating their disappointment with the patent system (Gilfillan, 1935, p. 93). But the very fact that so many inventors chose to patent their inventions in spite of the costs indicates that patents mattered. In countries in which there was no patent system, its absence was sometimes regretted. Goethe wrote that “we [Germans] regard discovery and invention as a splendid personally gained possession … but the clever Englishman transforms it by a patent into real possession … [and] is free to use that which he has discovered until it leads to new discovery and fresh activity. One may well ask why are they in every respect in advance of us?” (cited in Klemm, 1964, p. 173). Patents may also have encouraged entrepreneurs and investors to team up with patentees and supply venture capital; there is some evidence that Matthew Boulton, James Watt’s partner, invested in the project only after he had the certainty of patent protection (Scherer, 1984, p. 24).

The operation of the patent system as an incentive to inventions was far from perfect.”’ Hargreaves’s patent rights were denied by the courts on the technicality that he had sold a few jennies before applying for his patent. Arkwright, after a long and expensive case, lost all his patents in 1785, the same year as Argand. Similarly, Tennant lost his patent on bleaching liquid, though not on bleaching powder, on a technicality. A century later,,J. B. Dunlop, the inventor of the pneumatic tire, was denied a patent on the grounds that the pneumatic principle had appeared before in an obscure patent taken out in 1845, though Dunlop clearly had come up with the idea independently. Despite these setbacks, Arkwright, ‘Pennant, and Dunlop prospered. What this means for the importance of the patent system is ambiguous, however, because both Tennant and Dunlop relied on patents on secondary inventions.

Litigation over patent infringement could sap the creativity of great technical minds, and ruin inventors financially. Among the inventors who were destroyed by patent litigation were the flying shuttle’s inventor john Kay, the engineer Jonathan Hornblower, and Charles Goodyear, the inventor of the rubber vulcanization process. Eli Whitney’s patent wars over the cotton gin led to his arrest by his opponents and almost bankrupted him. In later clays he claimed that the gin actually cost him more in litigation than he earned on it (Hughes, 1986, pp. 133-34). The Foudrinier brothers, who introduced mechanical papermaking into Britain, went bankrupt in 1810 and spent much of the rest of their lives in prolonged and expensive patent litigation. Robinson (1972, p. 137) maintains that British judges were in general unsympathetic to inventors, and that the laws were so ambiguous that the outcome of any patent litigation was unpredictable. Moreover, inventors were caught between two difficult options. On the one hand, the more detailed it patent application, the more likely it was to he approved: the law required that the application be specific enough to allow it third party to reconstruct the device from the application alone. Supplying that many technical details, however, would rule out the use of secrecy as an alternative barrier to entry should the patent be denied. Despite these problems, Robinson’s negative verdict on the patent system in Britain is inconsistent with the fact that between 1770 and 1850 only 257 patent cases came before the courts, out of' 11,962 patents granted (Dutton, 1984, p. 71).

In sonic cases society circumvented the patent system to reward innovators whose private benefits were deemed to be much smaller than the social benefits of' their contribution: special grants from Parliament were awarded to Thomas Lombe, the inventor of the silk-throwing machine, whose patent was denied renewal; to Samuel Crompton, who never took out a patent on his mule; and to Edmund Cartwright, who lost the patent on his power-loom to creditors. The Swede John Ericsson, who made it crucial contribution to the invention of the screw propeller but who could not prove priority, was awarded £4,000 by the admiralty. Henry Cort also lost his patents through a series of financial mishaps and was awarded a small pension, but Richard Trevithick was denied a similar request. In the United States the South Carolina legislature awarded Eli Whitney $50,000 for his invention of the cotton gin. Prerevolutionary France routinely awarded pensions to the inventors of devices deemed socially beneficial and offered prizes for specific projects, such as the attempt to produce synthetic saltpeter between 1775 and 1794 (Mul- thauf, 1971). Between 1740 and 1780 the government paid out 6.8 million livres to inventors in subsidies and interest-free loans. The policy of' encouraging invention may have been inconsistent and sometimes corrupt, but it did provide an incentive similar to a patent system. I t

Despite the imperfections of the patent system, any other form of protection worked even less well. Secrecy was always a possibility, but by the nature of things could only be applied to a limited range of industries. Richard Roberts thought that "no trade secret can be kept secret very long; a quart of ale will do wonders in that way" (cited by Dutton, 1984, pp. 108-111). All the same, it was tried. Benjamin Huntsman was so compulsive about the secrecy of his crucible steel process that for a while he only worked at night. Henry Bessemer decided to keep one of his earlier inventions, bronze powder, secret rather than patent it because he believed that if the details of his system became known he would not be able to maintain the price (MacLeod, 1988, p. 95). If secrecy was an option, the decision to patent presented a particularly hard dilemma because patent application demanded that the inventor divulge all the technical details.

