TECHNOLOGICAL TRANSFORMATIONS AND LONG WAVES

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Preface

Over the past decade IIASA has sponsored several international conferences on long-wave phenomena. The latest of these was a conference on "The Life Cycle and the Long Wave," which took place in Montpellier, France, in July 1987. This paper was not presented at the conference, but it was (according to the author) inspired by it. In any case, it clearly fits into the general scope of the Technology, Economy and Society Program at IIASA.

F. SCHMIDT-BLEEK
Leader
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TECHNOLOGICAL TRANSFORMATIONS AND LONG WAVES

R.U. Ayres

1. Introduction

1.1. Background

The possibility of long cycles in prices and in economic activity of about 50 years from peak to peak was noted more than a century ago by W.S. Jevons (Kleinknecht, 1987, p. 2). In fact Jevons cited even earlier articles. However, the first author to subject the hypothesis of long cycles to systematic analysis was the Marxist Dutch economist Van Gelderen (1913), who anticipated much that has been rediscovered by others. Among these rediscoverers is the Russian economist N.D. Kondratieff (1926, 1928, 1978), whose classic work has resulted in his name being permanently associated with the phenomenon.

Van Gelderen was the first to suggest a plausible causal hypothesis: that a long period of rising prices (prosperity) is driven by the rapid growth of one or more leading sectors. Van Gelderen also discussed and tried to explain other important features of the process, including periodic over and under investment of capital, periodic scarcity or abundance of basic resources, and credit expansion and contraction.

Joseph Schumpeter's well-known study of business cycles was, in many ways, an extension and update of Van Gelderen's ideas (Schumpeter, 1939). He proposed that temporal clustering of a number of major technological innovations during periods of deflation and recession might account for the dramatic growth of the so-called leading sectors; in turn the leading sectors seem to drive the inflationary half of the cycle. This idea was immediately and sharply challenged by Simon Kuznets, who doubted both the existence of Kondratieff cycles and the causal explanation suggested by Schumpeter (Kuznets, 1940). However, Kuznets seems to have taken the idea more seriously in a later book (1953).

The subject has been revived yet again in recent years, especially by Rostow (1975, 1978), Mensch (1975), and Forrester (1976, 1979, 1981). Rostow's interest is primarily directed to the phenomenon of takeoff leading to sustained long-term economic development. He views Van Gelderen's leading sectors not only as the drivers of the long wave, but as the engine of long-term growth for the whole economy. Mensch attempted to document the innovation-clustering hypothesis and to explain the gaps between clusters by invoking a theory of investment behavior, namely, that during periods of general prosperity investors will shy away from risky long-term ventures (innovations) whereas during periods of stagnation or recession they may be more willing to invest in new ventures. The latter thesis, in turn, has spawned a new wave of critiques and variants, including studies by Mandel (1980); Clark, Freeman, and Soete (1982); Freeman (1983); Van Duijn (1983); Mansfield (1983); and Kleinknecht (1981, 1984, 1987).

At least one important variant of the Schumpeter-Mensch thesis, associated primarily with Freeman and his co-workers, has emerged from this debate. The rapid growth period of the long wave is not necessarily driven by innovations occurring in the immediately preceding trough. There seem to be other cases in which the rapid growth period was driven in some part by the adoption/diffusion of important technologies that were tentatively introduced much earlier, but which needed a long gestation or were not yet ripe for some reason. This notion does not dispute the importance of the basic innovation (or the key facilitating inventions preceding it), but it does put major emphasis on the subsequent processes of development, improvement, application to new (and sometimes unexpected) purposes, and subsequent adoption. In all this there is continuous and vital feedback between the innovator and the user, characterized by learning on both sides. The technology diffusion process, as this set of interactive phenomena is usually called, thus becomes quite central to any complete theory of long waves. Key theoretical contributions to the adoption/diffusion literature have been made in recent years by Nelson and Winter (1977), Sahal (1981), Dosi (1982), and Perez (1983, 1983a).

1.2. Summary of the argument

The starting point for this paper is Schumpeter, in the sense that the existence of long waves (but not necessarily cycles) in economic activity is taken for granted. The objective evidence indicates that since about 1780 there have been several extended periods of extraordinary economic growth followed by periods of reduced growth punctuated by deep recessions. A rough periodicity of 50 to 55 years can also be observed, although it varies from country to country. For several reasons, the notion of an underlying causal dynamic must remain highly speculative. In other words, waves can be seen somewhat clearly, at least in retrospect, but "cyclicity" remains doubtful.

Schumpeter's suggestion that temporal clustering of major innovations in a trough is the primary mover to the next wave is consistent with a growing weight of evidence that economic growth is, indeed, driven by technological change. But Freeman's variation on this theme is no less consistent and probably provides a more powerful explanation. This paper adds nothing to the empirical evidence for either waves or clusters, merely noting that the recent work of Kleinknecht (1981, 1984, 1987) has strengthened the case for the latter. The purpose of this paper is to explore why such clusters occurred when they did. It is equally important to test the Freeman thesis, seeking examples and explanations of growth driven by belated diffusion. In particular, the question is whether innovations are essentially independent events (in which case temporal clustering would imply the existence of an underlying causal dynamic) or whether clusters occur naturally in connection with mesoscale technological transformations – essentially the creation of new industries – because both innovation and diffusion depend in a fundamental way on prior and concurrent developments in other fields.

The essence of the latter view (which is the one adopted hereafter) is that advances in technology, together with an exhaustion of certain natural resources, have combined to bring about a series of coordinated technological transformations that are correlated with waves of economic activity. These coordinated transformations have affected virtually all aspects of economic life. In fact, the first and second waves (beginning ca. 1775 and ca. 1825) have commonly been combined and called the "first industrial revolution." The third transformation, which began around 1870, could very well be called the "second industrial revolution." A fourth transformation, affecting consumers more than industry, began in the late 1930s, was interrupted by World War II, and continued through the 1950s. A fifth transformation with some revolutionary implications for both industry and consumers seems to have begun in the 1970s.

The first transformation (1770–1800) was accompanied by a shift from dependence on charcoal and waterpower to large-scale use of coal for energy. This required a quantum increase in goods transportation capability, which was initially met by the building of canals to link the major rivers of the UK. The completion of the basic links of the canal system around 1790 coincided with the economic "takeoff," and canals (primarily for carrying coal) were extremely profitable for the next half century. The steam engine gradually made coal-based energy available for rotative motion, for a variety of purposes, regardless of location.

During the last two decades of the eighteenth century, a major new textile material (cotton) and a new structural material (wrought iron) decreased sharply in price and became widely available. The combination of steam engines with new iron-working and machine-tool technology made coal-based energy available for prime movers. First, stationary engines supplemented, and finally replaced, waterpower to drive factory machinery. Later mobile engines supplanted horses and the wind. It was the former development that led to the railroads (iron horses), beginning around 1830. Widespread application of steam power to manufacturing and transportation – diffusion – was the key to the second technological transformation. Railways, incidentally, broke the canal's monopoly on heavy goods transport in the UK, while steam engines were making river transport far more practical in the US. The decline in profitability of UK canals led to heavy losses in canal share prices (i.e., in nominal wealth) between 1838 and

1843, while the second and more massive railway construction boom in the mid-1840s undoubtedly contributed to the economic recovery that followed. Railway building, incidentally, provided the impetus for major expansion in iron production, the adoption of more efficient smelting technology (the hot blast), and the search for better ways of making steel (which culminated in the discoveries of Henry Bessemer *et al.* in the 1850s). It also triggered the creation of a telegraph network, at least in the UK. Meanwhile, the availability of an efficient transport infrastructure together with an evolving technology of coking, led to the innovation of the gaslight. The town-gas industry started very slowly, but accelerated rapidly in the 1840s and 1950s.

The third technological transformation (1870–1895) was more complex. It centers around the substitution of steel for iron as an engineering material, the beginnings of the petroleum and electric-power industries, and the development of the internal-combustion engine. Steel, gasoline, and the internal-combustion engine made the automobile possible, just as steam power and wrought iron combined to facilitate the railroad. New combinations and technological spin-offs from these basic changes resulted in the creation of a number of other new industries.

One was a spin-off of the gaslight industry: dyes made from coal tar began to replace vegetable dyes for textiles (mainly in Germany). During this period the chemical industry expanded rapidly, as growing use of textiles triggered greater use of soaps, bleaches, and dyes. Growth of the market for illuminating oil created a refining industry and new requirements for basic chemicals, especially sulfuric acid and sodium hydroxide. But above all, they permitted an enormous increase in manufacturing productivity, especially in the US. Just as coal, iron, cotton, and railroads spearheaded the great UK economic expansion from 1780 to 1860, the rise of the steel, petroleum, automobile, and electrical industries propelled a comparable US expansion from 1880 to 1930 and resumed after World War II. This expansion was clearly related to the diffusion of steel, automobiles, telephones, and electrification throughout society.

The period of greatest gains in prosperity occurred after an initial period of heavy investment in technology development and infrastructure buildup. The construction of the US railroad system had peaked by 1920. The same is true of the urban trolley system (since dismantled) that once connected Maine with Wisconsin. The urban road network was still growing, but more slowly. (The US government began a major highway-building program in the 1930s as an anti-depression measure. An even bigger program was begun in the 1950s.) The mining and distribution system of coal and the (coal-based) gas distribution were in place by 1920; at this time coal consumption was stable or declining. In fact, 1910 was the peak year for gas lighting. All cities and towns also had electric power generating and distribution systems of electric power and telephone exchanges, and many systems were already interconnected by 1920.

It has been suggested that the synergistic combination of telephone networks and road networks – which facilitated truck transportation – permitted a dramatic economic decrease in inventory requirements during the 1920s.[1] At any rate, capital productivity rose sharply during that decade, perhaps the most dramatic such rise of which we have reliable statistical evidence.

During the first 50 years of the nineteenth century labor productivity in the US rose a mere 0.5% per year. This increased to 1% per year from 1850 to 1890, then nearly doubled to 1.9% per year from 1890 to 1900, and continued at 1.8% per year through 1929 (Schurr *et al.*, 1983). Yet multifactor productivity grew only 0.8% per year from 1899 to 1920, so capital productivity increased very little, if at all, during that period. On the other hand, after 1920 the situation reversed: multifactor productivity significantly exceeded labor productivity for a time, which implies a sharp increase in the productivity of existing capital (Schurr, 1984). It is difficult to avoid concluding that this reflected the end of the buildup associated with the third transformation. It also suggests the possibility that such a synergistic combination of events might occur again, perhaps in the relatively near future.

The last half century shows marked deviations from the earlier pattern in several respects. The Great Depression, followed by World War II, resulted in a substantial accumulation of savings and pent-up demand, which propelled a renewed postwar period of expansion. It was fed by consumer demand and led, to a large extent, by the same group of industries as before (steel, auto, petroleum, and electrical). A slowdown in the growth of demand for steel was roughly compensated by growing demand for aluminum and plastics, but the dominant process, in economic terms, was the further diffusion of technologies that were already well established during the previous transformation. To be sure, the electrical industry expanded to embrace appliances and "white goods." Many new plastics and drugs were introduced. But despite the growing importance of a number of peripheral technologies, such as air transportation, consumer electronics, computers, and pharmaceuticals, as a group they were not important enough to take over the role of "locomotive" for the whole world economy. The slowdown of the 1970s may have been a case of simultaneous maturation of a number of the major growth industries of earlier times, most notably the automobile industry and its satellites.

The last decade has witnessed the start of a new and major technological transformation, leading (as many have suggested, e.g., Bell, 1976; MacRae, 1984) to a "postindustrial" society, in which information and telecommunication services are the primary generator of wealth and engine of growth. The very large cumulative investment in computers made over the past 30 years may now be starting to pay off in terms of a new jump in capital productivity (Ayres, 1989). Once again, synergistic gains arising from the combination of telecommunication and computer technologies appear to be on the verge of facilitating sharp improvements in the ratio of industrial output to inventory. Significant gains have already been recorded in many countries since 1980 (Dimitrov and Wandel, 1988, figs. 2 and 3). In this case, Japan has led the way by pioneering just-in-time manufacturing methods. However, the potential of so-called computer-integrated manufacturing (CIM) is far beyond anything seen to date. In fact, the goal of many manufacturing firms, once considered visionary, is no less than the ability to produce on demand (rather than for inventory) with a turnaround time measured in hours or days, rather than weeks or years (Ayres and Miller, 1983, chap. 6; Ayres, 1984, chap. 6). This goal is likely to be approached in many cases within the next 20 years.

1.3. Stylized chronology of long waves

The long (45–60 year) wave was originally observed as an alternating period of inflation or rising prices, followed by deflation or falling prices, each lasting about 25 years. Of course, price indices in the modern sense cannot be reconstructed for the full historical period of interest, except for a relatively few key commodities. *Figures 1* through *4* show price indices for the UK and the US, respectively. For each country two indices are shown. *Figures 1* and *2* display wholesale prices relative to the 50-year moving average for the UK and the US in two versions: unsmoothed and smoothed over an 11-year period. *Figures 3* and *4* display wholesale prices smoothed over a rolling 25-year period, again relative to the 50-year moving average. The long wave is most clearly visible in the smooth version, of course. Note that there are significant differences between the two countries:

		UK	US
First Wave	A period	1782–1820	–1808
	B period	1820–1839	1808–1842
Second Wave	A period	1839–1868	1842–1869
	B period	1868–1894	1869–1895
Third Wave	A period	1894–1920	1895–1920
	B period	1920–1945	1920–1945
Fourth Wave	A period	1945–?	1945–?

If the long wave is anything but a statistical coincidence, there should be a correlation between rising prices (inflation) and economic growth (prosperity). That is to say, basic economic theory suggests that sustained prosperity is likely to result in bottlenecks and scarcities that tend to drive prices up. By the same token, stagnation and recession tend to result in underutilization of capital and excess supply of many commodities, hence (where markets are unfettered) declining prices. The stylized scheme set forth by Van Gelderen (1913) focuses on turning points between inflationary (A) periods and deflationary (B) periods.

Various authors have suggested different long-wave chronologies, depending on the particular countries and time series they were studying. A summary can be found in Van Duijn (1983, p. 163). The most orthodox (i.e., consistent with the ideas of Kondratieff) is that of Mandel (1980), which is adopted hereafter for convenience. Bieshaar and Kleinknecht (1983) have shown that other chronologies are often better for particular countries, but not necessarily for the world as a whole. In any case, the differences are not great.

Bieshaar and Kleinknecht have also carried out econometric tests comparing six of the chronologies, including Mandel's, in terms of average growth rates during A and subsequent B periods for a number of time series for industrial production, net national product, gross national product, and gross domestic product, depending on availability. They concluded that statistical evidence of the existence of waves since 1890 is quite strong and robust, but in the case of the countries with large internal markets (the UK, France, Federal Republic of Germany, and the US) statistical evidence of the waves prior to 1890 is weak. On the other hand, for some smaller countries with more open economies,

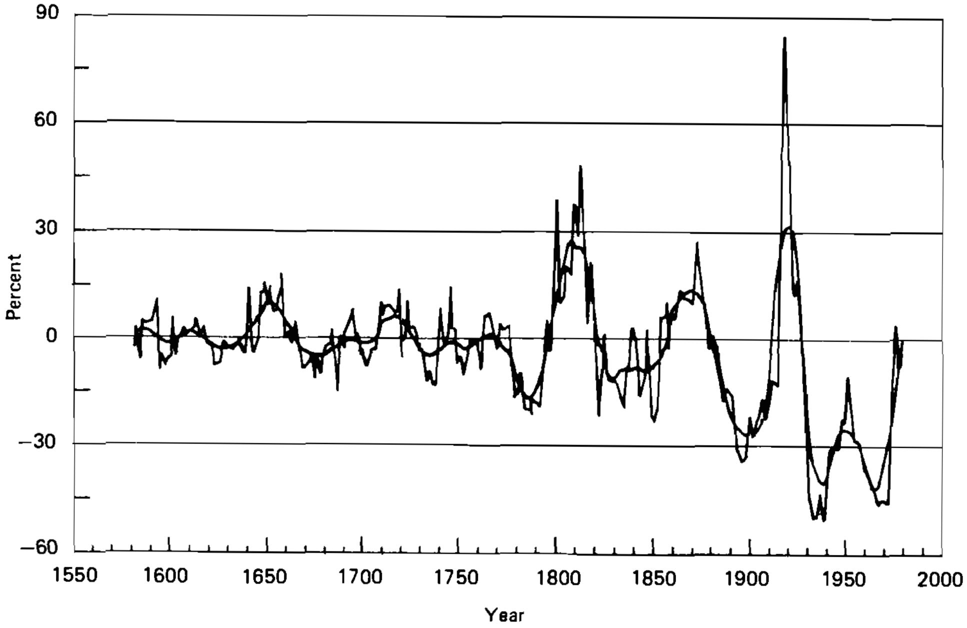

Figure 1. UK wholesale price index. (Source: N. Nakicenovic, IIASA, 1987.)

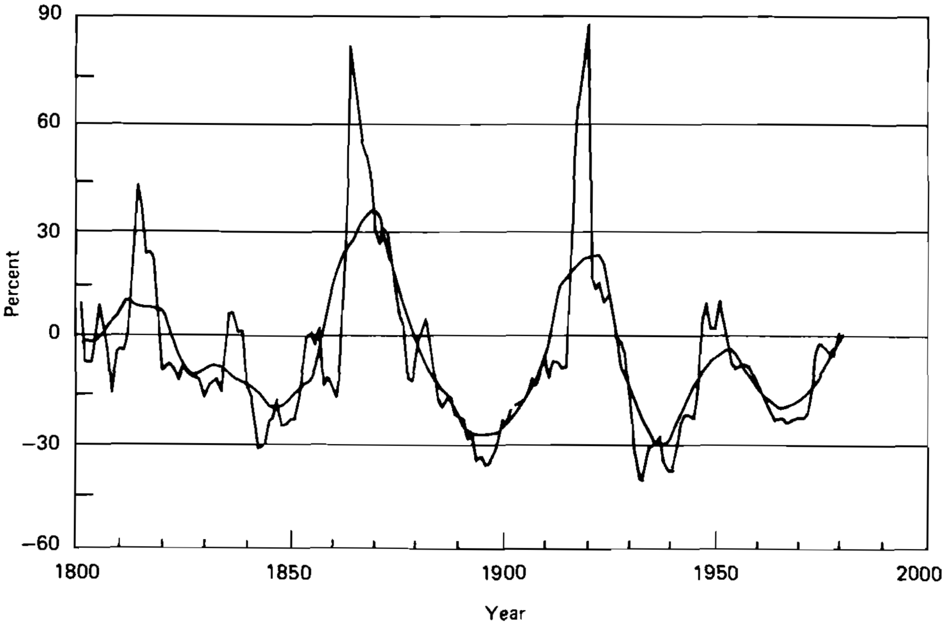

Figure 2. US wholesale price index. (Source: N. Nakicenovic, IIASA, 1987.)

notably Belgium, Sweden, and Italy – presumably better reflecting world market conditions – the statistical evidence for waves in the earlier period is stronger. Mandel's chronology is summarized in *Table 1*, respectively.

Table 1. Mandel's chronology of long waves.

Identification	*Phase*	*Years*
First Kondratieff Wave	A	1792–1825
	B	1825–1847
Second Kondratieff Wave	A	1847–1873
	B	1873–1893
Third Kondratieff Wave	A	1893–1913
	B	1913–1939
Fourth Kondratieff Wave	A	1939–1974
	B	1974–?

