The Second Industrial Revolution, 1870-1914

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Introduction

The second Industrial Revolution is usually dated between 1870 and 1914, although a number of its characteristic events can be dated to the 1850s. It is, however, clear that the rapid rate of pathbreaking inventions (macroinventions) slowed down after 1825, and picked up steam again in the last third of the century. This says little about the rate of technological progress as commonly defined in terms of productivity increase and the improvements in product quality, which depends much more on the smaller, cumulative, anonymous changes known as microinventions. Yet the great pathbreaking inventions in energy, materials, chemicals, and medicine described below were crucial not because they themselves had necessarily a huge impact on production, but because they increased the effectiveness of research and development in microinventive activity. Eventually such activity like everything else runs into diminishing marginal product, unless a major new breakthrough opens new horizons.

Technology is knowledge. Modern economic growth, Simon Kuznets (1965) argued more than 30 years ago, depends on the growth of useful knowledge. Yet as knowledge, technology differs from the knowledge of nature we think of as science, geography or a more pragmatic knowledge of natural phenomena. With some simplification we may divide all useful knowledge into knowledge "that" which seeks to catalog and explain natural phenomena and regularities, and knowledge "how" which should be thought of as huge compilation of recipes, instructions, blueprints and "do-loops" which constitute the totality of the techniques available to society (see Mokyr, 1998a and 1998b). The two forms of knowledge are of course related: on the whole, useful natural knowledge leads to or "maps into" the development of novel techniques. Yet there are two important qualifications to that somewhat mechanistic image. First, there was considerable feedback from technology to science. This took the form of refocusing scientific thinking in the light of novel inventions, as well as technology creating better instruments and equipment with which to register scientific facts and regularities, as well to test hypotheses. Second, a substantial number of techniques emerge with fairly little base in the understanding of the natural phenomena. The first Industrial Revolution -- and most technological developments preceding it -- had little or no scientific base. It created a chemical industry with no chemistry, an iron industry without metallurgy, power machinery without thermodynamics. Engineering, medical technology, and agriculture until 1850 were pragmatic bodies of applied knowledge in which things were know to work, but rarely was it understood why they worked. This meant that often people did not know which things did *not* work: enormous amounts of energy and ingenuity were wasted on alchemy, perpetuum mobiles, the stones of the wise and fountains of youth. Only when science demonstrated that such pipedreams were impossible, research moved into a different direction. Moreover, even when things were known to work, they tended to be inflexible and slow to improve. It was often difficult to remove bugs, improve quality, and make products and processes more user-friendly without a more profound understanding of the natural processes involved.

It was in this regard that the inventions after 1870 were different from the ones that preceded it. The period 1859-1873 has been characterized as one of the most fruitful and dense in innovations in history (Mowery and Rosenberg, 1989, p. 22). From the point of view of useful knowledge that mapped into new technology, this view is certainly correct. The second Industrial Revolution accelerated the mutual feedbacks between these two forms of knowledge or between "science" (very broadly defined) and technology. It should be stressed that the difference was one of degree. Even before 1870, some natural processes were sufficiently understood to provide some guidance as to how to make technology more effective. And certainly after 1870 there was still a role to play for luck, serendipity, and "try-every-bottle-on-the-shelf" type of inventions. Yet degree is everything here, and the persistence and acceleration of technological progress in the last third of the nineteenth century was due increasingly to the steady accumulation of useful knowledge. Some of this knowledge was what we could call today "science" but a lot was based on less formal forms of experience and information. Inventors like Edison and Felix Hoffman relied on some of the findings of formal science, but a lot more was involved. As a result, the second Industrial Revolution extended the rather limited and localized successes of the first to a much broader range of activities and products. Living standards and the purchasing power of money increased rapidly, as the new technologies reaches like never before into the daily lives of the middle and working classes.

The other aspect of the second Industrial Revolution worth stressing is the changing nature of the organization of production. The second Industrial Revolution witnessed the growth in some industries of huge economies of scale and "throughput" (to use Alfred Chandler's well-known term). Some vast concerns emerged, far larger than anything seen before. This change occurred because of ever more important economies of scale in manufacturing. Some of these were purely physical such as the fact that in chemicals, for instance, the cost of construction of containers and cylinders is proportional to the surface area while capacity is proportional to volume. Since the first depends on the square of the diameter and the latter on the cube, costs per unit of output decline with output. With the rise of the chemical industry, oil refining, and other industries using containers, as well as engines of various types, size began to matter more and more. Some economies of scale were organizational, such as mass production by interchangeable parts technology. Others were more in the nature of marketing advantages, or even the ruthless pursuit of monopolies. Yet it should be stressed that even with rise of giant corporations such as Carnegie Steel, Dupont, Ford Motors, and General Electric in the U.S. and their equivalents in Europe, these firms employed but a small fraction of the labor force and the typical firm in the industrialized West by 1914 remained relatively small, a niche player, often specialized yet flexible and catering more often than not to a localized or specific section of the market (Scranton, 1997; Kinghorn and Nye, 1995).

The consequence of changing production technology was the rise of technological systems (Hughes, 1983, 1987). Again, some rudimentary "systems" of this nature were already in operation before 1870: railroad and telegraph networks and in large cities gas, water supply, and sewage systems were in existence. These systems expanded enormously after 1870, and a number of new ones were added: electrical power and telephone being the most important ones. The second Industrial Revolution turned the large technological system from an exception to a commonplace. Systems required a great deal of coordination that free markets did not always find easy to supply, and hence governments or other leading institutions ended stepping in to determine railroad gauges, electricity voltages, the layout of typewriter keyboards, rules of the road, and other forms of standardization. The notion that technology consisted of separate components that could be optimized individually -- never quite literally true -- became less and less appropriate after 1870.

In what follows I shall briefly survey some of the most important developments in technology during the 1870-1914 years, and then summarize their broader economic significance.