Of particular interest is the phenomenon of collective invention suggested by Allen (1983). When technological progress results from experimentation that is a by-product of investment, when it is difficult to patent, and when it proceeds gradually, it can happen that firms decide to share information freely and build on each other’s results. Such cooperative efforts are hardly the rule, but Allen shows that the British iron-smelting industry conformed to this pattern between 1850 and 1875. Considerable progress was made in the design of the optimal blast furnace by the free sharing of information. Even in the iron industry, of course, what was patentable was patented and what could be protected by secrecy was protected. Collective invention occurred under rather special circumstances; normally firms will not release information that will increase their competitors’ profits. Only when the number of firms engaged in Research and Development is small and free riders can somehow be excluded can firms work out cooperative arrangements and binding reciprocal contracts that permit the sharing of technological information. The information swapped tends to be, as could be expected, the type of information that does not endanger the firm’s relative advantage over its competitors. Cooperation between innovators serves, however, as an important reminder that patents and property rights on new information were not strictly necessary for technological advance (Nelson, 1987, p. 79). Landes (1986, p. 614) claims that a large part, perhaps most, of the productivity increases in factory manufacture was the result of small, unpatentable improvements and concludes that patents were not the major incentive to invention. At this stage of our knowledge, such a claim remains premature. 12

The importance of patenting differed from industry to industry. Overall, patents were more likely to be taken out in mechanical than in chemical inventions, and more in competitive than in concentrated industries. The initial wealth and place of residence of the inventor also played a role. Not all patents were inventions, and not all inventions were patented. MacLeod (1988, p. 145) assesses that that nine out of ten patents arose in industries that saw little innovation. The use of' patent data as an indicator of' technological activity, which has recently become fashionable again among economic historians (Sokoloff, 1988; Sullivan, 1989) should therefore he carried out with extreme caution. Inventions are an example of "fuzzy objects," and are notoriously difficult to count and measure. It remains an open question whether a bad approximation such as patent statistics is better than no approximation at all, and whether an econometric analysis of patents adds anything to our understanding of technological progress.

The verdict on the importance of the patent system in explaining technological creativity is thus decidedly mixed. Given the private and social costs of patenting and patent litigation, and given the many alternatives to patenting, its impact on the technological creativity of societies is far from clear.'-" The patent system may have been a relatively minor factor because of the "free lunch" property of technological progress, that is, because the social benefits of invention often dwarf the development costs. Consequently, it is not necessary for the inventor to capture all, or even most, of the social surplus created by his or her creation; a small fraction may suffice to make the effort worthwhile. A patent system grants the inventor a part of the surplus for a finite time, thus paradoxically encouraging primarily marginal inventions. Of course, if' there are enough such marginal inventions, its effect on economic growth may still have been significant. More importantly, the patent system encourages those inventions whose expected social surplus is low because of a very low ex ante probability of success, that is, it encourages ideas that represent radical departures from accepted practice, which I have termed macroinventzons. It is thus important in generating the occasional spectacular breakthrough, the cases in which a crackpot hits the jackpot. Scherer's conjecture (1980, p. 448) is that such cases are rare. The social costs against which these breakthroughs must be weighed are the wasted hours of work of talented and original minds in search of the pot of gold at the end of the technological rainbow.

Was the patent system a factor in encouraging technological change during the Industrial Revolution? Dutton (1984) has argued that an imperfect patent system, such as the British system, represented the best of all possible worlds. Without patents, inventors would be deprived of their financial incentives. But if patent enforcement had been too perfect, the diffusion of inventions might have been slowed down. The patent system appeared to the inventors as providing more protection than it actually did. Such a gap between ex ante and ex post effectiveness may, indeed, have been beneficial. An economist's intuition would perhaps be that here, too, people cannot be fooled in the very long run. By that logic, however, Atlantic City would have gone out of business long ago. Moreover, invention is not exactly like gambling because by definition no two inventions are the same, and hence the information that a potential inventor can derive from the previous experiences of others is limited. It could thus well be that the patent system fooled would-be inventors into exerting more effort than they would have had they known how stacked the deck was against them. If that was indeed the case, it attained its goal.

Another possible reason technological progress was so much faster in Britain than on the Continent between 1760 and 1830 was that the Industrial Revolution happened to coincide with one of the stormiest episodes in the history of' Europe. If the French Revolution and the subsequent turmoil significantly slowed down technological progress on the Continent, it may be that the small head start that Britain had achieved by the late 1780s became a veritable gap by 1815 merely because of this coincidence. The evidence for such an interpretation is ambiguous. It became more difficult for British technology to cross the Channel during the war years, and after 1806 trade relations between Britain and both its overseas territories and the Continent became hazardous. As Cardwell (1971, p. 150) points out, Britain had the more advanced technology, whereas France was the leading scientific nation. Scientific ideas and literature continued to flow across the Channel, but technology transfer was the victim of the disruption of trade relations between 1793 and 1815. Furthermore, on the Continent in general and in France in particular, political and military matters absorbed the creative energies of talented persons and slowed down progress. Some inventors' careers were disrupted by political events. 14

Yet the French Revolution and Napoleon installed more forwardlooking governments in Europe. In France, applied research was subsidized, prizes were awarded for useful inventions, and schools such as the Ecole Polytechnique (established in 1794) and the Ecole des Arts et Metiers (established at the initiative of Bonaparte in 1804) mobilized technological talent and applied it to current needs, usually determined by the government. Similar institutions were established in Prague (1806), Vienna (1815), Zurich (1855), and Delft in the Netherlands (1863). Mining schools like the one in Leoben, Austria (founded in 1840), represented the same idea. The culmination of this movement was the establishment of the famous German technical universities, the first of which was founded in 1825 in Karlsruhe. Moreover, the enormous disruptions in international commercial relations also bestowed certain advantages on the Continent. For two decades its industries found themselves protected from cheaper British manufactured goods, giving rise to "hothouse" industries, especially in cotton. Despite this temporary relief from British competition, the infant industries on the Continent did not generate anything like the British Industrial Revolution. Some towns, such as Ghent in Belgium and Mulhouse in the French Alsace, did manage to build the beginning of a cotton industry before 1815, but they never attained the momentum of Lancashire. Still, under pressure of the blockades and stimulated by the French imperial government, important original technological breakthroughs did occur on the Continent, among theta the wet flax spinning process, the Jacquard loom, and sugar-beet refining.