It must be emphasized that the evidence for the first two waves (and the entire chronology) is derived largely from commodity price data, which are by nature unreliable and incomplete. It must also be pointed out that the Mandel chronology differs somewhat from the chronology derived from *Figures 3* and *4*, respectively.

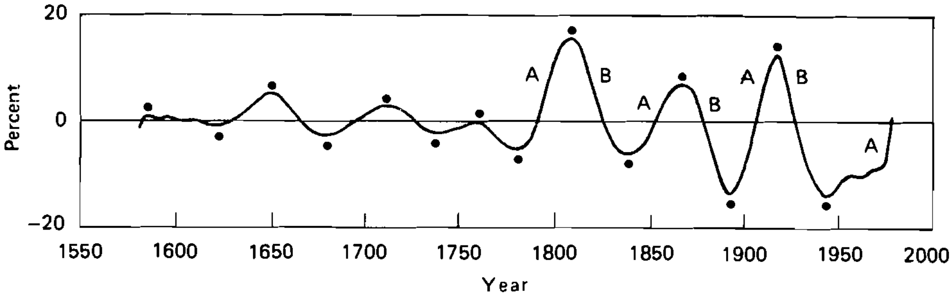

Figure 3. UK wholesale price index, smoothed. (Source: N. Nakicenovic, IIASA, 1987.)

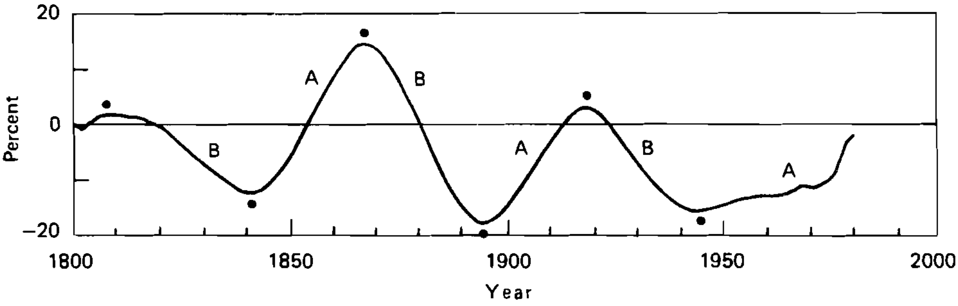

Figure 4. US wholesale price index, smoothed. (Source: N. Nakicenovic, IIASA, 1987.)

1.4. The Schumpeterian thesis in brief

The basic Schumpeter theory, as elaborated by Mensch (1975), combines the following two basic hypotheses:

(H1) Economic growth in A periods is propelled mainly by radical (Schumpeterian) innovations that create new, rapidly growing industries that, in turn, create jobs, income, and consumer demand.
(H2) Radical innovations tend to cluster during periods of economic stagnation (B periods) due to lack of favorable short-term investment opportunities.

There are possible refinements to this basic scheme. For example, Mensch argues that new products are inherently "demand-increasing," whereas new processes are inherently "cost-saving," and suggests that the latter tends to cluster during B periods. A direct test of this interesting corollary would require a much better database on the distribution of process innovations and/or improvements than exists currently. A further refinement would be to classify innovations as "Schumpeterian" (truly new combinations) or "Usherian" (gradual) improvements. One might then look for evidence that radical (Schumpeterian) innovations cluster in A periods while incremental (Usherian) improvements characterize B periods.

The basic hypothesis examined here (H3) is that periods of rapid economic growth in a sector tend to occur some time after a critical technological barrier is overcome (to allow for development and infrastructure buildup). The sequence is as follows:

(1) One or more "technological breakthroughs" occur(s).
(2) A flurry of applications, improvements, refinements, and spin-offs follows. These tend to define a "technological trajectory" (Nelson and Winter, 1977) that is determined by both the state of knowledge and feedback from early users.
(3) Finally, there is a period of widespread adoption and diffusion.

This characteristic sequence has been termed the "technological life cycle" (Utterback and Abernathy, 1979; Ayres, 1987, 1988). The significance of time lags for information diffusion and infrastructure buildup have been stressed by the neo-Austrian capital theorists (Faber, 1985).

To elucidate this link between the life cycle and the long wave it is necessary to define barriers (or, in some cases, bottlenecks) and breakthroughs in suitable terms. If the life cycle is to throw any light on the long wave, it is also necessary to explain why some technological breakthroughs have been particularly critical, in the sense of overwhelming all others in relative importance. A subsidiary hypothesis examined hereafter is that the most potent bottleneck-breaking innovations of the first two technological transformations were, essentially, energy, material, or capital saving in nature. These factors often go together, inasmuch as increased energy supply requires capital investment. Thus, the most important single use of early steam engines was to pump water out of the lower levels of coal and tin mines. Without the pumps many mines would have had to be closed, and new ones would have had to be dug – a massive capital cost. Capital-saving innovations were of particular importance in terms of economic growth, it would appear, because the binding constraint of limited consumer savings was thereby alleviated.

Labor-saving innovations appear to have been important primarily in the industrial history of the US, where labor was always scarce and expensive. A new category of "demand-stimulating" innovations has assumed increasing importance during the twentieth century, as other factors of production (energy, materials, capital, labor) have ceased to be binding constraints, at least in the industrial world. Scarcity of land, fresh water, and waste assimilative capacity are rapidly becoming binding constraints in the most crowded and industrialized parts of the world (especially in Japan). This trend strongly suggests that the next set of major technological breakthroughs will be focused on these problems. Thus, "telecommuting" to work could well become a major option in cities (like Tokyo) where all forms of local transportation are permanently overcrowded and approaching gridlock. The unavailability of landfills and the intractable problems associated with cleaning up and relocating toxic dump sites and reducing emissions of acids and greenhouse gases will eventually be reflected in the creation of a market demand for a variety of new technologies in metal recycling, biodegradable plastics and refrigerants, nontoxic solvents, photovoltaic cells, and so on. Obviously, capital is still the scarcest factor in much of the Third World.

The barrier-breakthrough metaphor is clear enough from common usage. In the last few decades the term breakthrough has been applied rather too freely. Often it has been used in cases where all that could be honestly claimed is a quantum improvement, even a small one. For present purposes, however, such cases are excluded. A breakthrough is, by definition, a discontinuous and very dramatic improvement in some technological capability. (Here a distinction is made between scientific and technological breakthroughs. The recent discovery of room-temperature superconductivity is an example of the former. The first commercially viable superconducting transmission line or generator will exemplify the latter. Other historical examples will be discussed later.)

A true breakthrough presupposes a bottleneck or a barrier. Some barriers are clearly perceived, and efforts to overcome them may be deliberate and even centrally coordinated – for example, the Manhattan Project, the war on cancer (unsuccessful to date), NASA's Apollo Project (successful in 1969), the space shuttle (a very limited success), and the Strategic Defense Initiative (initiated by President Reagan with such fanfare six years ago; jury still out, but increasingly skeptical). In other cases, especially in the past, the barrier may not have been clearly understood until it was on the verge of being overcome, or even until long afterward (Ayres, 1988). Nevertheless, the barrier was there. When a barrier is very high, as in the case where nobody really understands the problem (the beginning of the war on cancer) or the problem is of such a nature that only large-scale and expensive research can succeed (the atomic bomb, the Apollo Project, the synfuels program, or the harnessing of fusion power), there is no economic incentive for individual entrepreneurs to get into the game. This is because a small amount of technical progress is useful only to the next generation of researchers, and can have no short-term economic payoff. Putting it another way, as long as the state of the art is far away technologically speaking from the level needed to surmount the barrier, the return on R&D is likely to be low and therefore the actual amount of effort targeted at the barrier is likely to be low (Ayres, 1988).

Nevertheless, over time an accumulation of scientific and practical knowledge and experience from a variety of sources (or even a major but unexpected step forward in some other field of science) will gradually reduce the barrier. Eventually, it reaches the point where a relatively small increment of progress (in functional terms) may be enough to break through. (Indeed, this is the only way in which major breakthroughs occurred until recent decades). The most interesting cases with regard to the long wave seem to be of this kind.

It is important to emphasize that the economic (or social) importance of a breakthrough bears no particular relationship with the brilliance or originality of the inventor or discoverer. On the one hand, while major leaps of intuition do occur from time to time, they may as easily apply to problems of trivial economic importance. For instance, a fast efficient strategy for solving Rubik's cube might display great intellectual prowess but have no significant economic value. On the other hand, very important inventions may be made by a plodding, wholly unimaginative, process of elimination. A classic example of the latter is Edison's invention of the incandescent light, which involved neither great intuitive leaps nor significant use of basic scientific knowledge. His contribution was his systematic attention to the problem of electric lighting as a whole, rather than to its components (Josephson, 1959). It was, nevertheless, of enormous importance to the world by any standard.

It also follows from the above that some of the arguments about the relative importance of many small Usherian improvements, *vis-à-vis* a few big Schumpeterian leaps forward, are missing the point. Upon sufficiently microscopic examination almost every major invention can probably be shown to have evolved through a sequence of small improvements and modifications from some predecessor. Whether the process took place in many minds or one is essentially irrelevant to the question of its importance. An invention or discovery is a breakthrough in our terms if, and only if, it creates important new technical possibilities. An event is not a breakthrough simply because it was hard to achieve or because it represents an unusually rapid or discontinuous improvement over its predecessor, although the latter is also a characteristic of breakthroughs.

2. The First Technological Transformation ca. 1775

Schumpeter attributed the first Kondratieff A period (1792–1825, according to Mandel) to the "industrial revolution": cotton textiles, iron, and steam power. His thesis is supported by a cluster of major innovations centering roughly around 1775. Admittedly, the very existence of an industrial revolution in the last decades of the eighteenth century is a matter of dispute among historians. After all, the term itself was not coined until half a century later by the French economist J. Blanqui (1827) and popularized later by Alfred Toynbee, Sr. No doubt it conveys a sense of sharp discontinuity that contemporaries might have been hard put to recognize. The underlying continuity and overlapping multiplicity of causes and effects have been stressed by a number of distinguished historians, such as John U. Nef (1954), Fernand Braudel (1981), and David Landes (1969). Undeniably, the industrial revolution was no "bolt from the blue," but had roots deep in the past.

Yet a discontinuity in growth rates did occur, nonetheless, with a clear breakpoint around 1781, the slump year. Before that year, economic activity in England had been more or less stagnant since Agincourt (1415), with a plateau of prosperity during the fifteenth century, a decline in the first half of the sixteenth century, and a very slow recovery thereafter. After that watershed year of 1781, economic growth suddenly accelerated. It reached 2% per annum, on average, for the first time in history, and remained above that level for the next century (Hoffmann, cited in Deane, 1979, p. 3). Indeed, "more than half the growth in the shipments of coal and the mining of copper, more than three-quarters of the increase of broad cloths, four-fifths of that of printed cloth, and nine-tenths of the exports of cotton goods were concentrated in the last eighteen years of the century" (Ashton, 1949, p. 18). During this period "the production of cotton cloth quintupled, pig-iron production quadrupled, foreign trade (whether measured in shipping tonnage or values) nearly tripled, and total industrial production doubled" (Briggs, 1963, p. 93).

Evidently there is no difficulty in identifying the leading sectors, in Van Gelderen's terms. They have already been named above: cotton cloth, coal, and iron. The technological barriers that were broken through between 1760 and 1775 remain to be identified. Historians have largely settled this issue. In brief, the bottlenecks were scarcity of mechanical power and scarcity of "clean" (sulfur-free) fuel. Ironworks of the seventeenth century utilized charcoal, but charcoal availability was limited and its price was rising. The conversion from charcoal to coke (from coal) was one of the preconditions of the great breakthrough. This conversion began slowly between 1707 and 1709 at the ironworks of Abraham Darby in Coalbrookdale, on the Severn, but the techniques remained proprietary for more than four decades. Use of coke did not spread widely among other UK ironworks until the 1760s as decades of experiments with various ores and coals finally enabled smelters to produce pig iron of reasonable quality at competitive prices (with help from tariffs).

One of the main factors involved in substituting coke for charcoal was a need for higher smelting temperatures, which required larger volume blast furnaces (Landes, 1969, p. 90). This required more powerful air pumps than most contemporary waterpower sources could produce. John Smeaton introduced the first piston-driven air pump for the Carron Ironworks in 1762, but it was not until 1776 that Wilkinson first applied a steam engine (purchased from Boulton & Watt) to this purpose. The puddling-rolling process for making wrought iron of engineering quality, using coal instead of charcoal, was patented by Henry Cort (1783–1784), although the process was not widely adopted until around 1800. It was the key breakthrough in iron making and was an important prerequisite to the later large-scale use of wrought iron as a structural material, notably for rails.

To avoid the deadly effects of sulfur contamination from the coal, Cort followed the lead of Huntsman (1740) and others in adopting the so-called "reverberatory furnace" (first used by the copper smelters) to ensure that the molten iron had no direct contact with the fuel. As the pig iron was stirred (puddled) and progressively decarburized by reaction with added oxides, its melting point rose above the furnace temperature and it gradually solidified. The red-hot semisolid agglomeration of relatively pure iron flakes and liquid slag was then forged and deslagged by reciprocating "tilt hammers" or, after the introduction of rotative steam engines, hot-rolled by slotted rollers directly into bars. This last innovation alone cut the time required for forging by a factor of 15 (Landes, 1969, p. 91).

To cope with rising industrial demand for domestic iron, the supply of coal had to increase also. This meant more and deeper mines. Many mines were below the water table by the beginning of the eighteenth century, and the problem was rapidly becoming acute. The Newcomen-Savery steam-pumping engine (1712) was an elegant solution, for its time. In all, about 60 copies or minor variants of the Newcomen design had already been built in the UK by 1733, when the master patent expired. A few more were built elsewhere in western Europe and Russia. Some 300 were built between 1734 and 1781, entirely for pumping water from coal mines (Briggs, 1982, p. 51). The early Newcomen engines used from 30 to 45 pounds (lb.) of coal per horsepower-hour (hp-hr) Improvements in the design introduced by Smeaton (ca. 1770) cut the fuel consumption to 17–18 lb. per hp-hr, for engines built after that time (Von Tunzelmann, 1978, p. 67–69).

Smeaton's work was immediately overshadowed by James Watt's condensing steam engine. The invention of the condenser was a major breakthrough (1769). The new engine cut fuel consumption to as little as 7.5 lb. per hp-hr for pumping (Von Tunzelmann, 1978), about one-third of the level of the old Newcomen engines and less than one-half of the best Smeaton versions. This was a great improvement. As a direct consequence of its lower fuel (i.e., steam) consumption per unit of power output, Watt's engine was far more compact and therefore more suitable for rotative applications. It was also more standardized and probably better engineered than its predecessors. Its importance, however, cannot be deduced from these facts alone.

The firm of Boulton & Watt (B&W) was founded in 1774. It sold its first two new engines in 1776, one to the Bersham Ironworks of John Wilkinson (as already noted above), and the other to a colliery for pumping. Meanwhile, Wilkinson made another extremely important contribution by inventing an improved type of boring mill (based on earlier work by John Smeaton). This, in turn, made Wilkinson not only the first customer, but also the recommended supplier of cylinders for B&W steam engines until 1895 when the firm built a boring mill in its own shop. With regard to boring, Wilkinson's improvement over the earlier machining accuracy was as great as Watt's was for steam engines. Based on Boulton's assertion that a 50-inch cylinder boring "doth not err by the thickness of an old shilling," Wilkinson seems to have built the first true machine tool (Ferguson, 1967, p. 272). Again, we have an invention that allowed a large discontinuous improvement in performance. It added significantly to the efficiency, and hence the value, of the B&W engine. Indeed, Watt himself estimated that his engines would only have been able to cut the fuel consumption of Newcomen-type engines by a factor of two, based on the separate condenser alone (Scherer, 1984, p. 19); Smeaton actually did nearly as well. In any case, Wilkinson's invention of the boring machine was key to the effectiveness of Watt's steam engine.

Some further words of caution are necessary. The first few engines built by Boulton & Watt were scarcely more than prototypes, and Watt was fully occupied with problems of development and improvement, at least until 1785 when the design more or less stabilized. Among the major patented improvements were:

- *double-acting valve arrangement* (1781–1782), which doubled the power output of a single piston, thus further reducing the weight of metal needed to generate a unit power output
- *"sun and planet" gearing* (1781), to convert reciprocating motion to rotary motion
- *"parallel" motion* (1784), to keep a rigid piston rod moving vertically while attached to an oscillating beam.

All of the above were helpful or essential in supplying steam power for "rotative motion." This was a major obsession not only of Watt but of his contemporaries. The importance of this may be gathered from the fact that a number of Newcomen engines had been used simply to pump water from the tailrace of a waterwheel back to the head, so it could be used again and again to drive the wheel (Briggs, 1982, p. 56). This inefficient procedure may be regarded as the most effective method of converting reciprocating motion to rotary motion (given the availability of a waterwheel) prior to about 1780. The obvious solution, the standard crank-and-flywheel, was patented by James Pickard and Matthew Wasborough in 1780, thus forcing Watt to find another method; since the crank was well known, Watt may have thought it unpatentable. During the period of Boulton & Watt's official monopoly, which ended in 1800, about 490 engines were licensed (Von Tunzelmann, 1978, p. 27). Others built at least as many pirate versions. The fuel savings achieved by customers were indeed substantial, otherwise they would not have made the investment and paid the substantial royalties. But the direct incremental addition to the economic growth rate of the UK over the period 1780–1830 has been estimated by Von Tunzelmann at only one-quarter of one percent, when compared with what it would have been without those savings (Von Tunzelmann, 1978, chap. 6).

However, the assumption of other things being equal (*ceteris paribus*) is inappropriate, and Von Tunzelmann's "what if" calculation is fundamentally misleading. It assumed that customers of Boulton & Watt (or their imitators) could have used less efficient steam engines of the Newcomen-Smeaton type – albeit at somewhat higher fuel cost, the difference in fuel costs translating into a reduction in capital formation. This convenient assumption ignores the multiplicative power of the new capabilities. For instance, Wilkinson's boring machine and the various reciprocating-to-rotary power transmission devices were direct outgrowths of Watt's invention. Among them they made steam engines suitable for a host of new applications, such as driving flour mills, gristmills, cotton-spinning "water frames," and "mules"; introducing power looms and scouring and washing machines into the woolen industry; using bellows for blast furnaces; and installing rolling mills into the new puddling-rolling process. Frederick Konig's rotary press, on which the *London Times* began printing in 1814, depended on a steam engine for power. Given the shortage of suitable water-power sites, especially near London, there was really no choice. Newcomen engines would not suffice for these applications.

In addition, the superior efficiency of rotative steam-powered air pumps for iron smelters and rotative steam-powered rolling mills for wrought-iron manufacturing (as compared with the hypothetical alternative) would have had a major impact on the price of UK iron, and consequently on its ability to compete against Swedish imports. In 1750 the UK imported two-thirds of the iron it used. Yet with the help of the new technology it became the world's most cost-efficient iron producer and a major exporter of iron by 1814 (Landes, 1969, p. 95). In Von Tunzelmann's hypothetical case this could not have occurred.

The importance of the new capabilities created by steam power is revealed more clearly still when the high-pressure steam engine finally arrived after 1800, eventually making the steam railroad possible. To evaluate the economic impact of the railway in terms of fuel savings *vis-à-vis* horses would be to miss the point entirely. In short, the popular judgment that Watt's engine was the fulcrum of the first industrial revolution seems much sounder than Von Tunzelmann's attempt to debunk it. Yet his emphasis on the vastly greater economic impact of steam power in the period after 1825 due in part to further gains in efficiency (*Figure 5*) is entirely justified.