Steel. By 1850, the age of iron had become fully established. But for many uses, wrought iron was inferior to steel. The wear and tear on wrought iron machine parts and rails made them expensive in use, and for many uses, especially in machines and construction, wrought iron was insufficiently tenacious and elastic. The problem was not to make steel; the problem was to make *cheap* steel. As is well-known, this problem was definitively solved by Henry Bessemer in 1856. The growth of the steel industry following his invention has come in the popular mind to symbolize the technology of the second Industrial Revolution, and while steel was of course of great significance, such emphases tend to blur the advances in many other industries.

The Bessemer converter used the fact that the impurities in cast iron consisted mostly of carbon, and this carbon could be used as a fuel if air were blown through the molten metal. The interaction of the air's oxygen with the steel's carbon created intense heat, which kept the iron liquid. Thus, by adding the correct amount of carbon or by stopping the blowing at the right time, the desired mixture of iron and carbon could be created, the high temperature and turbulence of the molten mass ensuring an even mixture. At first, Bessemer steel was of very poor quality, but then a British steelmaker, Robert Mushet, discovered that the addition of *spiegeleisen*, an alloy of carbon, manganese, and iron, into the molten iron as a recarburizer solved the problem. The other drawback of Bessemer steel, as was soon discovered, was that phosphorus in the ores spoiled the quality of the steel, and thus the process was for a while confined to low-phosphorus Swedish and Spanish ores.

A different path was taken by Continental metallurgists, who jointly developed the Siemens-Martin open hearth process, based on the idea of cofusion, melting together low-carbon wrought iron and high-carbon cast iron. The technique used hot waste gases to preheat incoming fuel and air, and mixed cast iron with wrought iron in the correct proportions to obtain steel. The hearths were lined with special silica brick linings to maintain the high temperatures. The process allowed the use of scrap iron and low grade fuels, and thus turned out to be more profitable than the Bessemer process in the long run. Open-hearth steel took longer to make than Bessemer steel, but as a result permitted better quality control. Bessemer steel also tended to fracture inexplicably under pressure, a problem that was eventually traced to small nitrogen impurities. In 1900 Andrew Carnegie, the American steel king, declared that the open hearth process was the future of the industry. Like the Bessemer process, the Siemens-Martin process was unable to use the phosphorus-rich iron ores found widely on the European Continent. Scientists and metallurgists did their best to resolve this bottleneck, but it fell to two British amateur inventors, Percy Gilchrist and Sidney Thomas, to hit upon the solution in 1878. By adding to their firebricks limestone that combined with the harmful phosphorus to create a basic slag, they neutralized the problem. It seems safe to say that the German steel industry could never have developed as it did without this invention. Not only were the cost advantages huge, but the Germans (who adopted the "basic" process immediately) also managed to convert the phosphoric slag into a useful fertilizer. While the Bessemer and Siemens-Martin processes produced bulk steel at rapidly falling prices, high-quality steel continued for a long time to be produced in Sheffield using the old crucible technique. Cheap steel soon found many uses beyond its original spring and dagger demand; by 1880 buildings, ships, and railroad tracks were increasingly made out of steel. It became the fundamental material from which machines, weapons, and implements were made, as well as the tools that made them.

Steel's spectacular success after 1860 should not obscure important advances in other stages of the iron industry. In the blast furnaces, which smelted iron ore to produce pig iron, coke had long been the standard fuel by the 1850s. Most furnaces at that time were about 40-50 ft. high and heated the ore to about 600ºF. Following the discovery of ore fields in the Cleveland district in Northern Yorkshire in England, a set of improvement occurred which greatly increased the efficiency of the blast furnaces. Their height was gradually increased to 80 feet and more; temperatures were raised to about 1000ºF.; waste gases were recycled; and blowing engines were introduced. American inventors added a number of other improvements, such as "hard driving" (blowing large volumes of air at high pressure through the furnace); improved blowing engines; and direct casting of the pig iron into the steelworks.

Chemicals: In chemistry, Germans took the lead. Although Britain still was capable of achieving the lucky occasional masterstroke that opened a new area, the patient, systematic search for solutions by people with formal scientific and technical training suited the German traditions better. In 1840 Justus von Liebig, a chemistry professor at Giessen, published his *Organic Chemistry in Its Applications to Agriculture and Physiology*, which explained the importance of fertilizers and advocated the application of chemicals in agriculture. Other famed German chemists, such as Friedrich Wöhler, Robert Bunsen, Leopold Gmelin, August von Hofmann, and Friedrich Kekulé von Stradonitz, jointly created modern organic chemistry, without which the chemical industry of the second half of the nineteenth century would not have been possible. It was one of the most prominent examples of how formal scientific knowledge came to affect production techniques.

Despite German dominance, it was an Englishman, William Perkin, who by sheer luck made the first major discovery in what was to become the modern chemical industry. Perkin, however, was trained by the German von Hofmann, who was teaching at the Royal College of Chemistry at the time, and his initial work was inspired and instigated by him. The eighteen year old Perkin searched for a chemical process to produce artificial quinine. While pursuing this work, he accidentally discovered in 1856 aniline purple, or as it became known, mauveine, which replaced the natural dye mauve. Three years later a French chemist, Emanuel Verguin, discovered aniline red, or magenta, as it came to be known. German chemists then began the search for other artificial dyes, and almost all additional successes in this area were scored by them. In the 1860s, Hofmann and Kekulé formulated the structure of the dyestuff's molecules. In 1869, after years of hard work, a group of German chemists synthesized alizarin, the red dye previously produced from madder roots, beating Perkin to the patent office by one day. The discovery of alizarin in Britain marked the end of a series of brilliant but unsystematic inventions, whereas in Germany it marked the beginning of a process in which the Germans established their hegemony in chemical discovery (Haber, 1958, p. 83). German chemists succeeded in developing indigotin (synthetic indigo, perfected in 1897). and sulphuric acid (1875). Soda-making had been revolutionized by the Belgian Ernest Solvay in the 1860s. In explosives, dynamite, discovered by Alfred Nobel, was used in the construction of tunnels, roads, oilwells, and quarries. If ever there was a labor-saving invention, this was it.