Quite apart from political events, there is the matter of" the social environment in which inventors and innovators operated. In France, for instance, very few inventors did well financially or otherwise. The sad fates of Leblanc and Argand have already been mentioned. Robert (the inventor of the continuous paper process), Thimonnier (the inventor of the sewing machine), and Jouffroy (who built the first functional steamboat in 1783) also died penniless. Claude Chappe, the inventor of the semaphore, committed suicide in 1805 because of financial difficulties. Others, such as de Girard and Brunel, evenwally emigrated. An exception was Joseph Marie ,Jacquard, the inventor of the loom that hears his name, who was rewarded by a pension and royalties and became something of a national celebrity. On it more modest scale, Nicolas Appert, the inventor of food preservation, was awarded 12,000 francs by the French Society for the Encouragement of Industry, set up by Napoleon. Of' course, not all British inventors fared as well as Arkwright or Watt, but there were enough success stories in Britain to preserve a constant interest in inventive activity. The Continent seems to have suffered more from a scarcity of' innovative entrepreneurs than from a scarcity of inventors. Manufacturers such as Wedgwood, Crawshay, Boulton, or Strutt, who did not create much new technology but knew a good thing when they saw it and moved rapidly, seem to have been in short supply on the Continent. It is arguable that though Britain may have had an absolute advantage in both inventors and entrepreneurs, it had it comparative advantage in entrepreneurs and skilled workers, and thus imported inventions and inventors and exported entrepreneurs and technicians to the industrializing enclaves of the Conti- nent.Is Before 1860, some of the greatest industrialists on the Continent had names like John Cockerill, Isaac Holden, Samuel Lister, and William Mulvany. The movement of technically skilled and enterprising Britons to the Continent demonstrates not only that a disequilibrium existed in the first half of the nineteenth century, but also that equilibrating forces were at work, spreading technological change from leader to follower. As long as that disequilibrium was maintained, Britain reaped a quasirent derived from a temporary advantage. Hence the prohibition on the enlistment of skilled workers to work abroad (abolished in 1825) and the export prohibition on machinery (abolished in 1843), though neither of these measures was particularly effective. Britain's temporary head start during the Industrial Revolution was not different from other periods in which a European region held a temporary technological advantage over others. Efforts of the leading region's government notwithstanding, technical knowledge spread rapidly across European borders.

How do we explain concentrated clusters of technological successes such as those that comprised the Industrial Revolution? If innovations occurred at random independently of each other, we should expect their time pattern to be distributed more or less uniformly over time. The difference between the Industrial Revolution and previous clusters of technological change was in the extent to which innovations influenced each other. First, there was an imitation effect: James Watt and Richard Arkwright became famous and wealthy men whom many tried to emulate. Invention and improvement became, in some circles at least, respectable. Second, there was a com- plementatity effect: the successful solution of one problem almost invariably suggested the next step, and so chains of inspiration were created. Many of the most useful inventions were indeed not more than radical modifications of earlier ideas: Cort's puddling-androlling process, Watt's and Trevithick's engines, Crompton's mule, all fall under this definition. Neither of these "one-thing-leads-toanother" theories constitutes an explanation of the Industrial Revolution. Both merely explain its time pattern, which is that when agents strongly affect each other, it is likely that success will appear in clusters. Clustering can occur when a critical mass is generated by the continuing interaction and cross-fertilization of inventors, scientists, and entrepreneurs, as Musson and Robinson (1969) have shown. Clustering phenomena are not, of course, confined to technology: Dutch painting in the seventeenth century and Austrian music in the eighteenth- and nineteenth centuries come immediately to mind. Although the emergence of talent may be uniformly distributed over time, its focusing and employment surely are not There were few British artists of much importance between 1770 and 1830. Apart from a cluster of romantic novelists and poets, centerstage was held by engineers, scientists, and political economists.

One avenue that has barely been explored by scholars interested in the question of "why England first" concerns the political economy of technological change. A widespread concern during the Industrial Revolution was that machines would throw people out of work, a misunderstanding that has persisted over the centuries.15 A more legitimate concern was the fear of loss suffered by established firms in industries that were being mechanized. From hand-loom weavers to wagon drivers to blacksmiths, the Industrial Revolution forced firms to conform or go out of business because of competitive pressure. Resistance to innovation was more likely to come from existing firms than from labor (though in the case of craftsmen and hand-loom weavers that distinction is perhaps not very sharp). Technological progress reduces the wealth of those possessing capital (real or human) specific to the old technology that cannot readily be converted to the new. Resistance was therefore strongest in longestablished, skill-intensive industries such as printing and wool finishing.