This is not to suggest that other technological innovations played no major role in triggering the economic expansion that began in 1780. On the contrary, a series of very important innovations in the machine industries created the condition for the dramatic advances in all areas of manufacturing and engineering that occurred during the last decade of the eighteenth century and the first half of the nineteenth century. Starting with Wilkinson's boring machine, a series of key inventions created most of the modern types of machine tools, especially industrial lathes, over the next five decades. These tools could not function, of course, without hard steel-cutting edges. The source of this steel was Benjamin Huntsman's crucible steel process (ca. 1740s), a significant improvement over the earlier "cementation" process for hardening wrought-iron bars by heating them in a charcoal fire. Steel from Huntsman's process could only be made in small quantities, at very high cost in fuel. It was, nevertheless, indispensable for cutlery, watch springs, and cutting tools.

So far, the discussion has focused entirely on coal, iron, steam, and machine tools. Most historians, as well as engineers, have seen these developments as the more fundamental drivers of subsequent economic growth. Nevertheless, the most spectacular economic growth of the 1780–1830 period was recorded by the cotton-spinning and cotton-weaving industry, where mechanization and (later) the "factory system" were first applied on a large scale. In Rostow's words, this was the "original leading sector in the first 'take-off' " (1960, p. 53). Why

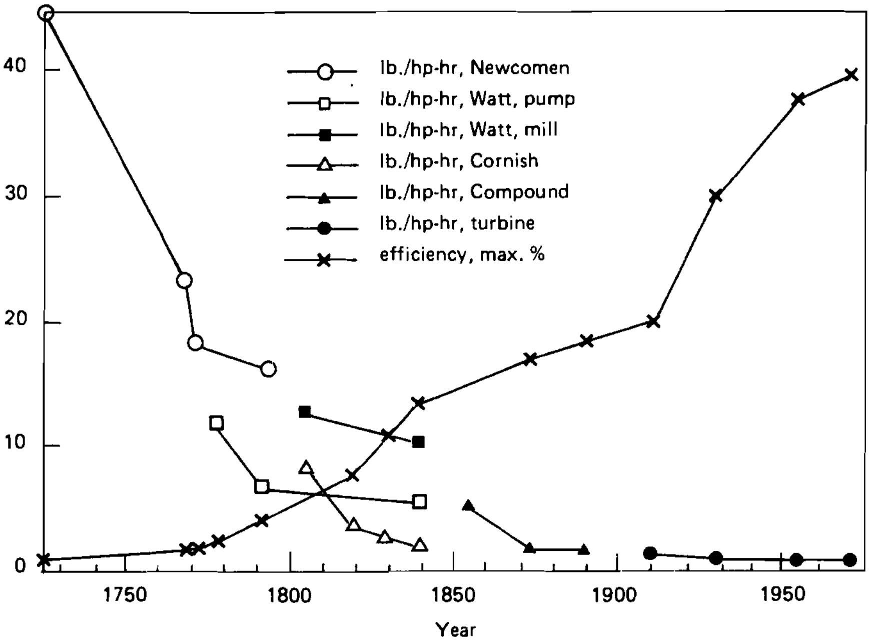

Figure 5. Performance of steam engines: fuel consumption and thermal efficiency.

cotton? The beginnings of this process can be traced to the increasing popularity of light cotton fabrics imported from East India in the seventeenth century. Cotton fiber was available also from other nearer sources, and imports of cotton cloth from India were cut off in the early 1800s to protect the woolen industry. Furthermore, UK consumers were interested in heavier fabrics for shirts, chemises, etc. As a result there was an opportunity for domestic cotton spinners and weavers to produce a cotton-linen hybrid (called fustian).

In the beginning of the eighteenth century the cotton-linen industry, like the woolen industry, was exclusively a family affair, confined largely to Lancashire. Most cotton workers were also farmers. During the off-season the man of the family would operate a hand loom and the wife would operate a spinning wheel to make the yarn. The capabilities of the two were unequal, however. It took three or four spinners to supply one full-time weaver by traditional methods (Deane, 1979, p. 89). An even more severe imbalance was created by the invention by John Kay in 1733 of the flying shuttle, which essentially doubled the output of hand looms when it was adopted widely in the 1750s. This created a powerful demand for more efficient means of spinning cotton thread.

There were various attempts to mechanize the process of cotton spinning, but the first that proved successful was James Hargreaves's spinning jenny, invented about 1764 and patented in 1770. The jenny duplicated the action of a spinning wheel (stretching accompanied and followed by twisting), but it permitted a single operator to control a number of spindles simultaneously. Hargreaves's patent specified 16 spindles. The number rapidly increased; by 1784 jennies could handle 80 spindles, and by 1800 the number had risen from 100 to 120. It reached 1,200 by 1832 (Mann, 1958). In effect, the productivity of a single operator was multiplied by 100-fold in the space of a generation and 1,000-fold in two generations (*Figure 6*).

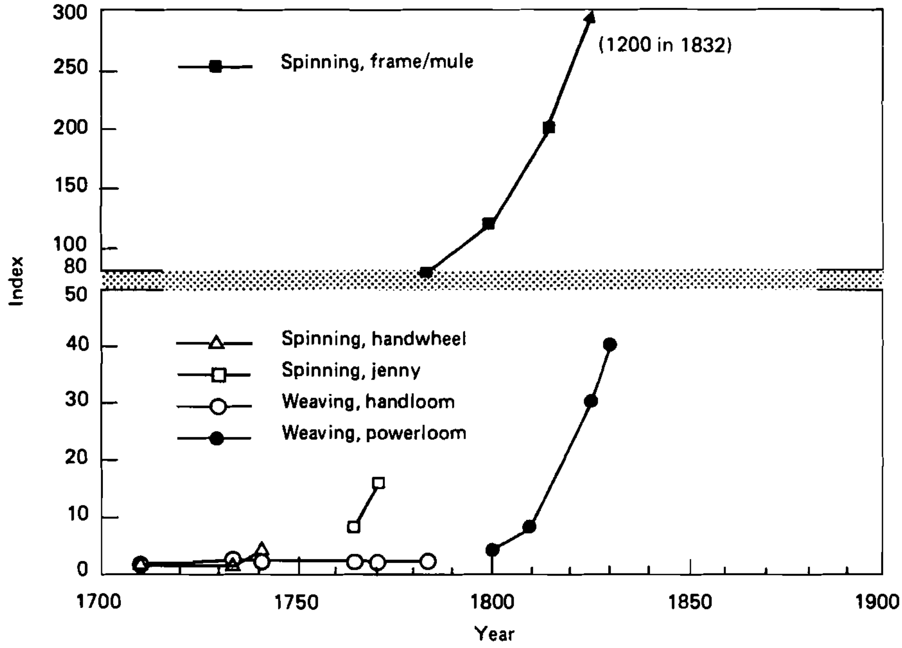

Figure 6. Cotton textile productivity measures: output per operator.

Quantity output of cotton thread was not the only problem that needed to be addressed. Wheel-spun cotton thread was generally too weak to serve as the warp on a hand loom, so flax was used for this purpose. The resulting products, fustian, was neither soft nor easy to sew. The breakthrough that permitted all-cotton fabrics was a spinning machine capable of spinning stronger thread. This was the so-called water frame or throstle of Richard Arkwright, patented in 1769. It operated in a manner different from the wheel or jenny and stretched the rovings by passing them between a succession of rollers to increase fineness. It was designed, from the start, for mechanization, using waterpower. Arkwright also used a steam engine (the first in the cotton industry), but it was of the Newcomen-type and was used to pump water to supply a waterwheel. The first steam-powered self-acting mule for spinning cotton was patented in 1792 by John Kelly. Even so, development for widespread factory use by Richard Roberts and the Sharp Brothers, of Manchester, took three more decades (Mann, 1985).

A few years later Arkwright's invention was surpassed by Samuel Crompton's mule, which combined the principles of the water frame and the jenny into a single machine for stretching and twisting simultaneously (patented in 1779). Crompton's thread was fine enough, for the first time, to enable UK weavers to rival Indian muslins and calicoes in quality. By 1885 the water-frame technology became generally available to other manufacturers and was widely used.

The imbalance between spinning and weaving was reversed by the 1780s. Since domestic and export demand for cotton cloth was soaring, the bottleneck was now at the weaving end of the process. Oddly, mechanization of weaving lagged, partly due to the opposition of cottage weavers, but mainly due to its greater complexity. The immediate response was for part-time farmer-weavers to become full-time weavers. Many of them gave up agriculture and moved into the towns of Lancashire. Other technical processes improved rapidly, creating new specializations and making household operation of looms more difficult.

The first power loom is credited to Edmund Cartwright (1787), but it had several drawbacks - notably a tendency to break threads - that made its use uneconomical. Cartwright's factory burned down a few years later. A second attempt in Manchester soon failed due to worker sabotage. However, a number of inventors continued to work on the problem. One of the most notable was Samuel Horrocks, who developed a commercial power loom (1813), which was fairly successful. It was later improved upon by Richard Roberts (1822) and manufactured in large numbers by the firm of Roberts, Hill & Co. Even so, power looms did not completely displace hand looms until mid-century, despite continuously declining wages for weavers as cotton cloth prices fell.

The full mechanization of the cotton industry and the building of the railroads could not have occurred much before 1830, as it happens, because the requirements for large-scale manufacturing of the necessary machines were not available until then. Most eighteenth-century machines, including spinning jennies, mules, carding machines, and looms, were built of wood. Even gears and axles were of wood in most cases. It was only in the first decade of the nineteenth century that cast iron began to be used for machine frames. This was a prerequisite for rigidity, without which cutting accuracy was unattainable. But of course a machinery-building industry requires more than rigid frames. There was a need for metal-cutting machines capable of making gear wheels, nuts and bolts, axles, flanged wheels, pistons, cranks, and other iron parts that could not easily be cast or rolled into final form.

Virtually all the necessary tools had already been invented by clockmakers, watchmakers, opticians, instrument makers, and cabinetmakers for use on softer materials like brass or wood. These tools were not robust or rigid enough for working on harder metals. The French mechanical genius Jacques de Vaucanson was a transitional figure. He developed prototype engineering versions of several key machines. However, his prototypes, built between 1750 and 1780, were not manufactured or widely used. Most are now lost or have ended up in museums. The same is true for Senot's advanced screw-cutting lathe (1795). In the UK, the demand for mechanization was more insistent, and inventors flocked to fill the need. Wilkinson's boring machine (1775) was the first. He was followed by Henry Maudslay, who built the first practical engine lathe (1797), and a host of others, including James Fox, Marc Brunel, Matthew Murray, Richard Roberts, Joseph Clement, James Nasmyth, and Joseph Whitworth in the UK. Some of the inventors from the US included Oliver Evans, Eli Whitney, Simeon North, and Thomas Blanchard. These men invented (or re-invented) all of the major types of machine tools and created the machine-tool industry, without which large-scale manufacturing would be impossible. By 1830 all major types (except the surface grinder) had been developed to the degree "that would be instantly recognizable to a machinist today" (Ferguson, 1967, p. 281).

It is worth emphasizing that the metallurgical innovations of the eighteenth century, culminating in Cort's puddling-rolling process, had the effect of breaking a binding constraint on energy availability (the shortage of wood for charcoal) by substituting coke for coal in iron making. A constraint on the availability of coal itself was relieved by the application of steam power to draining coal mines. Only the mechanization of cotton spinning can be regarded as a labor-saving innovation; it was part of a catalytic feedback process of demand growth, responding to falling consumer prices, in turn attributable to radical (Schumpeterian) innovations in production technology.

3. The Second Technological Transformation ca. 1825

Schumpeter attributed the second Kondratieff A period (1847–1873, according to Mandel) to "railroadization," although the mechanization of the cotton textile industry gave a tremendous impetus to iron-working and machine-tool development. The iron industry continued to grow rapidly also. The major breakthrough in this case would seem to be the opening of the Stockton-Darlington Railroad (1825), which operated successfully with several steam-powered locomotives as well as horsepowered vehicles. It was followed by the famous *Rainhill* trials (1829), which were decisively won by Stephenson's locomotive "Rocket."

It is unfair to ignore the accomplishments of others whose work was a necessary prerequisite to the success of railroads. Ironically, the condensing steam engine, discussed above, does not belong in this category. Watt's atmospheric engine was too bulky and heavy, in relation to its power output, to be mobile. An early attempt to use steam power for hauling heavy loads was the steam carriage of Nicholas Cugnot (1767–1769), of which two were built and one still survives in a Paris museum. Cugnot was also the first to use high-pressure steam and probably deserves credit as the real inventor of the steam locomotive, though he did not use iron rails. The long life of Watt's basic patent on the separate condenser and his opposition to high-pressure steam apparently discouraged other would-be inventors over the next several decades. Indeed, Ashton (1949) conjectures that this may have delayed the introduction of the railway by a generation.

Be that as it may, Richard Trevithick in Cornwall and Oliver Evans in the USA independently began serious experiments with high pressures about the time Watt's patent expired – although neither used a condenser, the heart of Watt's invention. (Most steam locomotives, even well into the twentieth century, simply "puffed" their exhausted steam into the atmosphere, but had to haul a replacement water supply). Trevithick patented a high-pressure steam-powered locomotive in 1802. Trevithick built several models and carried out several demonstrations, of which the most important was in February 1804 when a five-ton engine carried ten tons of iron and 70 men over a distance of nine miles on a cast-iron plateway in Wales. However, problems included a tendency of the cast-iron plates to break under the weight, not to mention the danger of steam explosions and fires. Trevithick persisted until 1811, when he went bankrupt and abandoned the business for a decade while trying to recoup his fortune in South America. After his return, he concentrated on developing steam-powered road vehicles, with only modest success.

Beginning about 1812 several large collieries introduced steam-powered tramways, designed and built by such men as John Blenkinsop, Matthew Murray, William Hedley, and George Stephenson. Stephenson was the first to make and run a locomotive with flanged wheels on a track laid with cast-iron rails (1814). This engine, along with others built by Stephenson, was well constructed and operated successfully for a number of years. His reputation grew thereafter and won for him the job of chief engineer for the Stockton-Darlington, mentioned above, and then the Liverpool and Manchester Railway, which opened in 1830. It was for the latter that the *Rainhill* trials were held, to select a locomotive design. The trial was won by Robert Stephenson's "Rocket," which sustained a remarkable 40 miles per hour (mph) over a distance of several miles.

A host of subsidiary problems had to be solved before railways could replace horse-drawn vehicles for freight (or passenger) transportation. The power source was only one of them. Another, very vexing, problem for the early railways was the conviction of most engineers that smooth steel wheels would lack adhesion on the rails, limiting track gradients to 1% or less. It was evident that adhesion could be increased by improving the suspension, to prevent wheels from losing contact with the rails. The first contribution to a solution was to mount the locomotive on "bogies," first used by William Chapman (patented 1812). Another possible solution to this problem was Stephenson's "steam spring" (patented 1815), which was used by him to avoid the Chapman patent until steam springs were in turn displaced by the development of laminated steel leaf springs. But the barrier, in this case, turned out to be more apparent than real. William Norris, a locomotive builder from Philadelphia, proved by direct demonstration in 1836 that a locomotive could haul a load up a 7% grade.

A more serious problem was the tendency of the brittle cast-iron rails to break. No single solution was developed, but a major step forward was the use of wrought iron. The rolling mill had already become an essential component of the Cort process. A further development was needed, however, to roll wrought-iron rails on a prescribed cross section. This was accomplished in 1820 by John Birkenhead of Bedlington Ironworks. The wrought-iron rails were about twice as expensive as cast-iron, but lasted much longer. Costs of iron declined sharply, too, between 1790 and 1830 because of technical improvements in the processes. For example, the original version of the Cort puddling-rolling process lost half of the pig-iron feedstock to the slag. A series of changes culminating in a substitution of roasted tap cinder for sand for the furnace bed in the late 1830s, finally reduced the loss to 8%, while speeding up the conversion (Landes, 1969, p. 93).

It should be pointed out that the railway-building booms of the 1830s and 1840s depended on the existence of a large-scale iron industry. Based on the iron-making technology of the 1820s as much as eight tons of coal were needed to make one ton of iron. A sharp increase in demand for iron, at this time, would have put an enormous, and perhaps unsustainable, strain on the coal-mining industry. Fortunately, this was obviated by a discovery by James Nielson – supervisor of a Glasgow gasworks – in 1828. His idea was to preheat the blast air for iron smelting. The first version of his blast stove at Clyde Ironworks, Glasgow, achieved a temperature of less than 100°C, but the benefits were immediately obvious. In a very few years blast air temperatures were up to 300°C (Schubert, 1958, p. 110). The impact on iron smelting was dramatic; fuel consumption per unit output dropped threefold (Schubert, 1958), while furnace output rose sharply. The reduction in fuel consumption and increased output made possible by these accomplishments (see *Figure 7*) were critical to the economics of rail transportation.

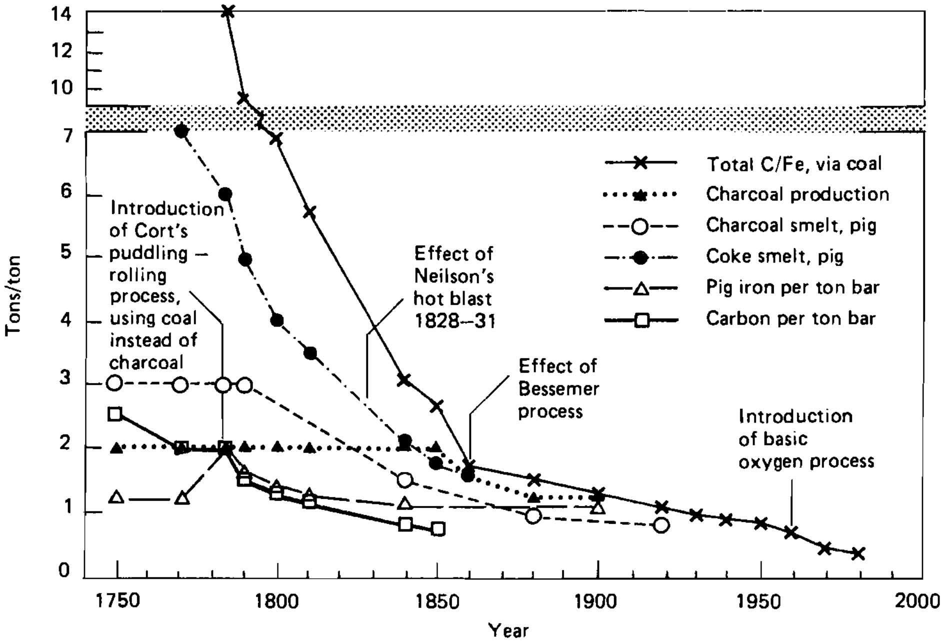

Figure 7. Production of iron and steel: tons of input (C or Fe) per ton of output (Fe).