In the production of fertilizer, developments began to accelerate in the 1820s. Some of them were the result of resource discoveries, like Peruvian *guano* which was imported in large quantities to fertilize the fields of England. Others were by-products of industrial processes (Grantham, 1984, pp. 199, 211). A Dublin physician, James Murray, showed in 1835 that superphosphates could be made by treating phosphate rocks with sulphuric acid. The big breakthrough came, however, in 1840 with the publication of von Liebig's work, commissioned by the British Association for the Advancement of Sciences. Research proceeded in England, where John Bennet Lawes carried out path-breaking work in his famous experimental agricultural station at Rothamsted, where he put into practice the chemical insights provided by von Liebig. In 1843 he established a superphosphates factory that used mineral phosphates. Yet Lawes' station remained isolated and the Germans once again took the lead.. Because the physical and chemical processes in agriculture are far more complex than in manufacturing, better theoretical knowledge was required, and serendipity eventually ran into diminishing returns. In Germany, especially Saxony, state-supported institutions subsidized agricultural research and the results eventually led to vastly increased yields. Nitrogen fertilizers were produced from the *caliche* (natural sodium nitrate) mined in Chile. The famous Haber process to make ammonia, developed by Fritz Haber and BASF chemists Carl Bosch and Alwin Mittasch and the discovery of how to convert ammonia into nitric acid around 1908, made it possible for Germany to continue producing nitrates for fertilizers and explosives during World War I after its supplies of Chilean nitrates were cut off. The ammonia-producing process must count as one of the most important inventions in the chemical industry ever. It used two abundant substances, nitrogen and hydrogen, in order to produce the basis of the fertilizer and explosives industries for many years to come. The third mineral crucial to plant growth was potassium, made from potash by burning wood. In 1870, forest-rich Canada was still the principal source of potash. By then, however, mineral deposits of potassium salts at Strassfurt in central Germany began to be exploited, the price of potash fell rapidly, and widespread application of this fertilizer began. By 1900 the Canadian asheries had disappeared.

Chemistry also began its road toward the supply of new artificial materials. Charles Goodyear, the American tinkerer invented in 1839 the vulcanization process of rubber that made widespread industrial use of rubber possible. Another American, John Wesley Hyatt, succeeded in creating the first synthetic plastic in 1869, which he called celluloid. Its economic importance was initially modest because of its inflammability, and it was primarily used for combs, knife handles, piano keys, and baby rattles, but it was a harbinger of things to come. The breakthrough in synthetic materials came only in 1907, when the Belgian-born American inventor Leo Baekeland discovered bakelite. The reason for the long delay in the successful development of Bakelite was simply that neither chemical theory nor practice could cope with such a substance before (Bijker, 1987, p. 169). Yet Baekeland did not fully understand his own process, as the macromolecular chemical theories that explain synthetic materials were not developed until the 1920s. Once again, science and technology were moving ahead in leapfrogging fashion.

Perhaps the classic instance of a "free lunch" in which large gains in well-being were achieved at low cost was in the fine chemical industry, which after 1870 began to rationalize the hitherto chaotic industry of pharmaceutics. The use of anesthetics became widespread after Queen Victoria used chloroform when she gave birth to Prince Leopold in 1853. Disinfectants and antiseptics, particularly phenol and bromines were produced in large quantities after Joseph Lister's re-discovery of the role of microbes in the infection of wounds. One of the most remarkable inventions was the acetyl compound of salicylic acid. The medicinal properties of willow bark had been known since antiquity, and in 1897, a Bayer chemist by the name of Felix Hoffman on a hunch took the old compound off the shelf for his father who could not tolerate the side effects of sodium salicylic acid. Immediately it became clear that of salicylic acid, later known as aspirin, was a true wonder drug: effective, without serious negative side effects, and cheap to produce. Within a few years Bayer sent samples to 30,000 German doctors and the new drug was soon used universally (Mann and Plummer, 1991, pp. 26-27). Yet in essence, aspirin remained an old-fashioned technology. While it was easy to catalog its many blessing, its biochemical modus operandi remained a mystery.

Electricity: Like chemistry, electricity was a field in which totally new knowledge was applied to solve economic problems. The economic potential of electricity had been suspected since the beginning of the nineteenth century. Humphrey Davy had demonstrated its lighting capabilities as early as 1808. Relying on the scientific discoveries of scientists such as the Dane Hans Oersted and the American Joseph Henry, Michael Faraday invented the electric motor in 1821 and the dynamo in 1831. The first effective application of electricity was not in power transmission, but in communication. The telegraph was associated with a string of inventors, the most important of whom were S.T. von Soemmering, a German, who demonstrated its capabilities in 1810; William Cooke, an Englishman who patented a five-needle system to transmit messages (1837); and Samuel Morse, an American, who invented the code named after him that made the single-needle system feasible. The first successful submarine cable was laid by Thomas Crampton's Company between Dover and Calais in 1851, and became a technological triumph that lasted thirty seven years.