Resistance to innovation was exacerbated by the fact that the gains from the innovations in the Industrial Revolution were captured by consumers (for whom joint political action is very hard), while the costs tended to be borne by a comparatively small number of people, many of whom may already have been organized, or knew each other and lived in the same regions. The losers could try to use extralegal methods (rioting, machine breaking, personal violence against innovators) or the political system to halt technological progress. Either way, the diffusion of technological progress became at times a social struggle, and politicians and judges became arbiters of decisions that should have been left to market forces. In this regard, technological change was similar to free trade. The benefits being diffuse and the costs concentrated, the survival of free trade has always been in jeopardy, and its lifespan usually short. And although we understand the forces at work, it is difficult to predict outcomes or even fully understand why a particular outcome came about. What is clear is that between 1750 and 1850 the British political system unflinchingly supported the winners over the losers, on both matters of technological progress and, increasingly, free trade. On the eve of the Industrial Revolution the British ruling class had most of its assets in real estate and agriculture; it had no interest in resisting the factory and the machine.

Once again, the difference between Britain and the Continent was one of degree and nuance. Before and during the Industrial Revolution, there were numerous examples of anti machinery agitation in Britain. In 1 551 Parliament prohibited the use of mechanical gig mills, used in the raising of the nap (a finishing process) of woolen cloth. The hosiers guild's opposition to William Lee's knitting frame (1589) was so intense that the inventor had to leave Britain. In 1638, the Crown declared a ban on the use of ribbon looms in Britain. John Kay's flying shuttle (1733) was met by fierce hostility from weavers who feared for their livelihood. In 1768, 500 sawyers assaulted a mechanical sawmill in London. Severe riots occurred in Lancashire in 1779, and in 1792 a Manchester firm that pioneered Cartwright's power loom was burnt down. Its destruction was said to have "inhibited the development of powerloorn weaving for several years in this area" (Stevenson, 1979, p. 118). In the southwest of England, especially in Wiltshire and Somerset, resistance to advances in the spinning and weaving of wool was strong and may have contributed to the shift of the center of gravity of the woolen industry to the northern counties. Between 1811 and 1816, the Midlands and the industrial counties were the site of the "Luddite" riots, in which much damage was inflicted on machines. In 1826, hand-loom weavers in a few Lancashire towns rioted for three days, and in 1830 the "Captain Swing" riots, aimed at threshing machines in agriculture, took place in the south of England.

By and large, these attempts were unsuccessful. Gig mills, ribbon looms, knitting frames, and flying shuttles were all adopted by British industry (though perhaps somewhat more slowly than they might have been). The laws prohibiting machinery remained ineffective. In the eighteenth century, the government took an increasingly stern view of groups who tried to halt technological progress. In 1769 Parliament passed a harsh law in which the willful destruction of machinery was made a felony punishable by death. In 1779 the Lancashire riots were suppressed by the army, and the sentiment of the authorities was well expressed by a resolution passed by the Preston justices of' the peace: "The sole cause of great riots was the new machines employed in cotton manufacture; the country notwithstanding has greatly benefited by their erection [and] destroying them in this country would only be the means of transferring them to another … to the detriment of the trade of Britain" (cited by Man- toux, [1905] 1961, p. 403). During the Luddite outbreaks in 181113, the British government deployed 12,000 men against rioters, a force greater in size than Wellington's original peninsular army in 1808. Riots were harshly suppressed and usually ended in hangings and deportations.

Attempts by legal means to stop the Industrial Revolution were no more successful. In 1780, cotton spinners petitioned Parliament to forbid cotton-spinning machinery, but the committee appointed to investigate the matter denied the petition. In 1794 wool combers petitioned against a wool-combing machine invented by Edmund Cartwright, but once more the employers carried the (lay. Other petitions were treated similarly, including one that sought to ban the gig mill on the basis of the 1551 law (Mantoux, [1905] 1961, pp. 403-8). Between 1803 and 1809 a battle between industrialists and workers raged in the woolen industry over the repeal of ancient statutes and regulations that were regarded by the industrialists as inimical to the new technologies. In 1809 the laws were repealed (Randall, 1986). In 1814, the 250-year-old Statute of Artificers was repealed, despite the demands of journeymen trying to protect their old technologies. The case of the workers was politically hopeless. The argument that stopping the new machinery would only lead to its flight abroad was persuasive, but there was more to it than that. The politically dominant classes in Britain were the propertied classes and the new technology did not threaten to reduce the value of their assets. Furthermore, not all workers in the traditional sector were initially made worse off. Although some workers, such as handloom weavers and frame knitters, lost out as a result of mechanization, many workers displaced by machinery eventually found employment in the factories. Some cottage industries that produced goods that were complementary to or inputs for the factories actually thrived for many years thanks to the new technology, until their turn came to compete with the new machines. The list of disturbances and riots, although long, is thus misleading. Most innovations were adopted without significant trouble, and not all trouble necessarily reflected resentment toward the new machines. 17