The basic components of railways – locomotives and rails – were mostly developed before 1830, thus opening the way to rapid and widespread railway building, not only in the UK but in other countries. The 29-mile Liverpool and Manchester line, which cost £ 820,000 was completed by Stephenson in 1830 and was an immediate success. Railways were opened for public traffic before 1830 in the United States, Austria, and France, and very soon afterward in many other countries. The first steam locomotive used in the US was the "Stourbridge Lion," purchased from England for the Delaware & Hudson Railroad (1827). Peter Cooper's "Tom Thumb," used by the Baltimore & Ohio Railroad was built in 1830. The first major railway-building boom in the UK occurred in

1835–1837, when many companies were formed, mostly local, and a number of disconnected point-to-point lines, such as the Newcastle and Carlisle, Canterbury and Whitstable, Leeds and York, and London and Birmingham (Great Western), were established. These early investments produced high returns, commonly returning 10% or more on their capital (Taylor, 1942, p. 23). This attracted more capital to the industry. In the second boom period (1844–1846) new railway companies were formed with an aggregate capital of £ 180 million. Indeed, this boom consumed virtually all the capital available for investment in the UK at the time (Taylor, 1942). Incidentally, railways cost twice as much to build in the UK as in Germany, and four times as much as in the US (Briggs, 1982, p. 110). It appears that this was mostly due to excessive costs imposed on the railway companies by Parliament to pacify influential landowners (Taylor, 1942, pp. 23–24). This excess cost burden may have seriously diminished the long-term benefits of railroadization in the UK, *vis-à-vis* other industrializing countries.

Another direct consequence of the railway-building boom, in the UK at least, was the very rapid introduction of telegraphy. William Cooke and Charles Wheatstone's first practical (five-needle) telegraph system was constructed for the Great Western Railway, from Paddington Station (London) to W. Drayton, a distance of 13 miles (1838). It was extended four years later to Slough (Garratt, 1958, p. 657). Thereafter, virtually all newly built railway lines were accompanied by telegraph lines. Wheatstone and Cooke formed the Electric Telegraph Co. in 1846; 4,000 miles of line had been built in the UK by 1852 (Garratt, 1958, p. 659). While telegraphic communication soon developed its own *raison d'être*, it was the needs of railways that provided a strong initial impetus and created a demand for still better means of communication.

By contrast, telegraphy got a slower start in the US, even though the system developed by Samuel Morse (with assistance from Joseph Henry and others) was technically superior and was eventually adopted in most countries. Morse's system did not achieve recognition until the US Congress appropriated money for a demonstration line between Washington, DC, and Baltimore, MD. The demonstration took place successfully in 1844. Again, it was railroads that were the early adopters.

The railway was, of course, an application of steam power, and an aspect of its diffusion. Steam power was also rapidly applied to ships and riverboats, especially in the US with its large territory and big rivers. The regular use of steam-powered ferries on the Hudson and Delaware – experiments began as early as 1763 (Henry), 1785 (Fitch), 1787 (Rumsey) – began in 1807 with Robert Fulton's *Clermont* (Briggs, 1982, p. 127). Fulton's rival, John Stevens, is credited with the first sea voyage (1809), when he steamed from Hoboken to Philadelphia around Cape May, NJ (Briggs, 1982).

Steamships began to displace sailing ships in the 1820s. At this time the US merchant marine had 22,000 tons of steam-powered shipping, 1.7% of the total fleet (USBOC, 1975). By 1850 this fraction had increased to 15% (USBOC, 1975). The pace of substitution slowed in the 1850s, for some reason, but increased thereafter. Nevertheless, only 33% of the fleet was steam powered as late as 1880 (USBOC, 1975). Thereafter, penetration was very rapid, but it took place mostly in the period of the third transformation rather than the second.

Undoubtedly the most important application of steam power after railways was in the textile industry, as a supplement (and later, substitute) for waterpower. Yet in 1800, when Watt's master patent expired, it is estimated that there were fewer than 1,000 stationary steam engines in the UK, totaling perhaps 10,000 hp (Landes, 1969, p. 104). By 1815, however, the total was apparently 20 times greater (210,000 hp), all in mines or mills. By the middle of the century the total of stationary engines had increased to 500,000 hp, in addition to nearly 800,000 hp in locomotives and ships (Landes, 1969). At that time (1850), the cotton industry was still using 11,000 hp of waterpower, but 71,000 hp of steam. The woolen industry, which was slower to mechanize, used 6,800 hp of waterpower, as against 12,600 hp steam (Landes, 1969).

The development of the gaslight industry also contributed significantly to the second technological transformation. The fact that coal could be "gasified" by heating it in a retort – a crude version of coking – was discovered in the sixteenth century. The first-known attempt to use coal gas for illumination was made by George Dixon, a colliery owner, in 1760. It was quickly abandoned. A number of people conducted experiments, but the two fathers of the gaslight were Philip Lebon in France, who began work in 1791 using gas from wood, and William Murdock in the UK, an associate of Watt, who began work in 1792 using coal gas. Murdock adapted the oil-burning "Argand" lantern to use gas as a fuel. The Argand lamp, designed by Pierre Argand, a Swiss, was the first oil lamp to house a tubular wick inside a class chimney. It gave a very steady flame. This lamp was introduced to the UK in 1783 (Elton, 1958, p. 263). Murdock substituted an annular gas burner, but retained the chimney. In 1802 he lit the main building of Boulton & Watt's Soho works, in Birmingham. By 1804 B&W was undertaking to build gaslight systems for factories; the first customer was a large cotton mill at Salford. Meanwhile, Lebon had been demonstrating his system, including his patented "thermolamp" in Paris. Unfortunately, Lebon was murdered in 1804 in Paris, and his work was not continued until many years later. Having seen one of Lebon's demonstrations, a German named Friedrich Albrecht Winzer (later anglicized to Winsor) came to London in 1803 with the intention of creating a complete gas-lighting system with a central gas plant and distribution of gas throughout a district (Elton, 1958). He found backers and succeeded in forming the National Light and Heat Co. in 1806, later changed to the Gas Light and Coke Co. (GL&C). Despite opposition by B&W (and others), the company received its charter in 1812 and construction finally began in 1815. By December of that year 26 miles of mains had been built (Elton, 1958, p. 269).

Nevertheless, as of 1815 four major technical problems remained to be solved before gas lighting could be a commercial success. The first was an efficient process to gasify coal and remove the tar and sulfurous impurities from the gas. Samuel Clegg (chief engineer of GL&C) was the first to introduce a crude gas purification process, bubbling the gas through a mixture of lime and water (ca. 1812). An improved dry-liming process was invented in 1817 by Reuben Phillips, and a process in which the gas was passed between layers of quicklime was developed in 1823 by Clegg's son-in-law, John Malam. It remained standard until the end of the nineteenth century (Elton, 1958, pp. 269–271). The retorting process itself was still very inefficient – much of the solid residue (coke) was wasted. The water-gas process, in which steam reacts with incandescent coke to produce a mixture of hydrogen gas and carbon monoxide, was invented in 1834 by A.F. Selligue in France (Williamson and Daum, 1959, p. 37). This process was eventually adopted widely by the gas industry.

Another technical problem was the distribution. Cast-iron pipes were suitable for the mains, but the smaller diameter pipes for distribution to individual burners were difficult to manufacture. For a few years old gun barrels were actually used, along with pipe fabricated from strip iron, welded down a seam. These pipes were prone to leak. The solution to this problem was a method of drawing wrought-iron pipe over a mandrel, invented by Cornelius Whitehouse (1825) and perfected over the next decade. A third problem, and a serious one, was the lack of an efficient and safe burner. Combustion was not well understood, and inefficient burners tended to allow unburned gas (partly carbon monoxide) to escape, thus making indoor use risky. The solution was simple enough: to draw air into the gas stream below the point of combustion. But it was not invented till ca. 1840 and eventually resulted in the development of the Bunsen burner in 1855. Thus, gas was used primarily for exterior lighting until the 1860s and even later. The gas water heater (geyser) was invented by Benjamin W. Maughan in 1865; the gas ring for cooking and heating was not introduced until 1867; and the use of radiants to increase the efficiency of a gas fire appeared in 1880 (Elton, 1958). Surprisingly, it was not until after Thomas A. Edison's incandescent electric light (in 1879) that a truly effective interior gaslight was finally perfected (in 1885) by Carl Auer von Welsbach: the incandescent gas mantle. The fourth major problem, metering, was not solved satisfactorily until the end of the nineteenth century. Thus, while gas lighting was an innovation of the first technological transformation, and grew rapidly throughout the second, it did not reach its full potential until the third. In fact, gas lighting reached its maximum penetration in 1910, when it was finally overtaken by the electric light.

Again, the nature of the key technological innovations of the second transformation is worth noting. The railroad offered a new service to a wide variety of customers, of course, but its first and foremost users (and investors) were the coal mine owners. Many of the first railroads linked coal mines to ports. Later, they supplemented, and finally supplanted, the canals for shipment of heavy goods (e.g., coal). Dramatic reductions in delivery time meant reductions in the amount of goods in the pipeline. This translated into significant capital savings for the economy. Steam power also made the mines themselves more efficient, again conserving capital as well as labor. Finally, as noted already, Nielson's hot blast both saved coal and increased the output of blast furnaces. This conserved capital in two ways: in mining and in iron making. The sharply increased demand for iron to build the railroads and for coal to supply the growing need for gaslight in the cities could probably not have been met otherwise. Continued mechanization of the textile industry was still the only significant example of a labor-saving technology.

4. The Third Technological Transformation ca. 1870–1890

Whereas the leading sectors of 1780–1800 and 1830–1850 are easily identified, this is less true of the 1880s and 1890s, for the simple reason that major advances occurred in a number of different industries at roughly the same time and the geographic center of the changes was less focused on a single country. There were, in fact, two clusters of innovations, corresponding to two distinct groups of leading sectors. The first two were steel and petroleum, each of which began a period of sustained boom in the 1870s in the United States. Later, electric light, telephones, and the engineering industries (sewing machines, bicycles, and automobiles) emerged. In addition, the gaslight industry continued to grow and prosper and produced an offspring: coal-tar based chemistry.

4.1. Steel

The boom in steel manufacturing after 1870 was a direct consequence of the introduction of the Kelly-Bessemer process in 1856 and the Siemens-Martin process in 1864–1867. Together, these constituted a technological breakthrough of the first magnitude, despite their apparent simplicity. The Kelly-Bessemer process converted tonnage quantities of molten pig iron to mild (low-carbon) steel by blowing air through it. The exothermic heat generated by the rapid oxidation of the dissolved carbon sufficed to raise the temperature high enough to maintain the purified metal in a molten state suitable for pouring and casting. It was soon realized that the Kelly-Bessemer process was very difficult to control because of its rapidity. Fortuitously, the answer appeared immediately in the form of Robert Mushet's "spiegeleisen" (1856), a manganese-iron alloy that could be added to the hot metal to prevent excessive oxidation. However, early applications of the Kelly-Bessemer process worked well only for pig iron made from low-phosphorus ores, a difficulty that was only finally overcome by the so-called basic version of the process developed by Sydney G. Thomas and Percy Gilchrist (1876).

The Siemens-Martin process – in contrast with the fast, exothermic Kelly-Bessemer process – was a slower, endothermic (heat-absorbing) process of decarburization whose success depended on an ingenious method of conserving waste heat (the regenerative furnace, 1856). There were two variants, William Siemens's "pig and ore" process (1861) and Emilo and Pierre Martin's "pig and scrap" process (1864). Both were implemented within a few years.

Rapid growth in steel production began after 1870, in both western Europe and the US. World production of iron in that year was 11.84 million tons, of which only 4.3% was converted to steel, mainly by the old crucible process. By 1880 the figures for iron and steel were 18.16 and 4.18 million tons, respectively. Two decades later (1900) iron production more than doubled to 39.81 million tons, but steel output increased more than sixfold to 27.83 million tons. Meanwhile, steel prices fell sharply: Kelly-Bessemer steel rails had cost $170 per ton in 1867. By 1898 steel rails cost only $15 per ton. Prices stabilized thereafter, but growth trends slackened only slightly through the 1920s. Steel production actually exceeded pig iron output by 1920, and the proportion of steel to iron has continued to increase ever since (*Figure 8*).

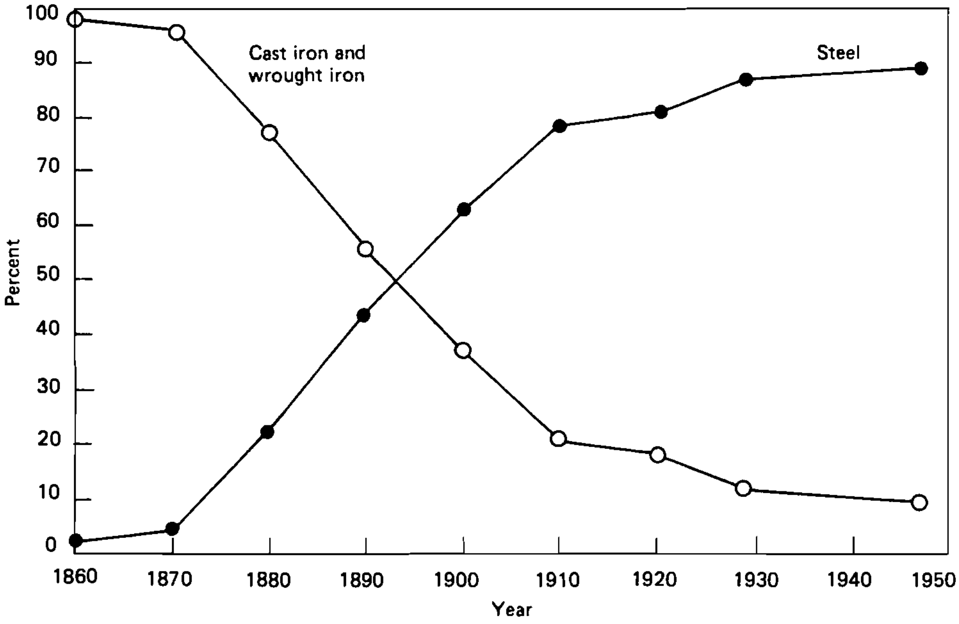

Figure 8. Penetration of steel as a percentage of all iron and steel products.

4.2. Coal-tar chemistry and color

The gaslight industry produced a major by-product: coal tar. In the UK this product was mostly used, at first, to caulk the hulls of ships and the like. However, the Germans recognized an opportunity for developing products of higher value and began to support fundamental research on coal-tar chemistry at several institutions. The key discovery occurred in 1858 when a UK chemistry student, William H. Perkin, accidentally synthesized a brilliant purple color from aniline, a derivative of coal-tar, while searching for a way to synthesize quinine. He then proved it to be identical to the natural dye "mauve." Perkin saw the value of synthetic dye materials for the UK cotton industry, and began to manufacture the purple dye commercially. In the following year Perkin succeeded in synthesizing a red dye, alizarin, the coloring agent in natural "rose madder."

In the latter effort, however, Perkin was beaten (by a single day) by German chemists, Caro, Graebe, and Liebermann, who also synthesized alizarin and began production. Three big German firms, Badische Anilin und Soda Fabrik (BASF), Bayer, and Hoechst, were manufacturing dyes by 1870. Thereafter, the Germans gradually forged ahead, by investing heavily in research. More and more aniline-based dyes were introduced in the 1870s and 1980s, culminating with a major triumph: the successful production of indigo by BASF in 1897. This remarkable firm also developed the successful contact process for manufacturing sulfuric acid in the 1890s and began work on the most important single industrial chemical process of all time: the synthesis of ammonia from atmospheric nitrogen for use as a fertilizer to replace the natural sodium nitrates that were then being imported from Chile. The basic research was done at a university by Fritz Haber; the industrial process development was led by Carl Bosch of BASF. The first laboratory-scale demonstration of the Haber-Bosch process was in 1909, but the process was shelved for a while due to the (temporarily) low price of a competing nitrogenous fertilizer, calcium cyanamide, made from calcium carbide. Finally, under the pressure of wartime shortages, a full-size plant began production of nitrates for fertilizers and munitions in 1916.

However, the German chemical industry was predominantly based on synthetic dye manufacturing through the 1920s. When the three biggest firms consolidated (ca. 1925) they took the name I.G. Farbenindustrie. Farben is the German word for color. Indeed, it was experience with color chemistry that led to several major pharmaceutical breakthroughs (including the anti-syphilis drug Salvarsan) and helped the Germans take a leading role in color photography.

4.3. Petroleum

The gaslight industry was created primarily to serve a growing demand for illumination. It could only do this in large cities where a central gas distribution system could be economically justified. However, in the 1850s most of the population of the world still lived in small towns or rural areas where gaslight was not an option. The alternative illuminants were liquid fuels: whale oil and kerosene. Whale oil was a cleaner-burning fuel and generally preferable, but the supply of whales from the oceans of the world was being depleted rapidly. Oil prices were rising. Kerosene could be produced in small quantities from coal, but petroleum was a far better source.

The year 1857 marked the beginning of commercial petroleum production in Rumania, followed by the discovery of oil in western Pennsylvania in 1859. These developments were prompted by the introduction of distilled coal oil by James Young in 1850–1851 and kerosene in 1853. Interest was further stimulated by Benjamin Silliman's pioneering work on fractional distillation of petroleum (1855) and the rising price of liquid fuels such as kerosene and whale oil for household illumination. The subsequent availability of volatile hydrocarbon liquids (natural gasoline, one of the lighter distillation products of petroleum) was crucial for the adaptation of Nikolaus Otto's stationary high-compression gas-burning internal-combustion engine to mobile transport purposes, discussed later.

The growth of the petroleum industry in the US was extremely rapid. Production in 1860 was about 0.5 million barrels (bbl.). Output in the first decade of production multiplied tenfold to five million bbl. Production nearly doubled again by 1874 and once again by 1879 to 20 million bbl. Thereafter, output of crude oil reached 24 million bbl. in 1884, 35 million bbl. in 1889, 49 million bbl. in 1894, and 57 million bbl. in 1899 (Williamson and Daum, 1959).

Throughout this period, the major product of the US petroleum industry was "illuminating oil" (much of which was exported to Europe). Other products, in order of importance, included "naphtha-benzene-gasoline," fuel oil (in the 1890s), lubricating oils, paraffin wax, and residuum (tar and bitumen). The gross value of refined products was about $43.7 million in 1880, $85 million in 1889, and $124 million in 1899 (*ibid.*). Only the steel industry was bigger at that time. Employment in US refinery operations averaged 12,200 in 1899 (*ibid.*). It is important to bear in mind that this was a very large industry long before demand for motor gasoline became significant in the years after 1900.

4.4. Sewing machines and bicycles

The sewing machine was a natural follow-up to the cotton-spinning and cotton-weaving technology that was one of the drivers of the first technological transformation, discussed in the previous section. However, cotton cloth is a bulk commodity, whereas clothing must be customized to some extent. Thus, a skilled operator remained essential, and economies of scale in garment making were not nearly as great as in textile production. In other words, whereas a single loom could eventually be made very large and fast to increase output, sewing machines were (and still are) needed in very large numbers. They were, also, inherently much more complex than any product produced in comparably large numbers (such as revolvers or pocket watches) up to the middle of the nineteenth century.

The sewing machine was slow to reach the marketplace in practical form because of its mechanical complexity, as noted above, and because most inventors attempted to simulate the actions of a human seamstress, rather than taking advantage of the attributes of machines. The basic invention was the double-pointed needle with an eye in the center, patented by Charles Weisenthal (1755). Actually, Thomas Saint came very close to inventing a practical sewing machine for leather work in 1790. His design lacked only Weisenthal's needle to anticipate most of the features of much later models. But metalworking technology at the time was crude, so that Saint's machine would have been far too expensive for widespread use. A mechanical stitching machine was successfully demonstrated by Barthélemy Thimonnier in 1830, and 40 copies were made to produce uniforms for the French army. However, Thimonnier's machines were destroyed by a mob of angry tailors, and his project was aborted.