The telegraph, together with the railroads, was an early example of a technological system, a combination of separate inventions that had to be molded together. Just as the strength of a chain can never be greater than that of its weakest link, the efficiency and reliability of a system can never be greater than that of its weakest component. The idea of utilizing electrical current to affect a magnetized needle to transmit information at a speed much faster than anything previously possible was a classic macroinvention. Long-distance telegraph, however, required many subsequent microinventions. Submarine cables were found to be a difficult technology to master. Signals were often weak and slow, and the messages distorted. Worse, cables were subject at first to intolerable wear and tear. Of the 17,700 kilometers of cable laid before 1861, only 4,800 kilometers were operational in that year --- the rest was lost. The transatlantic cable, through which Queen Victoria and President Buchanan famously exchanged messages in August 1858 ceased to work three months later. The techniques of insulating and armoring the cables properly had to be perfected, and the problem of capacitance (increasing distortion on long-distance cables) had to be overcome. Before the telegraph could become truly functional, the physics of transmission of electric impulses had to be understood. Physicists, and above all William Thomson (later Lord Kelvin), made fundamental contributions to the technology. Thomson invented a special galvanometer, and a technique of sending short reverse pulses immediately following the main pulse, to sharpen the signal (Headrick, 1989, pp. 215-218). In this close collaboration between science and technology, too, telegraphy was clearly a second generation technology.

The use of electricity as a prime means of transmitting and using energy was technically even more difficult than the development of the telegraph. Before it could be made to work, an efficient way had to be devised to generate electric power using other sources of energy; devices to transform electricity back into kinetic power, light, or heat at the receiving end had to be created; and a way of transmitting current over large distances had to be developed. In addition, electricity came in two forms, alternating and direct current, and a decision had to be made regarding which of the two forms was to dominate.

Electric generators were crucial. Although Davy had shown as early as 1808 how electricity could drive an arc lamp, apart from lighthouses it was not widely used in lighting. Following the discovery in the mid 1860s of the principle of the self-excited generator by C.F. Varley and Werner von Siemens, the Belgian Z. T. Gramme built in 1870 a ring dynamo, which produced a steady continuous current without overheating. Gramme's machine substantially reduced the cost of alternating current. The vacuum problem was solved in 1865, when Hermann Sprengel designed a vacuum pump. Only then could the arc lamp be made practical. In 1876 a Russian inventor, Paul N. Jablochkoff, invented an improved arclamp (or "candle"), which used alternating current. Subsequently factories, streets, railway stations and similar public places began to replace gaslight with arc light. In 1878, Charles F. Brush of Ohio invented a high-tension direct-current lamp, which by the mid-1880s had come to dominate arc lighting. Inventors such as Thomas Edison and George Westinghouse realized that electricity was a technological network, a system of closely interconnected compatible inventions. In this regard it resembled gas lighting systems, but electricity was recognized to be a general system of energy transmission. Edison was particularly interested in systems of technology, and his ability to see the holistic picture and to coordinate the research effort of others were as developed as his own technical ingenuity (Hughes, 1983, pp. 25-27).

The use of electricity expanded quickly in the 1870s. A miniature electric railway was displayed at the Berlin exhibition in 1879; electric blankets and hotplates appeared at the industrial exhibition of Vienna in 1883; and electric streetcars were running in Frankfurt and Glasgow by 1884. The early 1880s saw the invention of the modern lightbulb by Joseph Swan in England and Thomas A. Edison in the United States. An electric polyphase motor using alternating current was built by the Croatian-born American Nikola Tesla in 1889, and improved subsequently by Westinghouse. Of equal importance was the transformer originally invented by the Frenchman Lucien Gaulard and his British partner John D. Gibbs and later improved by the American William Stanley who worked for Westinghouse (Hughes, 1983, pp. 86-92). Tesla's polyphase motor and the Gaulard-Gibbs transformer solved the technical problems of alternating current and made it clearly preferable to direct current, which could not overcome the problem of uneconomical transmission. Led by Westinghouse and Tesla, the forces for alternating current defeated those advocating direct current, led by Edison. By 1890, the main technical problems had been solved; electricity had been tamed. What followed was a string of microinventions that increased reliability and durability and reduced cost. In 1900, an incandescent lightbulb cost one fifth what it had twenty years earlier and was twice as efficient. All the same, the effects of electricity on manufacturing productivity were slow to be realized, as factories only slowly learned the advantages of electricity as a form of industrial power (David, 1990a, 1990b).

Transportation. By 1870 the application of steam power to transportation was hardly a novelty, and they were properly speaking products of the first Industrial Revolution (though the screw propellor and the marine steam engine were both perfected in the 1850s). Railroads became faster, safer, and more comfortable during the second Industrial Revolution but these resulted from microinventions rather than from big breakthroughs. The only truly discontinuous changes to railroads in this period were the application of new power sources: the Diesel engine, invented in 1897 by Rudolf Diesel and the use of electrical locomotives. Rudolf Diesel was a good specimen of the "new inventor", an engineer trained in science, a "rational" inventor, in search of efficiency above all else. He started off searching for an engine incorporating the theoretical Carnot cycle, in which maximum efficiency is obtained by isothermal expansion so that no energy is wasted, and a cheap, crude fuel can be used to boot (originally Diesel used coal dust in his engines). Isothermal expansion turned out to be impossible, and the central feature of Diesel engines today has remained compression-induced combustion, which Diesel had at first considered to be incidental (Bryant, 1969).Although some electrical railroads were in operation by 1914, wholesale electrification and the conversion to Diesel occurred much later.

Changes in ships were more drastic. Despite the rather amazing improvement in sailing ships resulting in the famous clipper ships, wind power was destined for niches in sports and leisure boats. First, after 1870 increasingly ships were built of steel. This made it possible to build larger ships. Since the maximum speed of a ship is proportional to the (square roots of) the water line, and iron and steel ships could be made much larger than wooden ships, ships grew bigger, more powerful, and faster at unprecedented rates. The invention of the steam turbine by Gustav de Laval and Charles Parson in 1884 and its subsequent improvement led to a revolution at sea: the rotary motion of the turbine could develop enormous speed (the prototype that Parsons built in 1884 ran at 18,000 rpm and had to be geared down), was far more efficient, faster, cleaner, and quieter, than the old reciprocating marine steam engines, and their adoption after 1900, when most of the bugs had been removed, was led by naval ships. While the typical ship of 1815 was not much different from the typical ship of 1650, by 1910 both merchant ships and men-of-war had little in common with their steam-operated predecessors half a century earlier. The result was a sharp decline in transportation costs. In the first half of the nineteenth century freight rates fell by 0.88 percent a year, which reflected mostly improvements in sailing ships. The decline after 1850 accelerated to 1.5 percent a year, rates that are all the more impressive in view of persistently rising labor costs. Despite some organizational improvements, there can be little doubt that the decline in transatlantic freight rates was the result of technological improvements (Harley, 1988).