Were things significantly different on the Continent? As in Britain, resistance came from guilds of skilled artisans and from unskilled workers fearful of unemployment. Before the French Revolution, craft guilds, which still existed in most regions, held some new techniques back. In part, this was done by outright banning of inventions when established interests felt threatened. The ribbon loom, known in England as the Dutch or engine loom, encountered resistance all over the Continent, in striking contrast to its progress in Lancashire after 1616 (Wadsworth and Mann, 1931, p. 104). In Brandenburg, guilds succeeded in keeping out frame-knitting well into the eighteenth century. In France and elsewhere, printing and cotton textiles were among the industries in which new techniques were successfully resisted by pressure groups.t" Increasingly, the old urban guilds became a fetter on technological progress, less by outright resistance than through a vast body of regulations and restric tions on inputs and outputs." Under these regulations, for example, it would have been difficult for a barber like Richard Arkwright to set up shop as a cotton spinner. Yet the powers of the guilds were already declining in the eighteenth century. After 1760, guilds came under pressure in France and Germany, and were abolished in 1784 in the southern Netherlands. The French Revolution abolished then) in France in 1791 and subsequently in areas that fell under French domination. By 1815 guilds had either been fatally weakened or abolished altogether on the Continent. The political upheaval and disruptions incurred as the price for ridding the economies of obsolete institutions between 1790 and 1815 may in part explain the lag in the adoption of' some techniques into Europe. However, the Revolution's long-term effect was to clear up the debris of the ancien regime on the Continent, thus assuring Europe's ability eventually to follow Britain in revolutionizing its production system.

Not that there was a lack of resistance. Fears of technological unemployment surface in the 1789 cahiers (grievances sent to the Estates General). Between 1788 and 1791, workers rioted repeatedly in protest against machinery that they felt threatened their livelihood. In the summer months of 1789, the city of Rouen was the scene of antimachinery vandalism that spread to other (owns, including Paris and St. Etienne. The targets of the rioters' ire were spinning machines imported from Britain and locally made devices, such as pitchfork-making machines. Although the riots eventually New over, the damage may have been long-lasting. One historian (McCloy, 1952, p. 184) has stated that "the rioters … set back the clock of time, at least industrially, some two decades; for it was not. until after the wars … that France was able to introduce such machines again." Yet after the Revolution, Under the forceful protechnology government of Napoleon, opposition to new techniques appeared as moribund on the Continent as it did in England.L) The weavers of Lyons resisted Jacquard's loom in the first decade of the nineteenth century, but to no avail (Ballot, [1923 1978, p. 379). A decade later some resistance was encountered to the introduction of wool-shearing equipment in France. Nevertheless, some scholars believe that Luddism "surely cannot have impeded the introduction of machinery into French manufacturing" (Manuel, 1938).

It is misleading, however, to identify what is commonly called Luddism (machine breaking) with a rational resistance to a new technology by a group that stood to lose from its introduction. For one thing, machine breaking was often resorted to simply because machines were a convenient and vulnerable target in a labor dispute, and not necessarily because of a specific grievance against the new technology they embodied. More importantly, resistance to new technology often took a more subtle form that is not always easy to detect. Recent work in social history has emphasized the high level of organization of French workers. After 1815, the guilds were replaced by "mutual aid societies," which often served in secret the interests of the defense profes.sionelle. Small independent masters often supported illicit unions in fighting back against innovative entrepreneurs who introduced cost-cutting machinery (Sewell, 1980, p. 182). In 1895 these societies had almost 400,000 members (Shorter and Tilly, 1974, p. 176.21 The need to placate skilled craftsmen may well have steered France into choosing a technology somewhat different from Britain's. The industrial France that emerged in the nineteenth century thus continued to be based on skilled small-scale handicrafts producing for relatively local markets. Some economic historians have attributed this difference between Britain and France to differences in population growth, but there must be limits to the burdens that demography can bear. More so than in Britain, therefore, technological progress in France had to accommodate the artisans and to find compromises between their traditional skills and the needs of modern factories. In Belgium, Switzerland, Bohemia, and the Rhineland, resistance to new cotton-spinning technology crumbled. In the Netherlands, on the other hand, workers repeatedly smashed machines in the textile industries in the south. Though such cases were not numerous, they may well have deterred entrepreneurs from installing such equipment.

't'echnological progress was a multinational collaborative effort, in which Britain's advantage was qualitative and ephemeral. Yet there are important lessons to be drawn from comparing different expe riences in Europe between 1750 and 1914. The comparison can shed some light, for instance, on why Cardwell's Law that no economy remains technologically creative for extended periods of time seems to hold. Britain, the cradle of the technologies that created the Industrial Revolution, lost its preeminence in the late nineteenth and early twentieth century. Although it is still debated by economic historians whether the slowdown occurred before or after 1900, there is no question that by 1914 the cutting edge of technology had moved elsewhere.