The prototype of modern machines seems to have been built by Walter Hunt in 1832–1834, but it was not patented. Again, the machine was probably too complex to manufacture at that time. Hunt's ideas were independently rediscovered and patented by Elias Howe (1846). During the next decade many other inventors introduced useful improvements, or reintroduced the same ideas independently. Some of the names are Morey, Johnson, Bachelder, Blodgett, Lerow, Wilson, Grover, and Baker. Of course the most famous name is that of

Isaac Singer, whose 1851 machine was noted more for its successful combination of the important features of a modern sewing machine, than for its originality. A patent pool (1856) resolved most of the furious disputes over priority and gave Howe some royalties.

Production began on a modest scale in the early 1850s. The market was ready, and demand soared. Annual production reached 110,000 in the US alone by 1860 and continued to grow for decades thereafter. However, 1860 probably marked the point of maximum diversity. In that year there were 74 different manufacturers. In the following decade, as the product standardized, three of them began to outdistance the competition, and Singer took the lead.

At first the sewing-machine industry was a small outgrowth of the arms- and tool-making industry located in New England. Most early machines were built under contract by arms makers or machine shops. Specialized factories were built as early as 1858. In 1873, Singer built a new, vertically integrated manufacturing facility in Elizabethport, NJ, and revolutionized manufacturing. It was in that plant - between 1880 and 1882 - that the elusive goal of interchangeable parts was first fully realized by a mass-producer (Hounshell, 1984, p. 92).

Another important consumer product innovation toward the end of the nineteenth century was the bicycle. Its predecessors include a number of machines that were built by individual enthusiasts, such as Johnson (ca. 1818), MacMillan (ca. 1840), and Dalzell (1846). However, the rotary crank did not appear until 1865 on the first commercial velocipede, made in small numbers by M. Michaux from Paris. The Franco-Prussian War (1870) interrupted Michaux's business and moved the infant bicycle industry to the UK. The velocipede was soon imitated and improved upon by James Starley and William Hillman. Further innovations included the substitution of hard rubber tires (ca. 1870) and ball bearings (1877). The gear-and-sprocket drive was invented in 1879 by Harry J. Lawson and introduced on the "safety bicycle" manufactured on a large scale by J.K. Starley's Rover Company starting in 1885. The final major improvement was pneumatic rubber tires, the invention of John Dunlop (1889). Dunlop went on to manufacture automobile tires. Freewheeling (for coasting) and variable gears were introduced in 1894 and 1899, respectively.

The bicycle industry enjoyed a great but brief boom in 1892–1894. It is worth a mention here mainly because bicycle technology was a vital prerequisite of the automobile and the airplane. For instance, early automobiles employed bicycle-type wheels, tubular steel frames, ball bearings, and chain-and-sprocket drives. Aircraft bodies also utilized lightweight construction techniques pioneered in bicycles. Wilbur and Orville Wright, the first men to build a successful powered aircraft, had worked previously in a bicycle shop, as did Charles and Frank Duryea, the first Americans to build a gasoline-powered automobile, and W.S. Knudsen, who later became president of General Motors. In fact several major automobile companies began as bicycle manufacturers, including Peugeot (France), Opel (Germany), Hillman, Morris, and Rover (UK), and Pope, Winton, and Willys (USA).

4.5. Internal-combustion engine

The second great technological breakthrough of this period was the gasoline-powered internal-combustion engine. It, too, was in a sense an outgrowth of the gaslight industry, in the sense that the availability of "town gas" as a fuel was a prerequisite. But the driving force behind this innovation was the need for more compact and more efficient prime movers, especially for the smaller machine shops and factories that were springing up. Nikolaus Otto's successful high-compression gas engine (1876) was the culmination of a series of inventions. Some of the most noteworthy were the prototype "explosion engines" of R. Street in 1794 and W. Cecil in 1820 and the first commercial stationary gas engines built by Samuel Brown in the 1820s and 1830s.

Key steps forward were taken by Wright (1833) and William Barnett (1838), who were the first to try to use compression. Etienne Lenoir (1860) built and commercialized a double-acting gas engine modeled on the double-acting steam engine invented by James Watt. Like Watt's engine, it did not compress the fuel-air mixture. These engines were quite successful, despite being very inefficient in thermodynamic terms (about 4%).

The need to compress the fuel-air mixture prior to ignition had been recognized by Barnett, but the first to use compression in a two-stroke engine was George Brayton in 1872. His engine was exhibited at the "Century of Progress" in Philadelphia, 1876. The superior four-stroke cycle was described in theory by Alphonse Beau de Rochas (1862). This cycle was embodied in Otto's revolutionary engine 14 years later. The "Silent Otto" rapidly achieved commercial success as a stationary power source for small establishments throughout Europe, burning illuminating gas as a fuel. Otto's engine produced three hp at 180 revolutions per minute (rpm) and weighed around 1,500 lb., a much more compact package than any comparable steam engine.

The first "true" automobile engine was probably a 1.5 hp (600 rpm) model weighing 110 lb. built by Gottlieb Daimler (who had worked for Otto) and Wilhelm Maybach (1885). They built four experimental vehicles during the years 1885–1889. The first true (if impractical) automobile was built and operated for several years by Siegfried Markus (1864–1868) and shown at the Vienna Exposition in 1873. Karl Benz, an established manufacturer of (stationary) internal-combustion engines, motorized a tricycle in 1886. This is sometimes credited as the first practical automobile. Credit for that achievement probably belongs more properly to Emile Levassor in 1891, who designed the first car (the Panhard-Levassor) that did not resemble a horse-drawn carriage without the horse. Benz introduced the spark plug, however, a significant advance over Otto's "glow tube" ignition. A large number of subsidiary inventions followed, such as the carburetor (Maybach, 1893), the expanding brake (the Duryea brothers, 1898), the steering wheel (1901), the steering knuckle (Eliot, 1902), the headlamp, and the self-starter (Kettering, 1912).

Incidentally, the success of the spark-ignition high-compression "Otto cycle" engine created enormous interest in the technical possibilities of compression engines and led directly to the development of the compression-ignition internal-combustion engine by Rudolph Diesel (patented 1892). The diesel engine was first commercialized for stationary power in 1898, but acceptance was slow. It was adopted for the first time for railway use by the Prussian State Railways (1912) and for marine use shortly thereafter. However, large-scale railway use began in the 1930s (General Motors). The first automobile diesel engine was introduced in the 1930s by Mercedes Benz, but penetration of the automobile market has been negligible until recently. (The advent of the turbo diesel has changed this somewhat.) However, diesel power dominates the heavy truck, bus, rail, and off-road machinery fields today.

The most important technological barrier that stood in the way of practical self-powered road vehicles, from the time of Nicholas Cugnot (1770) on, was the unavailability of a prime mover with sufficient power in a small enough package. The same barrier applied to heavier-than-air craft. The key variable is power-to-weight ratio. In retrospect it is clear that the minimum feasible level for road vehicles was about 100 lb. per hp or .01 hp per lb. The Daimler-Maybach engine achieved 75 lb. per hp or .0133 hp per lb. Cars did not become truly practical until further developments brought the engine weight down (or the power up) to around 15 lb. per hp. *Figure 9* shows the progression in power output per unit weight.

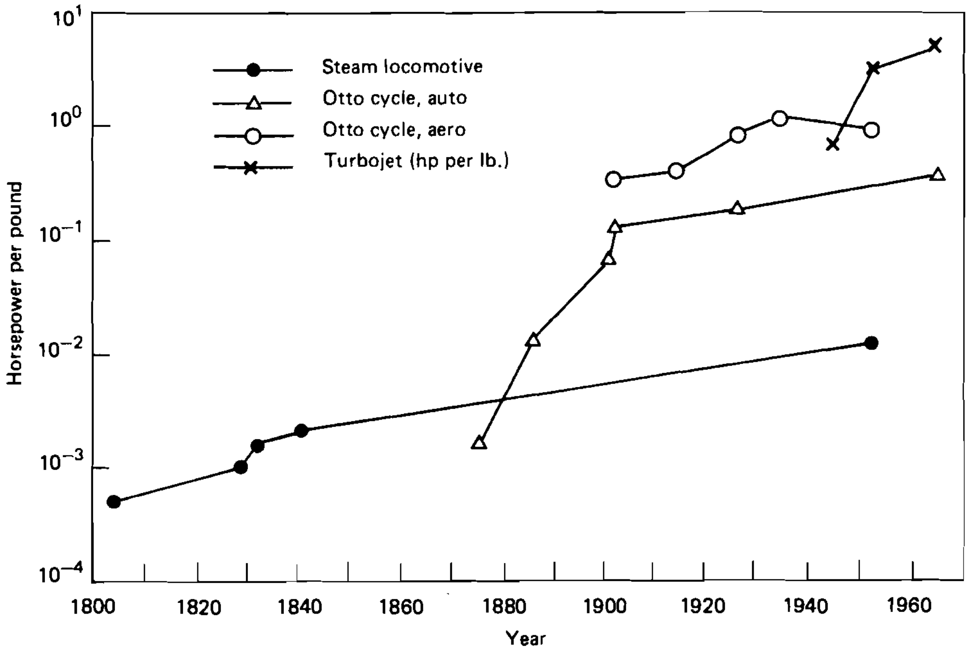

Figure 9. Mobile power per unit weight.

Actually, the 1901 Mercedes Benz engine produced 35 hp with an engine weighing 475 lb. (13.5 lb. per hp). But Charles Manly's engine, designed specifically for Samuel Langley's *Aerodrome* (1903), achieved 52 hp in a package weighing only 150 lb. or less than three lb. per hp. But the early aircraft engines obtained part of their punch by the use of special high-octane fuels (e.g., benzene) that permitted high-compression ratios – and hence greater power – but that could not be produced in large enough quantities for automotive use. Obviously practical air transportation (which came much later) required substantially reducing the weight of the engines. Progress in gasoline-refining technology in the 1930s played a major role in this.

4.6. Electric light and power

The third great technological breakthrough of the 1880s was the commercialization of direct current (DC) electrical generation, primarily for lighting and streetcar systems, initiated in the US and followed soon after in western Europe. The key inventions were the efficient DC dynamo (and its alter ego, the DC motor), the arc lamp, and the incandescent light. The dynamo-and-motor evolved over many years, following Michael Faraday's initial discovery of electromagnetic induction in 1831. The major milestones were made by Europeans, with significant contributions from John Stephen Woolrich (1842), Fredrick Hale Holmes (1857), Charles Wheatstone (1845, 1857), Werner Siemens (1856, 1866), Antonio Pacinotti (1860), Zénobie Théophile Gramme (1870), and F. von Hefner-Altaneck (1872) (Sharlin, 1961). Gramme's machine was the first capable of producing a relatively continuous current. Von Hefner-Altaneck (of the Siemens firm) perfected the drum winding, which was more efficient and cheaper, and has subsequently become the standard. The prevailing engineering doctrine up to 1878 was to produce large amounts of current for arc lamps at low voltages. The most widely used commercial dynamo before Edison (Gramme) achieved an efficiency of barely 40% in terms of converting mechanical energy to electrical energy. Indeed, at the time, 50% was thought to be the theoretical upper limit! (Josephson, 1959). The only significant application of dynamo electricity until the 1880s was for arc lamps, and only on a small scale.

Thomas A. Edison's decision in 1877 to develop a practical incandescent lamp suitable for household and office use (in competition with the gaslight), was momentous. He was the first to realize that the solution was to be found in much higher voltages, to minimize the need for copper wire in the distribution system (*ibid.*). This required a new generator design and led to his constant-voltage bipolar generator (1878), which raised the efficiency of energy conversion in one giant step to 90% (*ibid.*). This made possible Edison's system of central station electricity production and distribution (1882) and opened the door for widespread applications of DC electricity. The progression of efficiency is shown in *Figure 10.*

The first new application of DC power was for lighting. Arc lamps were already known, and a number of practical arc-lighting systems were developed in the late 1870s – preeminantly those of Charles Brush (1876) and Elihu Thomson with Edwin Houston (1878). These systems were suitable for outside use and large public rooms. Soon they were being produced in significant numbers. By 1881 an estimated 6,000 arc lamps were in service in the US, supplied by their own dynamos. Edison's high-voltage carbon-filament incandescent light (1879)

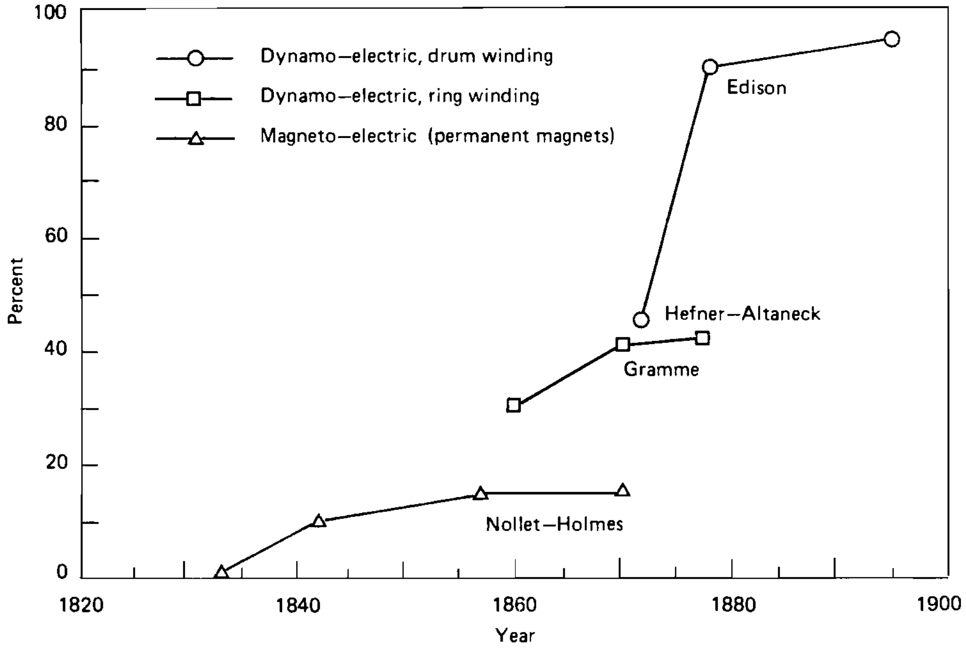

Figure 10. Efficiency of electric generators: electric power output per unit of mechanical power input.

was more suited for indoor use, of course, and it, too, went into production in 1881 – both by Edison's company and by several competitors. Both types of lighting system met rapidly growing demand. By 1885 the number of arc lamps in service was 96,000 and the number of incandescent lights had already reached 250,000. By 1890 these numbers had risen to 235,000 and 3 million, respectively.

Edison's success was bad news for the gaslight industry. After a long period of prosperous growth, gas shares slumped sharply in the late 1880s, which may have contributed to the recession of the early 1890s. As it happened, the gaslight system was temporarily reprieved by the invention of the "gas mantle" by Carl Auer von Welsbach in 1885. The incandescent thoria-ceria mantle increased the luminosity of a gas flame by a factor of six (Passer, 1953, p. 196), and its adoption kept gas lighting competitive for another 20 years. The electric light was adopted much more rapidly in the US than it was in the UK, primarily because gas was much cheaper in the UK, making electricity much less competitive for purposes of lighting in the 1890s. This, together with restrictive legislation, seriously impeded UK development in the competitive electrical industry.

Other applications of DC power soon followed, of which the most notable in terms of immediate impact was the electric streetcar (or trolley), which sprang up more or less independently in a number of cities. The contributions of Charles Van De Poele (especially the carbon brush, 1888) and Frank Sprague, who built the first practical heavy duty DC motors suitable for electric trams, deserve particular mention. The building of urban transit systems not only employed a good many people, but also permanently influenced urban geography, permitting much higher-density development than had previously been possible, as well as creating many new suburbs. A remarkable number of street railways (trolleys) were built in the following decade. As noted above, by 1910 it was said to be possible to travel by trolley from Maine to Wisconsin.

By 1890 DC power was already being challenged by alternating current (AC) for general distribution. To supply electricity in large amounts economically it was (and is) necessary to take advantage of economies of scale in production, whether from available hydro-power sources or from large steam-powered generating plants. In the US an obvious initial location for a large generating plant was Niagara Falls, which was some distance from the major centers of industry. In Europe, the first hydroelectric generating plants had to be located on tributaries of the Rhone, Rhine, and Danube, mostly in remote Alpine valleys. To serve a dispersed population of users from a central source, an efficient means of transmission was needed, and efficient (i.e., low-loss) transmission inherently requires high voltages.

AC power can be transformed easily from low to high voltages, and back, but DC power cannot. This simple technical fact dictated the eventual outcome. All that was needed was the requisite technology for generating and transmitting AC power at high voltages. Thomson had already developed a practical AC generator (1881). Lucien Gaulard and John Dixon Gibbs, in Europe, and Elihu Thomson and William Stanley, in the US, had developed prototype transmission and distribution systems for AC incandescent light by 1885. Nikola Tesla introduced the polyphase system, which in turn permitted the AC induction ("squirrel cage") motor by 1888.

The entrepreneur who saw the potential of AC power, acquired licenses to all the patents of Gaulard, Gibbs, Stanley, and Tesla, and "put it all together" was George Westinghouse. His success was assured by a successful bid for the first phase of the Niagara Falls generating plant (1891) and, subsequently, the great Chicago Exhibition (1893). It was Tesla, incidentally, who persuaded Westinghouse to establish the 60-cycle standard for AC, which ultimately became universal in the US.

Yet Edison, the father of DC power, strongly resisted the development and use of AC systems (as Watt, before him, had resisted the use of high-pressure steam). During the 1880s both the Edison companies and the Thomson-Houston companies had been growing rapidly and swallowing up competing (or complementary) smaller firms, such as Brush Electric, Van De Poele, and Sprague. In 1892 the two electric-lighting and traction conglomerates merged to form the General Electric Co. (GE), with combined sales of $21 million, as compared with $5 million for Westinghouse. In the mid-1890s the two firms fought hundreds of lawsuits over patent rights; this problem was finally resolved by creation of a patent pool, which gave GE 63% and Westinghouse 37% of the combined royalties for 15 years. The main benefit of this arrangement was that neither incompatible standards nor patent restrictions held back further technological progress of electricity, as might otherwise have happened. In the end, AC displaced DC for most purposes, as it was bound to do.

The first sharp burst of the electric light and power industry in the US during the 1880s slowed to a crawl during the early 1890s, due to the recession mentioned above and the uncertainty with regard to the DC-AC controversy. In any case, GE's revenues slumped sharply after 1893 and did not reach the 1893 level again until 1898. Rapid growth in the electrification of factories and households occurred thereafter, as indicated by *Figure 11*. This was accompanied by rapid growth in the manufacture of electrical equipment and the associated electrical utilities in the early decades of the twentieth century.