On some occasions, a technical solution looked simple, and it may seem surprising at first sight that it took so long before producers got it right. Throughout the entire nineteenth century, mechanics experimented with a device that would allow individuals to propel themselves rapidly while seated. A variety of velocipedes and "penny-farthing" types of bicycles were experimented with, largely for recreational purposes. Yet it was not until John K. Starley, a Coventry mechanic, built the Rover safety cycle in 1885 that the balanced position and easy steering of today's bicycles became feasible. The case of the bicycle illustrates that neither purely technical factors nor purely economic factors nor even a combination of the two can fully account for technological change. The bicycle was a novelty in the deepest sense of the word; it did not replace an existing technique with a similar, more efficient one. The people who adopted the bicycle in the 1890s had previously walked or used public transportation. The optimal design of the bicycle was difficult because the attributes of the bicycle span a number of dimensions: speed, comfort, safety, elegance, and price were all considered and had to be traded-off against each other. Long experimentation was necessary before the best type emerged. In cases of a completely new product, learning-by-doing on the part of the consumer is as important as learning-by doing on the part of producers. The bicycle became a means of mass transportation with incalculable effects on urban residential patterns, especially after the invention of the pneumatic tire in 1888 by a Belfast veterinary surgeon, J.B. Dunlop, who was unhappy with the comfort of his ten-year old son's tricycle ride. After a few years of further improvements, the design of the bicycle stabilized, and few further significant improvements were introduced after 1900.

The classic case of a novel combination of known techniques laced with a number of important original contributions was the development of the automobile. The internal combustion engine was first suggested by Huygens in the seventeenth century. In 1824, Sadi Carnot had described the limitations of the steam engine as an energy source and pointed to heated air as the best potential means to generate motive power. Despite prolonged research efforts, it turned out to be difficult to employ steam power for carriages. During the nineteenth century dozens of inventors, realizing the advantages of an internal combustion engine over steam, tried their hand at the problem. A working model of a gas engine was first constructed by the Belgian Jean-Etienne Lenoir in 1859 and perfected in 1876, when a German traveling salesman, Nicolaus August Otto, built a gas engine using the four-stroke engine. Otto worked on the problem from 1860 on, after he read about Lenoir's machine in a newspaper. He was an inspired amateur, without formal technical training. Otto initially saw the four-stroke engine as a makeshift solution to the problem of achieving a high enough compression and only later was his four-stroke principle, which is still the heart of most automobile engines, acclaimed as a brilliant breakthrough (Bryant, 1967, pp. 650-57). Interestingly, the four-stroke principle had been recognized earlier as the only way in which a Lenoir-type engine could work efficiently. The "silent Otto," as it became known (to distinguish it from a noisier and less successful earlier version), was a huge financial success. The advantage of the gas engine was not its silence, but that, unlike the steam engine, it could be turned on and off at short notice.

Otto's gas engine was soon to adopt a new fuel. Somewhat earlier, in the 1860s, the process of crude oil refining using a method called cracking was developed. At that time the main interest was in lubricants, paraffins, and heavy oils, with petrol or gasoline considered a dangerously inflammable by-product. In 1885 two Germans, Gottlieb Daimler and Karl Benz, succeeded in building an Otto-type, four-stroke gasoline-burning engine, employing a primitive surface carburetor to mix the fuel with air. Benz's engine used an electrical induction coil powered by an accumulator, foreshadowing the modern spark plug. The Dunlop pneumatic tire, first made for bicycles, soon found application to the automobile. In 1893 Wilhelm Maybach, one of Daimler's employees, invented the modern float-feed carburetor. Other technical improvements added around 1900 included the radiator, the differential, the crank-starter, the steering wheel, and pedal-brake control. The effect of the automobile and the bicycle on technology was similar to that of the mechanical clock five centuries earlier: mechanics involved in making and repairing the devices acquired the skills and the ideas to extend the principles involved. Yet they also combined with late nineteenth century ideas of interchangeable parts and mass production, and by 1914 Henry Ford sold almost a quarter of a million model T automobiles per year.

The conquest of the air is an excellent example of how formal knowledge about nature and pragmatic experience combined to produce one of the most dramatic macroinventions of all times, namely the Wright brothers' celebrated heavier-than-air flight at Kitty Hawk in 1903. The Wright brothers had access to and used the knowledge on aerodynamics that had been accumulating since the pathbreaking work of George Cayley early in the nineteenth century in part through the advice of Octave Chanut, one of the leading aeronautical engineers of his time. At the same time they were skilled mechanics who had earned their spurs as bicycle repairmen in Dayton. The development of the airplane in many ways is paradigmatic of the new mode of technological progress that emerged with the second Industrial Revolution: formal and informal knowledge combining together to produce a discontinuous "event" followed by decades of microinventions which eventually produced a major industry, with further technological progress stagnating when most of the obvious improvements were exhausted.