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The political economy of technological change is only dimly understood. To some observers, technological progress seems to resemble the human life cycle: the vigor of youth is followed by the caution of maturity and finally the feebleness of old age or the "climacteric." Such an anthropomorphic view makes no economic sense without more specific detail. Societies are aggregates; they do not age like individuals. If we are to understand why the fires of innovation die down, we must propose a model in which technological progress creates the conditions for its own demise. To begin, recall that part of the social cost of innovation is caused by the process of "creative destruction." Schumpeter, who popularized the term, associated it with capitalism, but in fact it is part and parcel of technological progress under any economic regime. The continuous obsolescence of specific, nonmalleable assets, both physical and human, is the price a society pays for sustained progress. Insofar as the groups that benefit from the new technology coincide with the groups that pay the price (which is lower than the benefit), resistance to technological progress will be weak. The greater the divergence between these two groups, the greater the incentive for the losing groups to try to slow down progress. It seems likely that the obsolescence of human capital is a crucial variable here, because its malleability declines sharply over the life cycle. But it could apply to physical capital as well. As long as free entry into an industry is guaranteed, however, the ability of any group to keep out new techniques is limited. A "life cycle" of a technologically advanced society would thus consist of three stages. First is the youthful stage, in which the new technology manages to break through, supplanting the previous technology by means of its greater efficiency. This stage corresponds with the period between 1760 and 1830 in Britain. The next. stage is one of maturity, in which the new technology is in control, but creative destruction by new techniques takes an ever-increasing toll, leading to a growing incentive by those currently in control to protect themselves. In the third stage, the by-now old technology develops social or political mechanisms with which to protect itself against innovation. If it is successful, technological creativity comes to an end. If it fails, the cycle begins anew.

Does such a schematic life-cycle theory of technological creativity have any value? Its predictive powers are very limited: without more information we cannot tell how long creativity will last, how it will end, or whether it will recur. Yet like most theoretical models, it suggests to the empirical economist and economic historian where to look for specific evidence. Societies that become conservative after a creative period need to obstruct innovation by setting up mechanisms to prevent existing firms from adopting new ideas, by preventing would-be innovators from entering an ossified industry, and by stopping the inflow of new ideas from abroad. japan practically closed itself to Westerners in 1638. Islam and China, as we have seen, tried to block Western influence using a combination of ideology and control. But in the West itself such defenses often took more subtle forms. Protective tariffs have been used for centuries to allow obsolete technologies to survive (under the pretext of softening the pains of transition). Guilds, labor unions, professional and manufacturers associations, and licensing requirements have been used to police conformism within the industry and to try to prevent the entry of homines novi with new ideas. As the fixed capital requirements in manufacturing rose, credit rationing was used to create another barrier that tried to exclude new ideas and techniques.22

In late Victorian Britain the new ruling class that had come to power defended its position by closing Britain's elite to the same kind of entrepreneurs from whom they had descended. They tried to reorder the hierarchy of values so that production and technology would once again occupy the lowly positions they had occupied centuries before the Industrial Revolution. Such attempts were largely unsuccessful. Competition with other industrial powers and the internal competition of British firms against each other guaranteed that Britain could not be passed by the Second Industrial Revolution. What the British tried to do, however, was to live through the Second Industrial Revolution with the tools of the First, much like generals apply the tactics of the last war to the fighting of the cur rent one. The systematic application of the newly developing natural sciences was delayed by the survival of 'a tradition of amateurishness and tinkering, and by the virtual absence of technical education. Onthe-job training through apprenticeship remained the chief mechanism through which skills were transmitted. Invention was largely the business of inspired outsiders, and British scientists (with some notable exceptions, such as Charles Parsons) were as little involved in exploring new opportunities as they were in the daily drudgery of production. As we have seen, Britain (lid not lose its central position in invention itself, but its position was reversed compared to a century earlier: during the heyday of the First Industrial Revolution, it was a net importer of technology; after 1850, it became an exporter. Technological creativity, defined as the application of new ideas to production, began to slow down in Britain. The ideas themselves were still forthcoming, but the economic environment slowly became less receptive to them.

An unexpected tool the ruling elite used for this purpose was the educational system. English public schools opened their doors to members of the new elite, but painstakingly avoided providing them with the kind of practical education that would enable them to threaten the technological status quo. Those who profited from the educational opportunities tended to choose careers in the professions. The educational system, never the most progressive of Britain's institutions, resisted the introduction of applied sciences into its curricula.” [i] The old British tradition of informal training remained the principal means through which technological information was transferred. In contrast, most other European countries established technical schools that played a central role in the catching-up phenomenon. The graduates of the German Techuische Hochschule amazed British businessmen and raised increasing fear about competition (Ashby, 1958, p. 795; }ulia Wrigley, 1986, pp. 172-73). Similar schools existed, as we have seen earlier, in the Netherlands (Delft), Switzerland (Zurich), and France (for example, the In.stitut Indus7riel du Nord in the manufacturing town of Lille).

It can hardly he maintained that demand factors alone were decisive here: there was great interest in Britain for scientific and technical development that, after the mid-nineteenth century, they increasingly were forced to import. Thus, the British Association for the Advancement of Science commissioned von Liebig's famous 1840 treatise, and the English translation was enthusiastically received. Liehig's student, August von Hofmann, was brought to London to teach chemistry at the Royal College of Chemistry and consulted to private companies as well as the British government. But after Hofmann returned to Germany in 1865 and particularly following the Paris Exhibition of 1867, it became increasingly clear that Britain was lagging behind. One Briton wrote in 1867 that at the Paris Exhibition "a singular accordance of opinion prevailed that our country had shown little inventiveness and made little progress in industry.… The one cause upon which there was unanimity of conviction is that France, Prussia, Austria, Belgium, and Switzerland possess good systems of industrial education … and that England possesses none" (cited by Ashby, 1958, p. 789). A number of royal commissions and select committees were appointed to look into the problem, and all recommended increasing the quantity and quality of scientific and technical education. Scientific education advanced significantly, but technical colleges had to wait for the Technical Instruction Act of 1889. Throughout this period, the overriding argument deployed by the supporters of technical education was that Britain would not he able to compete with other nations without it. The competitive states system was, as we have seen repeatedly, the most effective check upon the forces of technological reaction.