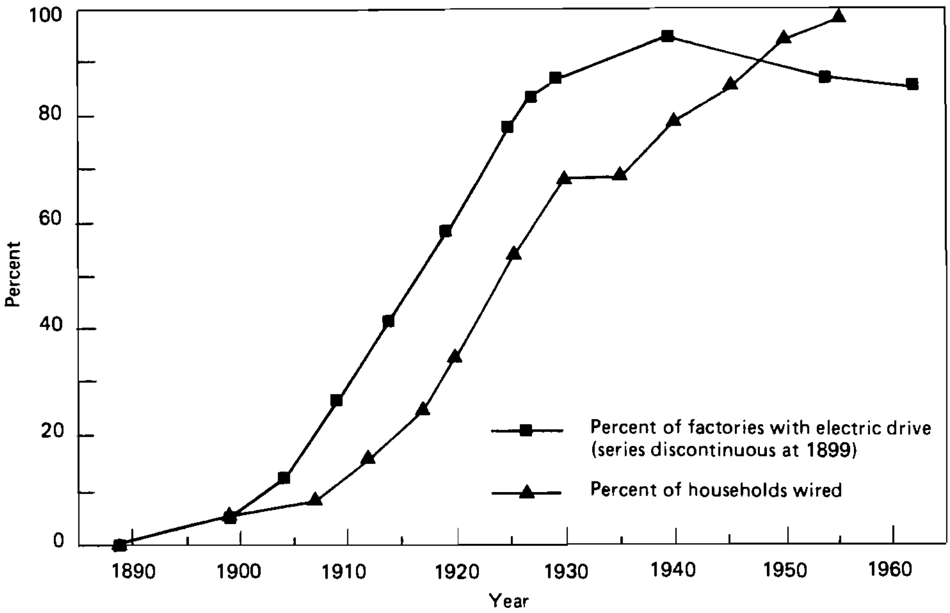

Figure 11. Electrification in the US. (Source: *USBOC, Historical Statistics of the United States.*)

4.7. Electrochemistry and electrometallurgy

Two new and important applications of electric power also appeared during the 1890s, *viz.*, electrometallurgy and electrochemistry. The high-temperature electric arc furnace, invented by William Siemens in 1878, was first used commercially by Alfred and Eugene Cowles in 1886 to manufacture aluminum alloys. The discovery of the use of acetylene as an illuminating gas by Henri Moissan in 1892 was a milestone. In the same year T.L. Willson demonstrated a method of producing acetylene from calcium carbide made in an electric furnace. Acetylene was rapidly adopted as an illuminant for towns without electricity. By 1899 a million acetylene gas jets were fed by 8,000 acetylene plants in Germany alone (Burke, 1978, p. 209). The boom collapsed almost as rapidly, due to the impact of the Welsbach mantle and cheaper electricity. Acetylene continued as a very important industrial chemical feedstock, however, until its displacement by ethylene (from natural gas) in the 1930s.

Another early application of electric furnaces was the discovery (Edward Acheson, 1891) and production of synthetic silicon carbide ("carborundum"). This was the hardest material known at the time, apart from diamonds, and found immediate use as an abrasive used by the rapidly growing metal-working industry, especially in so-called production grinding machines developed by Charles Norton in 1900. The vital importance of high-speed grinding machines to the mass production of automobiles has already been mentioned. It is noteworthy that modern grinding technology is dependent on the prior development of the electric furnace, and could not otherwise have been developed.

The research of Moissan in France in the late 1890s also led to the use of the electric furnace for melting metals with high melting points, such as chromium, molybdenum, nickel, platinum, tungsten, and vanadium. Paul L.T. Héroult further developed the electric furnace for industrial purposes, and his work was instrumental in permitting its use for the production of ferroalloys and special steels, beginning in Canada after 1903. The importance of abrasives (for grinding) and special tool steels and hard materials, such as tungsten carbide, is illustrated by *Figure 12* in terms of metalworking rates.

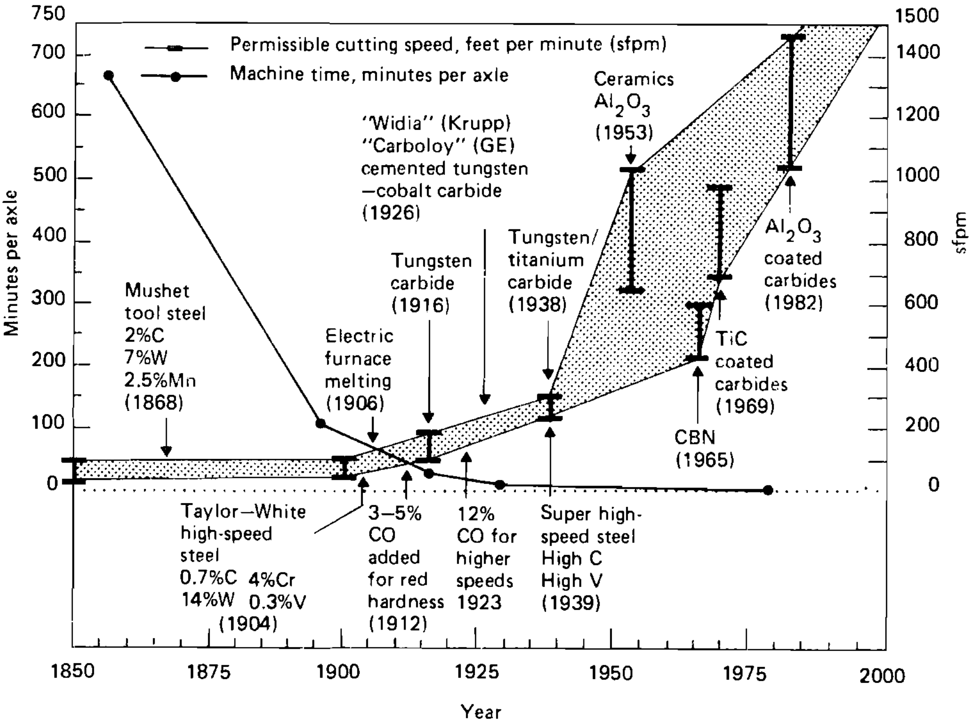

Figure 12. Machining speed (productivity) for steel axle: machining time and permissible cutting speed.

Electrochemistry – the application of electrolysis – also became practical for industrial use in the 1880s. The first, and most important, industrial electrolytic process was discovered in 1887 independently by Héroult in France and by Charles A.M. Hall in the US. They each developed a practical way of producing aluminum from aluminum oxide (alumina) dissolved in molten cryolite. This process was commercially exploited in both countries within two years. The price of aluminum dropped rapidly (from $17 per lb. in the 1860s to $8 per lb. in the 1880s to $.30 per lb. by 1897). Not surprisingly, many new applications emerged.

Curiously, the availability of metallic aluminum had no real impact on the infant aircraft industry in its first three decades, i.e., until about 1927 when the first all-metal plane (Ford Tri-motor) was built. Needless to say, the commercial airline industry, in its present form, could not exist without aluminum.

The second important electrolytic process (1888) was Hamilton Castner's system for manufacturing metallic sodium (and chlorine) from fused sodium chloride, or common salt. At first, it was sodium hydroxide that was the important product – used in making soap and for whitening illuminating oil – and chlorine was more or less a by-product. However, chlorine was soon in demand for a variety of chemical purposes, as well as for bleaching paper and purifying municipal drinking water. Today, chlorine is one of the most important basic industrial materials, with a host of important uses from plastics (e.g., polyvinyl chloride) to insecticides (beginning with DDT). The cumulative economic impact of electrometallurgy and electrochemistry has clearly been enormous, although most of it was not felt until many years after the key innovations.

4.8. Telephone

One last great technological breakthrough of the period must also be noted. The telephone (Alexander Graham Bell, 1876) actually preceded Edison's breakthrough in DC power, and its advances occurred, during the early stages, independently of it. Nevertheless, the telephone system in its present form is entirely dependent on the availability of inexpensive, reliable electric power in large amounts. Precursors of the telephone were, primarily, the telegraph (Charles Wheatstone, 1837; Samuel F.B. Morse, 1844) and its later improvements. The key invention, by some accounts the most valuable of all time, was – to some extent – serendipitous. Bell's backers were merely seeking to increase the capacity of the telegraph system, which was having difficulty expanding its network fast enough to accommodate growing demand. The original invention was the practical implementation of the notion that speech could be transmitted and reproduced as an "undulatory electric current of varying frequency." Others had previously worked on the idea of transmitting speech by wire, notably Charles Bourseul (1854) and Philip Reis (1861), but had adhered too closely to the make-or-break principle of the telegraph.

In any case, Bell's invention was soon followed by the creation of a business enterprise (American Bell Telephone Co.), which grew with incredible rapidity. Manufacturing began under license within a year, and 5,600 phones had been produced by the end of 1877. In 1878, the first commercial switchboard was

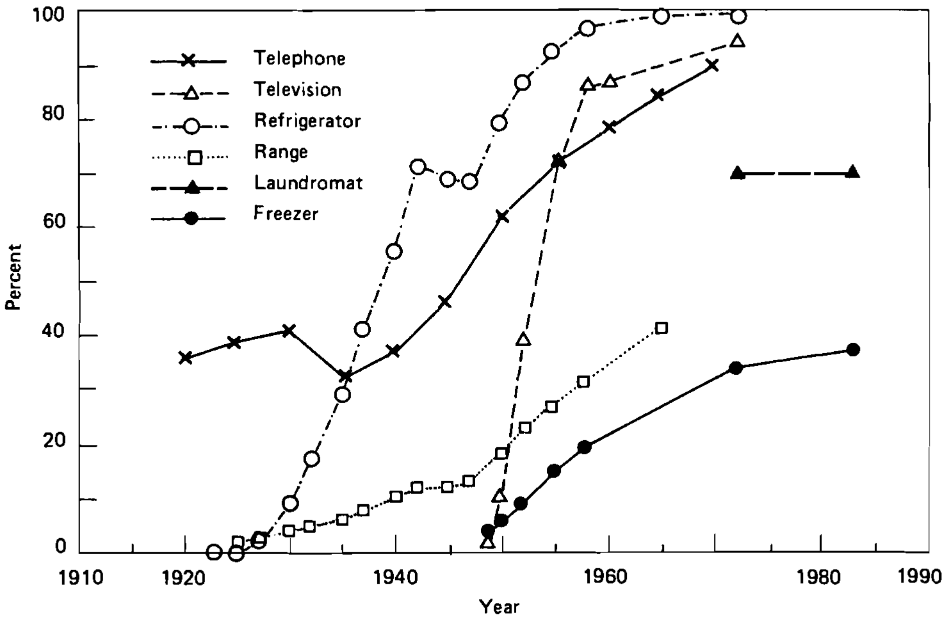

Figure 13. Household electrification: percent of households.

operating in New Haven, with 21 subscribers. Telephone companies sprang up in almost every town and city, not only in the US but also in western Europe. The annual rate of US production rose to 67,000 by 1880 (of which 16,000 were exported), and the number of units in the hands of licensed Bell agents in the US alone reached 132,692 as of 20 February 1881 (Smith, 1985, p. 161). The number nearly doubled two years later. The Bell licensees gradually evolved into local operating companies. Western Electric Company was acquired by American Bell in 1881 to become its manufacturing arm, and AT&T was formed to operate longlines interconnecting the local companies. AT&T gradually acquired stock in many of the operating companies and subsequently exchanged its stock with American Bell, becoming the parent company.

It should be noted that Bell's original patent, while the most essential, was only the first step in a massive technological enterprise. Telephony has spawned literally tens of thousands of inventions, some of them very important. One of the first and most important was the carbon microphone invented by Edison and Emile Berliner (1877). Many of the key inventions in sound reproduction, electronic circuitry, and radio were by-products of an intensive exploration of ways to reduce costs and improve the effectiveness of telephone service. There were 47,900 phones actually in service at the end of 1880, 155,800 by the end of 1885, 227,900 by the end of 1890, and 339,500 by the end of 1895. The original Bell patent expired in 1894, releasing a burst of activity. US demand skyrocketed: a million phones were added to the system in the next five years, 2.8 million in the period 1905–1910, and 3.5 million in the period 1910–1915. The US industry grew much faster than its European counterpart after 1895 (having lagged somewhat behind Sweden and Switzerland earlier). Penetration is shown in ***Figure 13***.

Employment generated by the telephone system has not been estimated, but was probably not less than one per hundred telephones in service. By 1900, Western Electric Co. employed 8,500 people and had sales of $16 million; by 1912 it was the third largest manufacturing firm in the world, with annual sales of $66 million. The telephone system could not have grown nearly so fast or so large without the concomitant availability of electric power.

An offshoot of the telephone (and another application of electricity) must now be mentioned, *viz.*, radiotelegraphy developed by Guglielmo Marconi in 1896. However, the technology was very limited at first, and its applications remained few and specialized for the next two decades, or more. They belong to the fourth technological transformation.

4.9. Automobiles

The automobile was not really a single invention (although it was patented several times), but rather a convergence or fusion of many inventions. Preconditions for a successful self-powered vehicle included an adequate engine, fuel, means of transmitting power to the wheels, means of controlling the engine and the vehicle itself, a suspension, a chassis or frame, suitable materials of construction, and efficient manufacturing techniques. Although steam power was sporadically adapted to propel road vehicles throughout the nineteenth century (and actually dominated automobile racing as late as 1906), it was the high-speed spark-ignition gasoline engine of Daimler and Maybach (1885) that uniquely met the first criterion. Gasoline was available for fuel, initially as a by-product of the fast-growing illuminating-oil industry. Cheap, high-quality steel used for bicycle frames, gears, and chains and pneumatic tires were important contributors. New manufacturing techniques, invented partly for the auto industry, completed the picture. Some of the tools developed for the new industry were a remarkable collection of new machines for precision grinding of crankshafts (1903), piston rings (1904), cylinders (1905), and camshafts (1911). Ford's rationalization of the assembly process, culminating in the moving assembly line (1913–1916), while hardly an original concept, also deserves mention.[2]

In 1900 some 8,000 motor vehicles were registered in the US, and production that year was 4,192 units. Production rose rapidly to 33,200 units in 1906, 181,000 in 1910, and no less than 1.5 million in 1916. The 3.2 million level was reached in 1924, rising to a (temporary) peak of 4.6 million in 1929. This astonishing growth carried with it a number of satellite industries, ranging from gasoline refining and tire manufacturing to storage batteries and safety-glass. It also brought about significant changes in the technology of manufacturing.

However, the major historical accomplishment of Henry Ford was more far-reaching, if less technical. By bringing together many innovations of others, he made automobile transportation cheap, reliable, and accessible to all. What had been a luxury for the rich in 1905 was becoming a household (and farm) necessity only 20 years later. The 1909 Model T sold for $950 (Hounshell, 1984, p. 224). The average annual wage of a US worker in that year was $545. By 1916 the price of a Ford was down to $360, whereas the average wage was up to $705. In the early 1920s Ford brought the price down even further (to retain market share) to $290 (Abernathy, 1978, p. 32). By comparison, the average annual wage in the last year of the Model T (1927) was $1,380. An average US worker in 1908 would need to work 21 months to buy a car. By 1927 the average worker could buy a car with the wages of 2.5 month's work. (No wonder many chose to spend more money and buy a more up-to-date car!) Ford did nothing less than create the mass consumption society.

4.10. Photography and moving pictures

Photography – the making and recording of visual images by physicochemical means – is not a single well-defined technology. The earliest experimental discoveries on photochemistry (especially the light sensitivity of silver compounds) date back at least to 1727 (J.H. Schulze). The optical prerequisites for cameras are even older. The camera obscura was invented in 1553, if not earlier, and the use of lenses, shutters, and mirrors to sharpen the image was established before 1600. Thus the means of fixing an image on some permanent medium was the major barrier to practical use. The first permanent photographic image (on glass) is attributed to Joseph Nicephore Niepce (1822). Means of fixing an image on a metal plate followed in 1826 and attracted the notice of Louis J.M. Daguerre. Daguerre joined Niepce in 1829, and 10 more years of development resulted in the daguerrotype process (iodized silver plate, fixed by mercury fumes), which was a commercial success. Nevertheless, it required an exposure of 4,000 seconds to obtain a good image (f/11) in sunlight. This was cut to 80 seconds a year later by resensitizing the plate with bromine.

The process of making "positive" reproductions from a "negative" image was invented by W.H. Fox Talbot (UK) in 1840. A new material, collodion (a stabilized form of cellulose nitrate) was developed as a by-product of the search for more effective explosives conducted by Christian Schoenbein in 1847. The wet plate collodion process developed by Fred Scott Archer in 1851 superceded the daguerrotype and increased sensitivity another tenfold. The next step was to coat plates with an emulsion of silver bromide in collodion advanced by B.J. Sayce and W.B. Bolton in 1864 and by Bolton alone in 1874. Sensitivity improved further with the introduction by C. Russell in 1862 of alkaline development, but this was not perfected until the advent of gelatino-silver bromide dry plates, which increased sensitivity by another factor of 16 by 1880 and a further factor of five by 1885. By this time exposure time was down to 1/10 of a second. Progress has continued rapidly since then: 1/100 of a second was achieved by 1930, 1/500 by 1950, and 1/2,500 by 1960 (*Figure 14*).

The substitution of roll film for glass plates, which vastly increased the market for photography, was the contribution of George Eastman (1884), and the first roll film (Kodak) camera was marketed by Eastman in 1888. This was

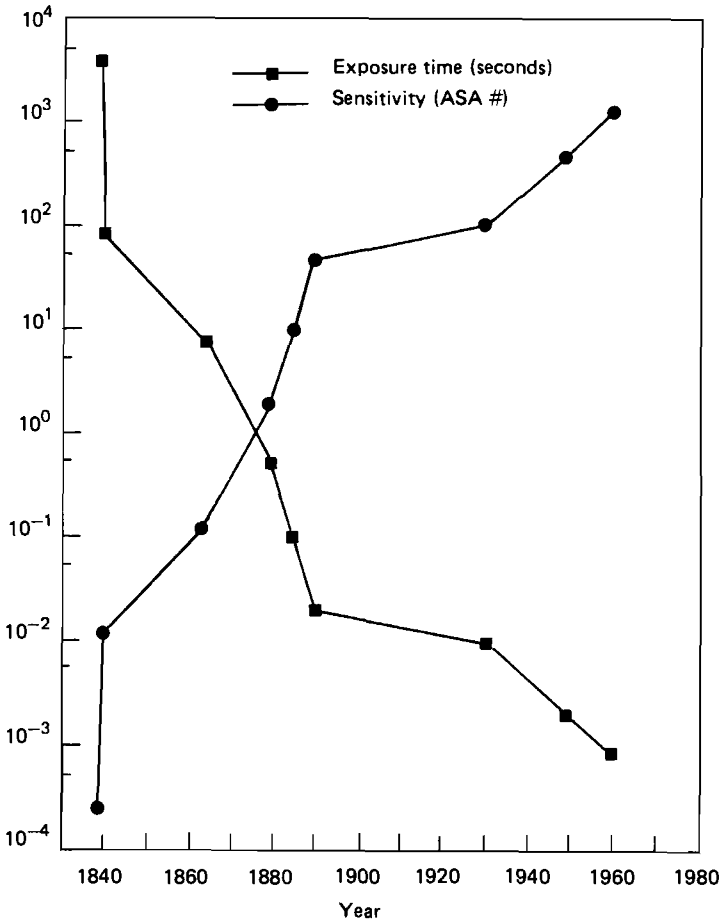

Figure 14. Technological progress in photographic imaging: normalized to f/11, full sun, and black and white.

the start of the Eastman Kodak Company. A new flexible nitrocellulose-based (celluloid) film was introduced by Hannibal Goodwin in 1888 and produced by Eastman in 1889. Edison's contributions to sound recording (the recording telegraph and the phonograph, 1877) attracted his interest to moving pictures. Edweard Muybridge's "zoopraxiscope" (1879) was the first system for rapid sequential photography. Edison applied it to the new flexible film and invented his kinetoscope (1893) for playing a strip of successive time-delayed images, using a stroboscopic light and a hole-and-sprocket system for pulling the film. The final idea of projecting the images continuously on a screen was patented by brothers L.J. and A.M.L.N. Lumière (1895). The silent movie became popular almost overnight thereafter. However, it became a great economic success only in the decades after 1930 when sound and later color were added.