Production Engineering: From a purely economic point of view, it could be argued that the most important invention was not another chemical dye, a better engine, or even electricity, since, with the exception of steel, most of the inventions described had serviceable albeit less efficient and more expensive substitutes, if not as efficient or as cheap. There is one innovation, however, for which "social savings" calculations from the vantage point of the twentieth century are certain to yield large gains. The so-called American System of manufacturing assembled complex products from mass-produced individual components. Modern manufacturing would be unthinkable without interchangeable parts. The term American is somewhat misleading: the idea that interchangeability had enormous advantages in production and maintenance had occurred to Europeans in the eighteenth century. Moreover, what was regarded in the 1850s as the American System was not exactly interchangeability, but the application of high-quality, specialized machine tools to a sequence of operations, particularly in woodworking, as well as higher operating speeds and sequential movements of materials. As Ferguson (1981) has pointed out, mechanized mass production and interchangeable parts were not identical, and the former did not imply the latter.

Interchangeable parts was not an "invention." It was eventually to become a vastly superior mode of producing goods and services, facilitated by the work of previous inventors, especially the makers of accurate machine tools and cheap steel. To be truly interchangeable, the parts had to be identical, requiring high levels of accuracy and quality control in their manufacture. It is now realized that full interchangeability was more difficult to achieve than had previously been believed. The use of interchangeable parts grew slowly after 1850, and recent research has shown that the American System was adopted far more haltingly and hesitantly than had hitherto been thought. Many American firms, such as McCormick, Singer, and Colt, owed their success to factors other than complete interchangeability (Hounshell, 1984). At first, goods made with interchangeable parts were more expensive and were adopted mostly by government armories, which considered quality more important than price (Howard, 1978; M.R. Smith, 1977). Only after the Civil War did U.S. manufacturing gradually adopt mass production methods, followed by Europe. First in firearms, then in clocks, pumps, locks, mechanical reapers, typewriters, sewing machines, and eventually engines and bicycles, interchangeable parts technology proved superior and replaced the skilled artisan working with chisel and file. Although in the long run true interchangeability was inexorable, its diffusion in Europe was slowed down by two factors: the demand for distinctive high-quality goods, which long kept consumers faithful to skilled artisans, and the resistance of labor, which realized that mass production would make its skills obsolete.

Of related importance was the development of continuous-flow production, in which workers remained stationary while the tasks were moved to them. In this way, the employer could control the speed at which operations were performed and minimize the time wasted by workers between operations. In the last third of the nineteenth century continuous flow processes were adopted on a large scale, especially in the great stockyards of Chicago and Cincinnati. Henry Ford's automobile assembly plant combined the concept of interchangeable parts with that of continuous flow processes, and it allowed him to mass-produce a complex product and yet keep its price low enough so that it could be sold as a people's vehicle. As Giedion (1948, p. 117) points out, Ford's great success was rooted in the fact that, unlike Oliver Evans, he came at the end of a long development of interchangeability and continuous flow processes. Success depends not only on the ingenuity and energy of the inventor, but also on the willingness of contemporaries to accept the novelty.

<u>Agriculture and Food Processing</u>: The standard of living of the population depended, above all, on food supply and nutrition. The new technologies of the nineteenth century affected food supplies through production, distribution, preservation, and eventually preparation. In agriculture, the adoption of the new husbandry based on fodder crops and stall-fed livestock continued apace, though in France and in most of eastern Europe progress was slow. New implements and tools appeared on the scene, but here the traditional obstacles to technological progress in agriculture retarded growth: inventions that were useful in some environments failed elsewhere. A few "general-purpose" technologies such as barbed wire (invented in 1868) were made, but the bulk of technology was site- and crop specific.

Agricultural productivity owed much to the extended use of fertilizers. Farmers learned to use nitrates, potassium, and phosphates produced by the chemical industries. In addition to the *guano* already mentioned, the large American stockyards produced fertilizers made from animal bones combined with sulphuric acid. The productivity gains in European agriculture are hard to imagine without the gradual switch from natural fertilizer, produced mostly in loco by farm animals, to commercially produced chemical fertilizers. Fertilizers were not the only scientific success in farming: the use of fungicides, such as Bordeaux mixture, invented in 1885 by the French botanist M. Millardet in 1885, helped conquer the dreaded potato blight that had devastated Ireland forty years earlier.

Technological progress outside agriculture affected food supplies in many ways. Steel implements, drainage- and irrigation pipes, steam-operated threshers, seed drills, and mechanical reapers slowly but certainly improved productivity and expanded the supply of food and raw materials. Yet here more than anywhere else the old resisted the new, and modern tools and techniques continued to coexist with manual operations that had not changed in centuries. Mechanizing agriculture involved overcoming some technical difficulties. Much work in agriculture, such as weeding, picking, and milking, was carried out by movements of the human fingers, as opposed to the sweeping or beating motions of the human arm. Furthermore, the mechanization of agriculture was slow (compared to manufacturing) because of the lack of power substitutes. In most industrial processes, the act of production can occur at the site of the power source. The utilization of more efficient energy sources was thus rather simple. In agriculture, the power sources had to be brought to the production site (i.e., the land) for most activities, and thus plowing, harrowing, reaping, raking, and binding remained dependent on draft animals long after manufacturing and transportation had adopted the steam engine. The application of steam power to agriculture was not a success. Only when the work could be carried out near the power source, did mechanization come relatively early: the threshing machine built in 1784 by the Scotsman Andrew Meikle spread quickly, as did the winnowing machine built in 1777 by a London mechanic, James Sharp. These machines were attached to steam engines in the first half of the nineteenth century, but they remained something of an exception. The internal combustion engine solved all that, and by the eve of World War I, the first tractors and combines were being introduced on both sides of the Atlantic. In 1880, it still took 20 man-hours on average to harvest an acre of wheat in the United States; by 1935 this figure had fallen to 6.1.