Of course, the weakness of British technical education should not be naively attributed to some kind of fiendish conspiracy on the part of the status quo. It is clear, however, that the existing political and economic order had little to gain from the increased state intervention that would be needed if technical education was to be brought to a par with the Continent. Just as that order successfully combatted state intervention in the form of protective tariffs, they resisted any increase in expenditures that would pay for education. But conservatism permeated not only the universities and government, but penetrated the workplace as well. What Landes has called the "mystique of practical experience," the idea that technical skills could not be taught as a part of formal education but had to be acquired on the job, worked against the establishment and expansion of the technical schools. The business world tried to establish an "old boy network" in an attempt either to bribe or to exclude those who would challenge the technological status quo. The "gentleman mentality" was resurrected, not as a quirk of British character, but as a defense mechanism against those who would do to the British elite as their grandfathers had done to others a century earlier. Once again, profits became a source of guilt rather than pride.24 One tactic was to co opt the would-be rebels into the old elite, by admitting them to public schools and universities, on condition they did not rock the boat. Those who did not go along were treated like social pariahs. Even men like William Perkin or Edward Nicholson (also a dye chemist), who made their fortunes from their scientific knowledge, subsequently retired to dedicate their lives fully to pure research.

After the middle of the nineteenth century labor, too, took an increasingly negative attitude toward machinery, though their motives were directed as much toward higher wages and better working conditions as toward keeping machines out to protect their special skills. Alfred Hobbs, the American lockmaker who introduced interchangeable parts to lockmaking, stated in 1857 that the "great obstacle in the way of the gunmakers of Birmingham in introducing machinery was the opposition of the workpeople to such innovations." Joseph Whitworth, in his 1854 report on the differences between American and British manufacturing, emphasized that British workers were far more hostile to new technology than American workers, because they were more skilled, better organized, and less mobile (Rosenberg, ed., 1969). The installation of a sewing machine was prohibited in the center of the shoemaking industry, Northampton, after three strikes against it in the late 1850s, and new machinery was successfully kept out in some centers of carpetmak- ing, printing, glassmaking, and metalworking where resistance was stiff (Samuel, 1977, pp. 9-10, 33). In most cases, however, resistance took the form of hard bargaining over changes in wages and working conditions resulting from any changes in the production environment.

Lazonick (1979, 1986) has shown in detail how strong labor unions in nineteenth-century Britain succeeded in modifying the process of innovation and later in creating an atmosphere inimical to technological change. The bargaining power of skilled workers made it costly for manufacturers to introduce new machinery in the cotton industry, the ageing flagship of British industry. In cotton spinning in particular, workers forced the capitalists to retain the system of "minders" that had sprung up in the first quarter of the nineteenth century. In this system, the capitalist delegated some of the supervisory and recruiting functions to a male worker in charge of a mule. This system did not prevent the adoption of the selfactor, though it may have slowed it down and prevented the capitalists from using it to strengthen their bargaining power vis-a-vis the laborers. By the 1880s, however, the limits of the mule had been reached and ring spinning passed Britain by. Lazonick (1987, p. 303) concludes that "vested interests-in particular the stake that British workers had in job control and the historic underdevelopment of British management-stood in the way of … promoting the diffusion of advanced production methods." All this did not necessarily lead immediately to inefficiency in the narrow economic sense of a poor allocation of resources. We should recall that, as Cardwell (1972, p. 193) points out, the failure at the time (of late Victorian Britain) was not an economic failure, but a technological and scientific one.25

Economies reaching the third stage of their technological life cycle can choose different defense mechanisms, depending on their political system and social customs. A powerful ruler can be enlisted either to protect the status quo or to support the forces of progress. Sometimes a compromise is reached. As a result, the outcome is indeterminate and the technologically creative stages in the life cycle may last for longer or shorter periods. Still, this type of political mechanism can shed some light on the forces underlying Cardwell's Law. These mechanisms cannot be made more explicit without a more complete specification of the complicated series of games played between those who stand to gain from technological change and those who stand to lose. Yet what is clear is that the game is structured in a particular way. Every time a new technology emerges, it has to struggle with the status quo. It has some probability p of winning. If it does, it becomes the dominant technology and it will in turn be challenged in the next period. If it loses, the forces of reaction will establish a new antitechnological set of institutions that will make it far more difficult to be challenged, so that the next round the game is played the new technology has only a chance of p' to win, where p' < p. It is conceivable that p' = 0, so that a society locks itself forever into an existing technology, in which case a victory of the status quo would be a true absorbing state. There are some reasons to believe, however, that this is unlikely to be the end of the story. For one thing, p and p' are both likely to depend on the ratio be tween gains and losses associated with a new technology. A more drastic change will increase both the gains and the losses but not necessarily pari passu, so that it may become possible for a sufficiently advanced technology to break through despite reactionary institutions. Moreover, in a global setting p' will depend on the size of the gap between the reactionary and the progressive economies. At some point the gap will become intolerable, and the reactionary forces will be defeated, as they were in Japan in 1868 and in China more gradually after 1898.