4.11. Conclusion

It is clear that the simple well-defined clustering of critical innovations that occurred near the years 1775 and 1825, and kicked off the first two Kondratieff waves, did not repeat with the third technological transformation, ca. 1875. A far more complex pattern ensued. The third wave of growth was characterized by no less than five distinct leading sectors, which did not coincide exactly. The first two were the steel industry and the petroleum industry. The next three, which were displaced by about 20 years, were telephones, electric light and power, and automobiles. (Indeed, still other industries, such as industrial chemicals and agricultural machinery, could well have been included.)

The time displacement was hardly accidental. It has been pointed out that a highly developed steel industry was a prerequisite for both the electric power industry and the auto industry. A sophisticated petroleum refining industry was also a prerequisite for autos. Lastly, electric power was a prerequisite for both telephones and products using the electric furnace, which, again, were a prerequisite for the high-speed grinding technology that made truly large-scale automobile manufacturing economically feasible.

Another difference between the third transformation and the first two is that the role of labor-saving (or time-saving, labor-extending) technologies appears to have been significantly increased. This characterization applies to telecommunications, electric light, and electric traction, for instance. It also applies to a variety of kitchen and household appliances, such as the sewing machine, and to agricultural machines, such as the harvester, which were not explicitly discussed. The internal-combustion engine (ICE), the steam turbine, and factory electrification are examples of innovations that conserved energy. Capital was also saved, if the capital invested in the central generating and distribution system can be allocated to all users. Petroleum refining was, in effect, a resource-extending innovation. The use of steel rails in place of iron rails was also an energy-saving innovation, inasmuch as steel rails lasted much longer than their iron counterparts. To the extent that they permitted heavier trains and higher speeds, they also conserved (or extended) capital.

Many of the key innovations of the third technological transformation cannot well be characterized by any of the above labels, inasmuch as they really offered new services to consumers, either directly or indirectly (as in the case of new materials). The boundary between labor-extending innovations and new services needs clarification. Gaslight and the electric light are labor extending insofar as they facilitate production. They are new services insofar as they increase the quality of life for consumers. This is true of the electric streetcar, the telegraph, the telephone, the bicycle, and many household appliances, as well. The automobile (and its relative, the truck) also can be counted under both headings today, though the private car was mainly a luxury – except for farmers – until the 1950s.

5. The Fourth Technological Transformation ca. 1930–1950

If the initial 50-year cycle had continued on schedule the fourth major cluster of innovations should have occurred earlier than it did, *viz.*, ca. 1925. In actuality, there seems to have been a slowdown in the rate of major innovations during the period that economic growth accelerated, 1895–1930, and a speedup only after 1930. If what occurred during the period 1930–1950 can be called a cluster, it was certainly delayed and spread out over many innovations of smaller magnitude. There were just three truly significant innovations: television, semiconductors, and the computer.

Three possible explanations for the pattern are obvious. First, the previous growth phase was stretched out considerably by the sequential development of five leading sectors (steel and petroleum, followed by electric power, telephones, and automobiles). Second, four of the major growth sectors of the previous century reached or passed maturity: textiles, railways, gaslight, and coal mining; this diluted the impact of the new growth sectors. Third, World War II intervened. It may be argued, indeed, that the war actually accelerated innovation, rather than impeded it. This certainly appears to be true in some instances, such as radar, jet engines, atomic energy, and computers. However, the reverse may be true in others such as synthetic fibers and television. The net effect of the war will have to be sorted out by others.

An additional point that cannot be dismissed lightly is the suspicion that the Great Depression was a historical accident. Far from being the inevitable consequence of a long period of growth that occurred too rapidly, it may well have been, instead, the result of human error: a panicky misinterpretation of the "message" from the great stock market crash of October 1929.[3] According to some current neo-Keynesian theorists it was the actions of the government, not the stock market, that converted a normal cyclic recession into a major disaster.

If the human error interpretation of events is anywhere near correct, the Great Depression was not the inevitable result of long-wave dynamics. In other words, had it not been for the misguided actions of the Hoover administration, the long surge of consumer-driven economic growth that began in 1890 might have continued for another decade or two, if not longer. Certainly neither the trend toward "automobilization" nor the electrification of households had run its course by 1930; in fact, the latter had barely begun. Yet both trends were interrupted for nearly two decades.

Whereas a new set of leading sectors appeared in the 1870s and 1980s, the primary leading sector of the 1930–1950s was, once again, the automobile industry and its satellites. In fact, as seen in retrospect, the diffusion of the automobile throughout society had scarcely begun by 1930. Satellites of the auto industry included the petroleum industry (which had to switch from supplying illuminating oil to supplying motor fuel) and the highway construction industry (and its suppliers, such as cement and steel). The electrical industry also benefited from the growth of the auto industry. It began by selling spark plugs and magnetos to the auto manufacturers, and subsequently provided starter motors, headlights, batteries, instruments, and finally a whole galaxy of electronic controls. Today's automobiles contain thousands of electrical and electronic components, and the ratio of value added by electrical to mechanical parts continues to rise. Indeed, microprocessors now control many of the important subsystems of the car, including (in some models) fuel injection and brakes.

The electrical industry entered the twentieth century as a capital goods supplier with one major consumer product: light bulbs. By mid-century the emphasis had begun to shift to making a wide range of consumer products (apart from components for automobiles), both for saving household labor and for entertainment. Electronics and telecommunications began to converge. Growth in induced demand for electricity was, of course, a natural consequence.

To this list of leading sectors, the chemical industry and the aircraft-aerospace sectors should be added. Several important new sub-industries, including synthetic fibers, synthetic rubber, plastics, and pharmaceuticals, were really spawned by chemical technology. It is certainly noteworthy that the commercial airline industry took off in the depths of the Great Depression of the 1930s, although the rapid growth (diffusion) era began in the 1950s.

It was noted above that a large number of household electric appliances were either first introduced or vastly improved after 1930. The electric refrigerator was first commercialized in the US. The refrigerator was based on a French design developed in 1911, but it was GE's "monitor top," introduced in 1928, that began the era of rapid growth, which actually accelerated during the 1930s (*Figure 13*). The first electric washing machine appeared in 1912, but the convenient automatic washer arrived in 1939. An electric range (of sorts) was introduced as early as 1906, but the modern "white-enamel" version appeared in 1930, along with the electric clock. The first electric dishwasher also appeared in 1930; it became automatic in 1954. The room air conditioner followed in 1932, the garbage disposal in 1935, the electric blanket in 1936, and the fluorescent light in 1938. Of course, in all these cases the growth rate accelerated sharply after World War II as these innovations diffused throughout the US economy and then the European economy.

Was there really a major technological transformation beginning around 1930? From a very long-term perspective – notwithstanding the glamor of rockets, supersonic planes, and nuclear weapons – the answer is unclear. One major change was the institutionalization of R&D and the large-scale participation of governments to finance it. Because of the so-called "miracle drugs," the atomic bomb, the space program, and the computer, the public has become more aware of the power of technology to change the lives of people than (perhaps) it was earlier. Doubtless for this reason it is often asserted that technology in recent decades has been changing more rapidly than ever before. The reality is probably otherwise. Nevertheless, the postwar era witnessed 20 years of the fastest economic growth in US history. This growth was based on many innovations, to be sure, but few (except the transistor and the electronic computer, whose major impact was later) could be termed revolutionary.

5.1. Chemicals: petrochemicals, synthetic fibers, plastics, and pharmaceuticals [4]

The innovations that accompanied the fourth transformation were many in number but individually less important in relative terms than some of the earlier ones. There were, for instance, thousands of new chemicals and new processes to produce them. The chemical industry actually took off in the last decades of the nineteenth century, based on synthetic dyes, and gradually moved into other fields. The powerful German chemical industry of today had its origins in those earlier decades.

The synthesis of ammonia from atmospheric nitrogen during World War I was mentioned earlier. Another important product, stimulated by wartime shortages, was synthetic detergents. The first research on soaplike properties of nonsoapy substances was in Germany by Krafft in 1886–1987. The first detergent on the market was Nekal, produced by BASF in 1917. It was not suitable for washing but later found markets as a wetting agent. The sulfated fatty alcohols investigated by Daimler and Platz of I.G. Farben were introduced commercially as Igepons in 1930. A more important class of detergents, characterized by minimal production of lather (making them useful for washing machines), was discovered by Schoeller and Wittwer while working for I.G. Farben (1930). A further improvement in performance in "hard" water came about from the addition of complex phosphates resulting from research in several companies during the 1930s. In the late 1960s it was discovered that phosphate-based detergents were polluting lakes and streams (eutrophication). As a result of public outcry and environmental regulation, they were eliminated.

Other products of wartime shortages were synthetic rubber and synthetic gasoline (by the Fischer-Tropsch process). Synfuels had not yet reached the marketplace except during wartime and in South Africa. But in the case of rubber, the substitute displaced the natural product. Natural rubber had been shown to be a polymer of isoprene by C. Greville Williams in 1875, and isoprene from turpentine was first polymerized in a laboratory in 1892 by W. Tilden, but nothing further was done because of scarcity of natural sources of isoprene. The Russian I. Kondakow first polymerized butadiene in 1900; S.V. Lebedev made a rubberlike product from butadiene in 1910. The use of metallic sodium (Na) as a polymerization catalyst for butadiene was discovered in 1910 independently by C. Harris in Germany and by F.E. Matthews and E.H. Strange in the UK, also in 1910. The pressure of wartime needs and UK blockades in 1914–1918 induced German chemists to develop an alternative synthetic elastomer by polymerizing dimethyl butadiene, which they were able to synthesize on a small scale from acetylene (made from calcium carbide).

The wartime German synthetic rubber was expensive and of poor quality. The next commercial synthetic was Thiokol developed by Patrick in 1922. The first important commercial synthetic rubber was Dupont's Neoprene (a polymer of chloroprene) discovered by Arnold M. Collins in 1929 at the suggestion of Wallace Carothers. The raw material for chloroprene is monovinylacetylene. This is a compound accidently discovered in 1920 as an impurity in divinylacetylene, a trimer of acetylene (which was discovered by Julius Nieuwland in 1906). Neoprene was commercialized by Dupont in 1931. Another synthetic rubber, Butyl, was introduced by Standard Oil Co. of NJ ca. 1935.

Meanwhile, the German firm I.G. Farben concentrated on butadiene-based polymers, under the name Buna (taking the na from the sodium catalyst), beginning in 1925. But the Buna rubbers, at first, did not have good properties and commercial success was considerably delayed. The most successful version, Buna-S, was a copolymer of Buna rubber with styrene, which went into production in 1939.

The second world war cut off natural rubber supplies from both the Germans and the Allies, which resulted in almost total replacement of the natural product by a variety of synthetics. The type of synthetic rubber that is most common today is styrene butadiene rubber (SBR), a copolymer of styrene and butadiene. Both styrene and butadiene are now derived from ethylene (itself derived from ethane obtained from natural gas or petroleum refineries).

The petrochemical industry, which currently produces most of the basic feedstocks for synthetic rubber, plastics, and many other products, was essentially created by a dramatic shift in the economics of petroleum refining. This came about as a consequence of the growth of the automobile industry after 1910 and the need to produce motor gasoline in large quantities. Before 1913 gasoline was obtained as a by-product of illuminating oil (kerosene). It was simply the lightest, most volatile of the liquid "fractions" obtainable by distillation of crude oil, and consisted mainly of light paraffins. Only about 15% of the refinery output was directly usable as motor fuel. It had an octane number of around 50, which limited gasoline engines to a compression ratio of about 5:1, due to engine knocking.

The first to recognize the problem, and to exploit the opportunity it created, was William Burton of Indiana Standard (later Amoco). Burton successfully developed and commercialized the batch-type thermal-cracking process in 1913. By cracking heavier paraffin fractions, it enabled refiners to double their gasoline output. The process also increased the amount of some other hydrocarbons, such as aromatics, which increased the octane level as well. This made the process an extraordinarily profitable one. Oil companies started searching immediately for better processes (partly to cut down on royalty payments). By 1922 several continuous versions of the original batch-cracking process had been developed. The development of thermal-cracking processes incidentally opened the door to large-scale production of other petrochemicals, such as ethylene, propylene, and butadiene. Another response to the problem of engine knocking, mentioned above, was the search for a suitable gasoline additive to increase the octane number. The result was tetraethyl lead, discovered in 1921 by a small team of chemists led by Charles Kettering and Thomas Midgley, sponsored by General Motors (GM). The problem then shifted to production, and a process developed by Charles A. Kraus and Conrad C. Callis was commercialized by Dupont in 1924. The additive was then sold to gasoline refiners by Ethyl Corp., jointly created by GM and Standard Oil, for use in premium gasoline.

In 1923 the French chemical engineer Eugene Houdry began working on a new catalytic approach to petroleum cracking. The technology was developed slowly, with help from Vacuum Oil Co. (later Socony-Vacuum and later still Mobil) and from Sun Oil Co. The Houdry (batch) process was finally commercialized in 1938. It sharply increased the octane level, permitting 100-octane gasoline (for aircraft engines) to be produced on a large scale in time for World War II. To achieve further efficiency gains, and again, to avoid paying royalties, a consortium led by Standard Oil of NJ (later Exxon) was formed in 1938 to develop a continuous catalytic process. The first success was achieved in 1942. Mobil introduced its own continuous process in the same year. German needs for aviation gasoline during World War II resulted in the further development of catalytic hydrogenation processes, both for petroleum and for coal.

The first synthetic fibers were based on a reconstituted natural polymer, cellulose. Nitrocellulose was discovered by Christian Schoenbein (Switzerland) in 1846. Joseph Swan (UK) made fibers from nitrocellulose in 1883 (searching for an improved carbon filament for incandescent light bulbs). In fact, such a process was successfully introduced for light bulb filaments in 1894 and continued to be used until tantalum and tungsten filaments appeared after 1908. Hilaire de Chardonnet (France) spun them into the first artificial silk (1878–84). The cuprammonium process for polymerizing cellulosic fibers was discovered by M.E. Schweitzer in 1857, tried out in the search for filaments for light bulbs by Edward Weston in 1882, and applied to artificial silk by the French chemist Louis Henri Despeissis in 1890. It was briefly commercialized in Germany (1898) but was soon displaced by the viscose process developed in the UK by C.F. Cross and E.J. Bevan (1893). The latter was commercialized after 1905 by Courtaulds. A third process, the acetate process, was also anticipated by Cross and Bevan but developed and commercialized by Henri and Camille Dreyfus (1902–1912). A method of making the yarn was developed in the US by Arthur D. Little and others (1902). The cuprammonium process was revived after 1919 when the process of stretch spinning (invented by Edmund Thiele) was perfected by Elsaesser. Cellulosic fibers made by all of the processes, under the composite term rayon, carved out a modest market niche over the ensuing decades for clothing (e.g., lingerie) and for insulation, carpets, upholstery, furnishings, blankets, and tire cords.

The next and somewhat bigger step was the development of true (noncellulosic) synthetics, beginning with polyamides (Nylon) and polyesters (Dacron). These were natural targets for industrial research once the basic principles of polymer chemistry had been unraveled in the 1920s by Hermann Staudinger, Karl Freudenberg, and others at I.G. Farben, building on a growing fund of knowledge of coal-tar chemistry, acetylene chemistry, and basic research on protein synthesis conducted by Emil Fischer. The most famous (and profitable) synthetic fiber was Dupont's Nylon discovered by Wallace Carothers in 1930. The method of drawing the molten polymer into a fiber was found by Julius Will, working under Carothers. Production began in 1938 and was immediately diverted to parachutes for the duration of the war. Perlon, a similar fiber, was developed independently by P. Schlack of I.G. Farben. After the war both Nylon and Perlon were spectacular successes and were used to make many of the same products that had originally used rayon (especially hosiery). There were also some new applications, such as "stretch" Nylon developed by Louis Billion in 1950. Nylon was almost immediately challenged by polyacrylics (e.g., Orlon 1950) and polyesters (e.g., Dacron). The latter was discovered by J.R. Whinfield and J.T. Dixon in the UK in 1941 and commercialized in 1953 by ICI and Dupont. By 1980 there were 23 generic types of synthetic fibers, and both natural silk and rayon had largely disappeared. To date, synthetics have failed to displace either cotton or wool in absolute terms, though they have captured virtually all growth in the textile sector for the last three decades or more and now dominate the market as a whole (*Figure 15*).

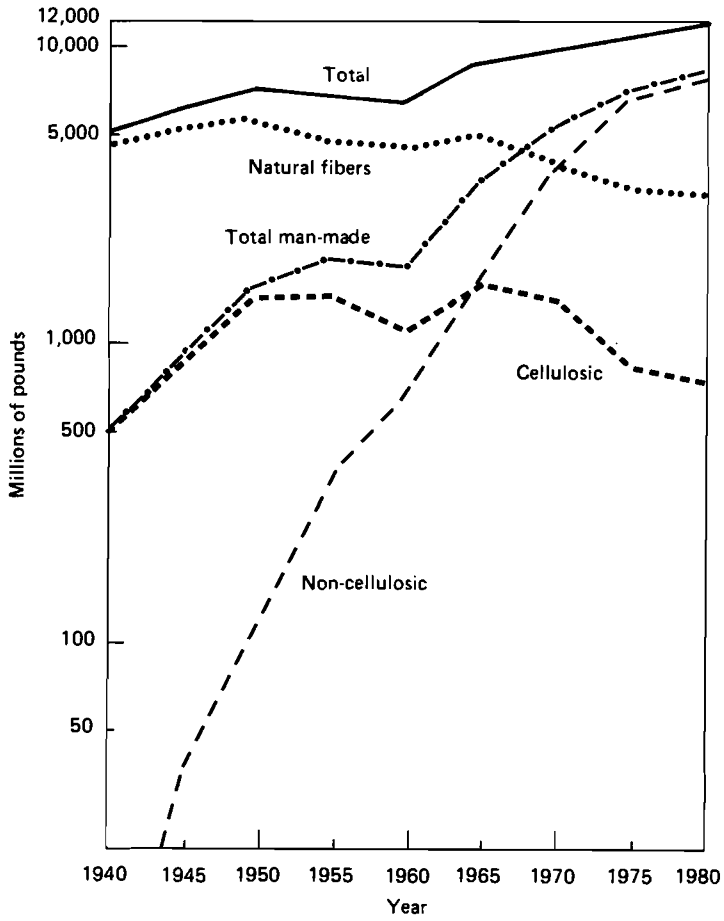

Figure 15. Consumption of natural and man-made fibers. (Source: *Textile Organon* **52**, March 1981.)

Actually, the first commercially important bulk plastic was Bakelite (the first phenolic made from phenol and formaldehyde), patented in 1909 by Leo

Baekeland and commercialized soon after. It is widely used in consumer products, such as telephones. Basic research in polymer chemistry was later applied successfully to other bulk polymers such as polystyrene, polyvinyl chloride (PVC), and polyethylene. Both vinyl chloride and styrene were first resinified in the laboratory before 1840, but practical applications awaited greater understanding of polymer chemistry and better manufacturing techniques. PVC and polystyrene were commercialized by I.G. Farben in 1930 and 1931, respectively.