Of special interest to the historian interested in economic welfare is the development of food preparation and preservation. Much human suffering has been caused over the ages by nutritional deficiencies and by the unwitting consumption of contaminated foods. Food-canning had been invented in 1795, but because the process was not understood, the food was overprocessed and tasted poorly. Only after Louis Pasteur's path-breaking discoveries was it understood why canning worked, and not until the end of the century did it become clear that the optimal cooking temperature was about 240°F. Canned food played an important role in provisioning the armies in the American Civil War, and led to vastly increased consumption of vegetables, fruit, and meat in the rapidly growing cities. Other food preservatives were also coming into use. Gail Borden invented milk powder in the 1850s and helped win the Civil War for the Union and a fortune for himself. By the end of the century his dehydration idea was also successfully applied to eggs and soups. The centrifugal cream separator, invented by Gustav de Laval in 1877 soon became the cornerstone of the dairy cooperatives in Denmark, the Netherlands, and Ireland. Pasteur himself showed how to sterilize bottled cow milk. Cooling was an alternative form of preservation. In the eighteenth century, ice was preserved in special icehouses, and an international market in ice emerged in the early nineteenth century, though in the warm seasons the price of ice was so high that only the rich could afford it. Mechanical refrigeration was gradually developed and improved upon between 1834 (when the first patent for the manufacture of ice was issued in Britain) and 1861 (when the first frozen beef plant was set up in Sydney, Australia). By 1870, beef transported from the United States to England was preserved by chilling (29° - 30° F). The efficient method of preserving beef, however, was by deep freezing at about 14° F. In 1876 the French engineer Charles Tellier built the first refrigerated ship, the *Frigorifique*, which sailed from Buenos Aires to France with a load of frozen beef. By the 1880s, beef, mutton, and lamb from South America and Australia were supplying European dinner tables. Farming in Europe suffered from this competition, but the consumer, the ultimate and final arbiter of all questions of economic progress, benefitted greatly. Technological changes reduced the price of food in general to the point where after 1870 in many countries farmers, rather than consumers, turned to their governments for help. The decline of the price of proteins relative to carbohydrates helped to augment and improve European diets.

Other Manufacturing Sectors. In textiles, progress after 1870 was gradual and not marked by great breakthroughs. One major innovation that came to its own in this period was the sewing machine. Apparel making had lagged behind the rest of the textile industry during the early stages of the Industrial Revolution despite an international search for a machine that would replace the motion of the human hand in the stitching process. These machines were at first technically unworkable, but after 1830 a solution began to appear on the horizon. Elias Howe, an American, is usually credited with the invention, but he merely perfected one crucial feature, the lock stitch, patented in 1846, and made his machine of metal parts. The man who deserves the most credit for perfecting the sewing machine is Isaac Merritt Singer, who powered his machine with a foot treadle. A conservative estimate of the increase in productivity resulting from the sewing machine puts it at 500 percent (Schmiechen, 1984, p. 26). It was later adapted to make shoes (the McKay shoe sewing machine dates from 1861) and carpets (1880). Annual production of sewing machines went from 2,200 in 1853 to half a million in 1870. Unlike many other inventions in textiles, the sewing machine did not lead to factories, as it did not require a centralized power source. Instead, it kept struggling domestic workers (mostly women) occupied, and created a system of notorious sweatshops. The sewing machine was slow in adopting interchangeable parts; the Singer Company was successful primarily because of brilliant marketing, but still used skilled fitters long after its competitors had switched to fully interchangeable parts (Hounshell, 1984, pp. 67-123).

In the rest of the textile industry, the period after 1870 had the character of a mopping-up operation. The combing of wool, which had long defied mechanization, was further improved by the introduction of the Lister-Donisthorpe nip machine in the 1850s, reviving the fortunes of the Yorkshire worsted industries. The Heilmann combing machine was used widely on the Continent, especially in Alsace. In spinning, the throstle that had dominated the scene until the 1860s was slowly superseded by ring spinning. Unlike mule spinning, in which the twist was imparted by the combined action of rollers and the revolving spindles, ring spinning involved the twisting of the yarn by the circular movement of a clip on the rapidly turning ring, called the *traveler*. The traveler guided the thread and ensured its winding on the spindle. Ring spinning was continuous rather than intermittent, and required less skill and strength than mule spinning. It produced a slightly inferior product, however, especially for fine yarns. Ring spinning did not spread widely until the second half of the nineteenth century, but then it conquered the U.S. textile industry rapidly. Lancashire in Britain remained loyal to mules, however, a fact that has long intrigued economic historians, as it seemingly indicates a reluctance on the part of British industry to adopt a superior technology. In weaving, the power loom continued to replace handloom weavers after 1850, but automation came to weaving only after J.H. Northrop built the first automatic loom in 1894 and it was widely adopted in the U.S. and the Continent in the next two decades. By this time, Britain's textile industries had lost their position at the cutting edge of technology, and British adoption of the Northrop loom was slow.

Finally, I turn briefly to what may best be called information technology. Following the telegraph in the 1830s, a "modern" pattern starts to emerge, in which practice followed theory. Thus, Hermann Helmholz, a German physicist, experimented with the reproduction of sound, which inspired a Scottish-born speech therapist teacher at Boston University named Alexander Graham Bell to work on what became the telephone (1876). Supplementary inventions such as the switchboard (1878) and the loading coil (1899), made the telephone of the most successful inventions of all time. Wireless telegraphy is another outstanding example of the new order of things, in which science led technology rather than the other way around (Aitken, 1976). The principle of wireless telegraphy, as yet unsuspected, was implicit in the theory of electromagnetic waves proposed on purely theoretical grounds by James Clerk Maxwell in 1865. The electromagnetic waves suggested by Maxwell were finally demonstrated to exist by a set of brilliant experiments conducted by Heinrich Hertz in 1888. The Englishman Oliver Lodge and the Italian Guglielmo Marconi combined the theories of these ivory tower theorists into wireless telegraphy in the mid-1890s, and in 1906 the Americans Lee DeForest and R.A. Fessenden showed how wireless radio could transmit not only Morse signals but sound waves as well.