An alternative way of understanding why periods of technological creativity were finite and usually short centers on the connection between market structure and innovation. Economists have been discussing the Schumpeterian hypothesis for many years, and the literature is summarized elsewhere (Kamien and Schwartz, 1982; Scherer, 1980, ch. 15; Baldwin and Scott, 1987). In brief, Schumpeter argued that large firms with considerable market power, rather than perfectly competitive firms, were the "most powerful engine of technological progress" (1950, p. 106). Free entry, in his view, was incompatible with economic progress based on technological change. Much of this debate is of questionable relevance to anything that happened before 1914. The version of the Schunipeterian hypothesis associated with Galbraith, who tried to relate firm size to the propensity to innovate, is even less relevant here." Before 1850, large firms were highly unusual and production took place largely within family firms, sometimes assisted by domestic servants and hired hands. It seems unlikely, therefore, that firm size will have much explanatory power for technological history before the modern age. At any rate, Schumpeter referred not to size but to the degree of competition. Here the historical record offers much more variation. Small firms do not guarantee competitiveness. If firms are catering to a small enough market (that is, if transport costs are sufficiently high), even a single artisan could be a monopolist. Moreover, competitive industries can devise cushioning mechanisms that mitigate the sharp edges of competition and eventually make the industry behave as a monopolist in some respects. The guild system, although not set up for that purpose, clearly carried out that task in Europe for many centuries. In the nineteenth century, competitive pressures were mitigated by cartels, professional associations, government regula tion, and unwritten gentlemen's agreements on what constituted proper business behavior. Perfect competition was rare. Instead, a bounded set of rules defined a game that favored innovation at some times more than others.

Much of the modern empirical literature on the market structure best suited to technological change is inconclusive and sometimes contradictory. The historical evidence is not much more helpful here. After 1750, Anglo-Saxon economies tended to be more competitive than others; cartels and formal barriers to entry were far more common on the Continent. In Germany and Austria, cartels were encouraged and forced by the state in the late nineteenth century; in the United States after 1890 they were illegal and in Britain they were extra-legal, neither enforceable nor illegal. In practice, however, most British firms remained small, and British industry fragmented and decentralized. In and of themselves these differences do not imply that the Continent was less competitive than Britain or the United States. Moreover, the record on technological change between 1750 and 1914 does not provide much support for any simple Schumpeterian hypothesis. Britain, the more competitive economy, gained an initial advantage in innovation, but then lost it after 1870 to the European Continent and the United States. Either we are mismeasuring competitiveness, and (appearances notwithstanding) Britain was becoming less competitive in the late nineteenth century, or the new technology associated with the Second Industrial Revolution was inherently different in this respect from the earlier technology. Inventions such as chemical dyes, the internal combustion engine, electrical appliances, and steel required considerable development and improvement after their conception. Here the less competitive German oligopolies, led by a small number of powerful investment banks, and the large firms that emerged in the United States by the end of the nineteenth century may have provided a better environment for technological change (Mowery, 1986).

In spite of the inconclusiveness of the literature on the connection between market structure and innovation, it may provide an additional insight into the causal roots of Cardwell's Law. The relationship between technological change and market structure is reciprocal. Market structure is said to affect the technological creativity of an industry or economy, but a feedback mechanism leads hack from technological change to market structure. Here, too, the effects are indeterminate. Some forms of technological change tended to enhance competition-improvements in transportation and communications diminished local monopoly power, the availability of electrical power led to a decline in the optimal size of a firm, and the introduction of new products competed with established products. Other kinds of changes (for instance patents) reinforced economies of scale and created barriers to entry. Yet the remarkable conclusion is that whatever the relationship, the model implies that technological change is likely to be ephemeral. A highly simplified exposition of the model suffices to illustrate how the relationship between firm size and technological change might explain Cardwell's Law. Suppose there are only two forms of market structure, i, which is conducive to technological change, and j, which is not. This ranking of market structures according to their conduciveness to technological change depends itself on the technology in use, and technological change may cause the existing structure to switch from i to j as well as reverse the ranking. Suppose we start with market structure i and technological change takes place. There are now four possible outcomes: (1) the next period remains dominated by market structure i, and i is still the more conducive to technological change; (2) the next period leads to a switch from i to j, and the ranking of i and j is preserved; (3) the next period still finds the economy in i, but the ranking is reversed; and (4) the next period leads to a switch from i to j, but now j is the more favorable market structure for technological change. Outcomes (1) and (4) imply that the process is repeated; outcomes (2) and (3) imply that technological progress ends. If all four outcomes are thought of as random events with positive probabilities, the process will inexorably come to an end when either outcome (2) or outcome (3) occurs.' The use of such Markov processes in characterizing Schumpeterian dynamics was pioneered by Futia (1980), who has shown how industry structure and the chances for technological progress are determined by ease of entry and technological opportunities. This research could be extended to produce further understanding of Schumpeter's insight that technological change is temporary in nature.

In examining technological progress, the question arises whether we should consider creativity or stagnation the normal condition. The answer to this question determines the explicandum: is it the periods of' progress or the periods of stagnation that need be explained? This question cannot he answered based on historical evidence alone. Clearly, over the entire human historical record, periods of technological change have been exceptional. The present and the future may be radically different, however, as a result of the Industrial Revolution. On the other hand, Cardwell's Law seems too pervasive a phenomenon to take anything for granted.