Little science but a lot of experimentation was necessary for another invention that had an enormous effect on information technology: the typewriter. The idea of the typewriter is conceptually obvious, but a number of minor technical bugs, such as bars clashing when two letters were typed very closely together, bedeviled its perfection. These problems were finally solved by Christopher L. Sholes of Milwaukee, reputedly the 52nd person to invent the typewriter. Sholes sold his patent to the Remington Company in 1874, and a small revolution in the office began. The technical problems in the printing industry were more complex. Typesetting had always been laborious and slow work, and the need for improvement was becoming acute as literacy rose and the thirst for information grew in the late eighteenth- and nineteenth centuries. The first rotary press was built in Philadelphia in 1846. A horizontal cylinder contained the printed material, and rotated in contact with smaller cylinders, each of which corresponded to a page, with automatic grippers guiding the pages from cylinder to cylinder. This machine, originally conceived by Robert Hoe, found its way to Europe, where many leading newspapers adopted it. It was fast but labor intensive. Typecasting, equally revolutionary in that it recast the type each time anew using an automatic process, was perfected in the United States in 1838; by 1851 it had spread all over Europe. An alternative technique, invented by Henry Bessemer (of steel fame), was the *pianotype*, where the operator worked at a keyboard. For a while, a confusing multitude of automatic typesetting techniques were in operation at the same time. Between 1886 and 1890, a German immigrant to the United States, Ottmar Mergenthaler, invented the linotype machine, which cast and set a whole line at a time using a keyboard controlling hundreds of matrices, from which the letter molds were made. Linotype machines were primarily used for newspapers; for books, a related machine, the monotype typesetter, was developed in the 1890s. With the increase in demand for paper, new raw materials became necessary and, after much experimentation, the use of woodpulp was perfected in about 1873.

Household Technology and Human Welfare From a purely material point of view, the technological changes described above must have increased the well-being of the populations of Western Europe and North America, with somewhat delayed and smaller effects being felt in Eastern Europe and in a few areas in Asia and South America. Yet one could argue that it is not easy to establish the net effect of technological progress on human well-being. Industrialization led to urbanization, to the concentration of large numbers of workers in dangerous and unpleasant factories and mines, to alienation, the breaking-up of traditional communities compounded by large waves of emigration. Moreover, the half century of technical advance I called the second Industrial Revolution was punctuated by a cataclysm of unprecedented dimensions. The sheer massiveness of the destruction of the First World War was in large part attributable to the power of the new technology: steel, chemicals, high explosives, barbed wire, internal combustion engines, mass production -- the nightmare of 1914-18 reflects the achievements of the previous decades faithfully.

And yet it is clear that until 1914 life was getting better, incomes were rising, work-hours slowly declining, some forms of social insurance emerging, nutrition and housing slowly improving. The statistical evidence from demography seems to bear this out without any question. Between 1870 and 1914 infant mortality declined by about 50%: in France, which was fairly typical, the rate fell from 201 per thousand in 1870 to 111 in 1914. In Germany the corresponding numbers were 298 and 164. Life expectancy at birth increased accordingly, in Britain it went from about 40 years to 50. This decline was in part due simply to rising incomes:

as people enjoyed higher incomes, they could buy more and better food, live in less congested and better heated dwellings, own better clothes, and had access to running water, sewage, and medical care.

Yet the period of the second Industrial Revolution witnessed another technological development which has not been properly appreciated for it huge impact on human welfare. We tend to think of technology as occurring in manufacturing and service firms and on the land, but economists have long understood that household technology in many ways resembles production technology in that knowledge leads us to employ techniques and routines by which we manipulate natural regularities to better our material conditions: economic agents cooked food, sewed clothing, took care of babies and the elderly and so on, based on what they knew.

The knowledge used in household production went through its greatest transformation ever in the years surveyed here. Once again, the change was not quite as sharp: some important precedents can be discerned long before, and the process was far from complete in 1914. Yet changes in household technology were crucial in reducing mortality after 1870 (See Mokyr ,1996; Mokyr and Stein, 1997; and Easterlin, 1996)). The knowledge underlying these changes was the sudden growth in the understanding in the nature of infectious disease due to the work of Pasteur, Koch, and their associates. Within a few decades the medical profession managed to work out a more or less complete theory of infectious disease in which many of the causative agents were identified and their modes of transmission established. Medical practices before 1914 improved only in isolated areas, and had but little effect. The main impact that the new bacteriology had was in *preventive* techniques. Households increasingly realized that by following certain simple "recipes" they could reduce the incidence of infectious disease. Germs could not be seen, but they could be fought by simple household techniques, available at relatively low cost. Once water was established as a carrier of certain diseases, people began to realize the importance of filtering, boiling and later chlorination. When insects were identified as a carrier of malaria and yellow fever, a war against insects erupted. Food-borne diseases could be reduced by proper cooking, cleaning, and preservation. All this had to be taught and the teaching took time. Many mistakes were made, wrong turns made, causal mechanisms mis-identified and false recommendations made. Yet when all is said and done, the effects of this technological revolution on human welfare are the most unequivocal: the sharp decline in mortality rates in this period speaks for itself.

Conclusions. The second Industrial Revolution was, in many ways, the continuation of the first. In many industries there was direct continuity. Yet it differed from it in a number of crucial aspects. First, it had a direct effect on real wages and standards of living which clearly differed significantly in 1914 from 1870. Second, it shifted the geographical focus of technological leadership away from Britain to a more dispersed locus, though leadership remained firmly the monopoly of the industrialized Western world. Finally, by changing the relation between knowledge of nature and how it affected technological practices, it irreversibly changed the way technological change itself occurs. In so doing, what was learned in these years prepared the way for many more Industrial Revolutions to come.

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