Methyl methacrylate was first polymerized in 1877 by the German chemists Fittig and Paul. The acrylics were first developed for use in automobile safety glass by Otto Röhm in 1912. Commercialization of acrylic esters for adhesives and paints began in 1927 by the firm of Röhm and Haas. Polymerization of methacrylic ethyl ester and methacrylic nitrile was demonstrated by William Chalmers in 1929–1930, and glasslike acrylic polymers were developed for the market by Rowland Hill and J.W.C. Crawford of ICI in the early 1930s. Röhm and Haas introduced Plexiglass in 1935. Dupont and ICI followed a year or two later with their own versions. The success of clear glasslike polymers stimulated a research group at Corning Glass Co. to explore silicone-based alternatives. Silicones did not succeed in this application, but by the mid-1930s silicones found many other uses, especially as specialized electrical insulating materials. Dow-Corning Co. was created to specialize in these materials.

By contrast, polyethylene (the first of a larger class called polyolefins) was first synthesized at ICI (UK) in 1936 by R.O. Gibson and M.W. Perrin, and manufactured commercially soon afterward. It found an important early use as a high-quality electrical insulation material. It subsequently has found a host of other applications such as the thin transparent films used for packaging. Polyurethanes (based on the polymerization of isocyanates, another product of German research) reached the marketplace in 1954 for applications such as foamed insulation, foam rubber, and upholstery materials.

DDT was first synthesized in 1874 by Othmar Zeidler, but discovery of its insecticidal properties in 1940 by Paul Mueller, a chemist at Ciba-Geigy, deserves mention. It played a major role during World War II itself and afterward, in controlling malaria and other insect-borne diseases. Its great success stimulated a considerable amount of research during the 1940s and early 1950s by chemical companies to find other useful insecticides, fungicides, herbicides, rodenticides, and so on. Among the most important was the family of insecticides, including chlordane (1944), aldrin, and dieldrin (both 1947), all discovered by the chemist Julius Hyman and his associates. Other useful insecticides introduced about that time included hexachlorobenzene (HCB), toxaphene, heptachlor, and the herbicide 2-4-D. Since the early 1960s, however, increasing concerns about the environmental impact of these chemicals have triggered a shift toward biodegradable pesticides.

Still another outgrowth of the coal-tar-based synthetic dye industry in Germany was the sulfonamide family of drugs, better known as sulfa drugs. They are all based on the chemical p-aminobenzenesulfonamide, which was synthesized in 1908 by P. Gelmo. Its first use was as the basis for a family of dyes (azo dyes), commercialized in Germany before World War I. The antibacterial properties of these chemicals were discovered later by accident. The first sulfa drug patented by Fritz Mietsch and Josef Klarer of I.G. Farben was Prontosil (1932). Research and testing accelerated after 1936, by which time French, UK, and American research teams were also at work.

By 1943 a large number of drugs in this family had been synthesized, including sulfanilamide, sulfathiazole, sulfasuxadine, sulfaguanidine, sulfadiazine, sulfamerazine, and sulfapyradine. They were found to be highly effective against many bacterial infections, ranging from puerperal ("childbed") fever to meningitis, gonorrhea, pneumococcic pneumonia, wound infections, and burns. As a result, the death rate from many bacterial diseases and infections dropped sharply, and some (such as gangrene) have virtually disappeared. Sulfa drugs cut the mortality rate of wartime casualties dramatically in World War II.

The sulfas were soon overshadowed by another class of therapeutic agents, the antibiotics. The starting point was the discovery of the bactericidal effects of a natural mold discovered by Alexander Fleming in the UK in 1928. Research proceeded slowly in the 1930s as methods of growing the mold and separating the active ingredient had to be developed, mainly by Raistrick. This work was completed at Oxford by a team headed by Howard Walter Florey. Semisynthetic penicillins were finally isolated and commercialized by the Beecham Group (UK) in 1957. The second major antibiotic was streptomycin, discovered in 1943 after an intensive search of soil organisms by Selman Waksman. Pilot production began at Merck in 1944 using the submerged-vat fermentation process. Wartime needs certainly accelerated its commercialization and motivated the search for other "miracle drugs." There was a spectacular increase in the number of antibiotics discovered and brought to market in the first few years after the war, including teramycin, aureomycin, tetracyclines, and chloramphenicol. In later years chemists modified the natural molecules themselves to create new antibiotics such as ampicillin and cephalexin.

The advances in antisepsis and chemotherapy, especially for bacterial infections, have been cumulatively very important. Many of the killer diseases in the past have now been vanquished. The hazards of infection resulting from surgery have been correspondingly reduced. This, in turn, has increased the practicality of far more aggressive surgical procedures such as multiple heart bypass operations and organ transplants. These advances have significantly cut infant mortality and increased human life expectancy by more than 30 years. This has indirectly contributed to the growth of a large health-care industry focused on the treatment of heart disease, cancer, and geriatric degenerative diseases associated with advanced age.

However, notwithstanding the economic importance of the various branches of the chemical industry cited above (and others not discussed, such as refrigerants and color photography), it is difficult to identify a single turning point or a critical breakthrough of the kind that seems to have occurred several times in the eighteenth and nineteenth centuries. Progress seems to have been fairly smooth and continuous over a broad front and over many decades. The fact that the chemical industry has been, from its beginnings, largely "research driven" may be responsible for this.

5.2. Radio, television, and microwaves [5]

The second area of dramatic progress during the fourth transformation is that of electronics. This is also a direct outgrowth of developments in the nineteenth century, beginning with Michael Faraday's discoveries, continuing with James Clerk Maxwell's theory of electromagnetism with its momentous prediction of traveling electromagnetic waves (1860), followed by Heinrich Hertz's experimental demonstrations of the effect (1887). Oliver Lodge in the UK in 1894 developed a relatively practical detector for radio waves (a vial filled with metal filings, which he called a "coherer") but did not patent the idea.

It was Guglielmo Marconi in Italy and the UK who conceived of a system of wireless telegraphy and carried it to realization. In 1896 in Italy, he used Lodge's device to transmit Morse code over a distance of two miles. He then moved to the UK and formed a company (with Lodge and Fleming as consultants) to develop a commercially successful radio-telegraphy system. In 1901 he began to provide ship-to-shore telegraph services for the British Admiralty and for Lloyds of London. Marconi's breakthrough was followed by a burst of inventions and innovations.

The first to transmit speech by radio was Reginold A. Fessenden in 1900. Fessenden developed an electrolytic detector, consisting of a fine platinum wire resting on the surface of an acid bath. This became the standard of sensitivity for a decade. He then patented the heterodyne system of transmission and detection in 1905, although it was not feasible until a decade later, when vacuum tubes were available. He also commissioned the development of a high-frequency alternator, to produce the carrier signal with the help of Ernst Alexanderson of GE. Fessenden continued to develop voice transmission technology, achieving the 100-mile range in 1907.

The first vacuum-tube diode (switching device) was patented in 1904 by John Ambrose Fleming in the UK. It was a straightforward adaptation of the "Edison Effect," discovered in the 1870s in connection with the development of the incandescent light. The crucial invention – one of the most important of all time – was an improved version with an extra element, called the triode, or "audion." It was invented by Lee De Forest and patented in 1906, though Fleming always claimed it to be a trivial variation (by adding a "bent wire") of his diode. Even in its crude form, the audion was far superior to any other form of radio detector. De Forest actually neglected his own invention for several years, due to other distractions, but he took it up and developed it further starting about 1911. He subsequently sold the rights to AT&T and Western Electric in 1913–1914 for use in radiotelephones and repeaters for longlines. The original triode spawned thousands of specialized vacuum tubes over the next two decades and made radio, television, radar, and all other electronic devices feasible.

In 1911 Edwin Armstrong in the US and von Lieben in Germany (Telefunken) both realized that the triode could be used for amplification. The next step was the feedback or regenerative circuit (1912), which greatly improved both the selectivity and sensitivity of detection circuits. Claimants to this invention include Armstrong, De Forest, Irving Langmuir (GE), Meissner (Telefunken), and C.S. Franklin and H.J. Round (Marconi Company). Armstrong and De Forest litigated for more than 20 years regarding US patent rights on regenerative curcuits; the case was finally resolved in favor of De Forest. In 1913 the triode was first used in a high-frequency oscillator, the first nonmechanical means of producing high-frequency radio waves. Again, rival claimants included Armstrong, Meissner, and Franklin and Round. Meanwhile, electron tubes (valves) were greatly improved by Langmuir's introduction of "hard" vacuum in 1914–1915, which gave GE an important patent position in the radio industry. The vacuum-tube oscillator quickly replaced the Fessenden-Alexandersson electromechanical system for transmission.

In 1918 Armstrong invented and patented the "superheterodyne" circuit (an improvement of Fessenden's scheme for transmitting radio signals as differences), which he sold to Westinghouse. Westinghouse operated the first commercial radio station, KDKA, in Pittsburgh (1922) and soon began commercial manufacture of radio receivers. Superheterodyne radios were commercially available in 1924. In the meantime, Radio Corporation of America (RCA) was created by separating the US Marconi Company from its UK parent, and endowing it with GE's radio patents (in exchange for part ownership). RCA later acquired the radio patents owned by AT&T.

The diffusion process was rapid thereafter. Sales of radio sets in the US skyrocketed from $60 million in 1922 to $900 million in 1929. In 1922 Armstrong invented and patented the ultra-sensitive super-regenerative receiver (mainly for shortwave use), which he sold to RCA. In 1933, Armstrong introduced essentially the present frequency modulation (FM) system, although the system was resisted by the major networks because of a potential conflict with TV for frequency bands. However, commercial FM broadcasting began in 1939.

Television is another of the three revolutionary innovations of the fourth technological transformation. It is an obvious extension of radio, though it is as much of a qualitative improvement over radio as the telephone is over the telegraph. Indeed, the first device suitable for a scanner (to divide a picture into individual "chunks" suitable for sequential transmission) was the so-called Nipkow disk (1884). All the basic principles of a mechanical scanning system suitable for picture transmission were set forth at that time, even though the radio itself had not yet been invented.

Obviously practical implementation of radio and TV was impossible without amplification, broadcasting, and receiving circuitry. Indeed, these technologies, like the automobile, resulted from a convergence of many predecessors. Thus it was not until the 1920s that experimental television became possible. Demonstration transmissions using Nipkow disks were made by John Logie Baird (UK) and Ernst Alexanderson and C.F. Jenkins (US) from 1929 until 1935. However, the first TV picture had only 30 lines. The mechanical Nipkow disks were a technological dead end. Electronic-scanning and image-reproduction tubes were a far better solution. The cathode-ray oscilloscope, invented by Ferdinand Braun (1897), and an improved photoelectric cell, invented by Julius Elster and Hans Geitel (1905), were crucial. The electronic TV system was first conceived in 1907 by Boris Rosing in St. Petersburg and by A.A. Campbell-Swinton in the UK about the same time. The first successful TV scanner was the iconoscope, a specialized cathode-ray tube, invented by Vladimir

Zworykin – a former student of Rosing – at Westinghouse (1919) and patented in 1923. It was later transferred to RCA (1930). The iconoscope was challenged later by a competing approach, the "dissector tube" invented by Philo Farnsworth (1927), and further developed by Philco.

The first TV transmission based on electronic technology was carried out by the British Broadcasting Corporation (BBC) in 1936. It used a system developed by EMI Ltd. based on the Zworykin iconoscope. RCA commercialized TV in the US in 1936, and Telefunken did the same in Germany. Regular commercial broadcasts were being made from at least 10 cities in the US and Europe before 1940. Progress in commercial use was interrupted by World War II, but research continued and broadcasting was resumed after the war with much better equipment. By 1953 there were 328 stations in the US and 27 million receivers. Color TV broadcasting began in the US in 1954, and transistorized portable TV sets were first produced in 1955. TV is now found in virtually every household in the US.

Radar is an extension of radio technology in another (higher) frequency domain. The purpose, of course, is not to transmit a message to a receiver but rather to bounce a simple signal off a distant object repeatedly and detect the reflected pulse-echo with enough accuracy to compute its distance, size, shape, and speed. It was used for scientific purposes as early as 1924, and the pulse principle was demonstrated in 1925 by Gregory Breit and Merle Tuve. An obstacle detector using pulsed radar was installed on the French liner *Normandie* in 1935. It was later developed for military purposes, to detect incoming bombers at a distance, by secret research projects carried out independently during the 1930s by the US Navy, the German Navy, and the Royal Air Force. The UK program, led by Robert Watson-Watt, was the most advanced, and the first five UK military radar installations were in place in March 1938. The first successful US test was in 1939, and commercial manufacturing began shortly thereafter. Radar is the basis of all aircraft navigation and traffic control today.

The key UK invention that made radar practical was the multi-cavity magnetron (H.A.H. Boot and J.T. Randall). By 1940 this device was capable of generating 10 kw. of pulse power at a wavelength of a few centimeters. An alternative power source, the klystron, was invented in the US by R.H. and S.A. Varian (Varian Associates). Both the magnetron and the klystron were developed from De Forest's triode beginning in the 1920s. More compact microwave power generators are also in microwave ovens used today in millions of restaurants and households. The microwave oven is a revolution, of sorts, inasmuch as it reduces energy consumption and cuts cooking time by a large factor.

5.3. Solid-state electronics and computers [6]

The two most significant inventions of the second world war and the immediate postwar era were the electronic digital computer, developed at the University of Pennsylvania by J. Presper Eckert and John Mauchly in 1944, and the transistor, developed at Bell Labs. by William Shockley, John Bardeen, and Walter Brattain in 1948. The transistor was the outcome of an R&D project seeking a substitute for the vacuum tube, which would be more reliable, would be cheaper to manufacture, and would use less electric power. Low-power consumption was a primary motivation for the search, since large telephone-switching systems consumed a great deal of power. Within a decade transistors (mainly based on the semiconductor germanium) had replaced tubes in many applications.

By the late 1950s, in fact, a serious manufacturing problem had emerged. Electronic circuits (especially computers) were getting so complex that wiring and interconnections were becoming costly and unreliable. This problem motivated the development of the monolithic integrated circuit (elements of which were independently invented by Jack Kilby of Texas Instruments and Robert Noyce of Fairchild in 1958). This, in turn, launched the line of silicon-based semiconductor development that led to large-scale integration (LSI) in the late 1960s, very large-scale integration (VLSI) in the late 1970s, and finally ultra-large-scale integration (ULSI) in the 1980s. These, of course, are the acronyms for successive generations of silicon chips, the basic building blocks of virtually all modern electronic devices, from radios and radar to telephone-switching systems, computers, and most other electronic products. By the 1970s, in fact, telephone-switching systems were essentially specialized digital computers, and computers were increasingly linked by telephone lines. In fact, the computer industry and the telephone industry had become so inextricably intertwined that a major restructuring of the regulated telephone industry became inevitable.

The history of the computer cannot be told without giving due credit to the punched paper-tape control system used in the famous Jacquard loom (1804) [7] and the mechanical inventions of Charles Babbage during the 1820s and 1830s, not to mention earlier efforts of Blaise Pascal, Gottfried Wilhelm Leibnitz, and others. A large gear-operated "difference engine," with 15,000 moving parts (based on some of Babbage's ideas), was built by George B. Grant in 1872. It was displayed at the Philadelphia Centennial (1876), and a copy of it was used for actuarial calculations for 20 years.

The first mechanical calculating machine was patented by Frank Baldwin in 1873. Baldwin went into business with J.R. Monroe, and after 1911 the machine became known as the Monroe calculator. A keyboard-operated desktop calculator ("Comptometer") was developed by Dorr Felt in 1887, and it became commercially successful almost immediately. William Burroughs invented an adding machine that would automatically print results on a paper tape (1888). It, too, was the foundation of a major company. All of these machines found a useful niche in offices. The cash register, which embodied a mechanical calculator, was also the basis of a very successful company. Both Burroughs and NCR later became important computer manufacturers.

The punched-card sorting, tabulating, and calculating machines invented by Herman Hollerith during the 1880s constituted a powerful new application of the Jacquard-loom punched-card control technology. It was successfully put to use for tabulating the results of the 1890 and 1900 US censuses. The Census Bureau's discomfort with total dependence on a single supplier combined with the expiration of Hollerith's basic patents created opportunity for other firms (e.g., Powers, later Remington-Rand) though hardly a major new industry. In

1912 Hollerith's Tabulating Machine Co. became the core of a merger that created Computing-Tabulating-Recording Co. (later changed to IBM). These two firms later dominated the computer business, at least in its first decade. But the critical computer inventions came from outside.

There were two strands of computer development. One, began with the "differential analyzer," a mechanical analog computer consisting of gears, wheels, belts, and shafts linked by torque amplifiers built by Vannevar Bush and H.L. Hazen in 1930. It was designed to solve simple differential equations, especially in the analysis of electrical circuits. A second-generation differential analyzer followed in 1935, with electrical devices substituting for some of the mechanical components. When complete it contained 150 motors, 2,000 vacuum tubes, thousands of relays, and 200 miles of wire. It weighed 100 tons (Shurkin, 1984, p. 79). However, this too was a technological dead end.

The second strand of development was the digital computer, based on the mathematical ideas of George Boole in the 1850s (Boolean algebra and logic) and Alan Turing in the 1930s. It was Turing who designed a conceptual idealized computer (the "Turing machine") using Boolean logic. With it he introduced fundamental notions such as computability (1937). Turing was, in effect, the first modern computer scientist. At Bell Labs., George Stibitz designed the first-known electromechanical relay computer, the Model I. It was completed in 1939, and Models II–V were completed in subsequent years (1940–1946). John Atanasoff (Iowa State University) worked on his ABC electronic computer from 1938 to 1942. Atanasoff completed a small prototype device in 1939 using electronic circuitry only. But no follow-up machine was ever completed by him (due to lack of funding), nor did he obtain any patents. However, a later court case between Remington-Rand and Honeywell involving Eckert and Mauchly's claims gave Atanasoff legel credit for the invention of the general purpose electronic computer. Recent scholarship suggests that this was a miscarriage of justice (Shurkin, 1984). However, Atanasoff certainly made a major contribution.

Starting in 1939, with help from IBM, Howard Aiken of Harvard built the IBM Automatic Sequence Control Calculator (Mark I), which was completed in 1944. It contained 750,000 parts and was able to compress six months of calculations into one day using a desktop machine. It was said to be the world's first automatic computer.[8] By the time of its completion it was, however, already obsolete. The progenitor of most future general purpose computers was the Electronic Numerical Integrator And Computer (ENIAC), designed by a team led by Eckert and Mauchly at the University of Pennsylvania, under a contract from the US Army. The contract was signed in 1943, and the computer was operating in 1945 (doing calculations for the A-bomb project, among other things). It was publicly unveiled in 1946. ENIAC contained 17,248 vacuum tubes, 1,500 relays, 70,000 resistors, 10,000 capacitors, and 6,000 switches. It could perform a multiplication in 2.8 milliseconds, divide in 24 milliseconds, and calculate a trajectory in 30 seconds. It consumed 174 kw. It lacked a stored program, but the decision to leave it out was made in the interests of shortening the development period. A contract to build a second computer containing that feature (EDVAC) was already signed by late 1944 (Shurkin, 1984).

After the war (1947–1949), the UK government sponsored the development of a general purpose computer, called Electronic Delay Storage Automatic Calculator (EDSAC). The UK government did support early computer development projects during the war, primarily in connection with deciphering German codes. By some accounts the first true electronic computer was COLOSSUS, built by the UK team of Turing, A.H. Flowers, and M.H.A. Newman (1943). It had 1,800 vacuum tubes and used a high-speed (5,000 character per second) punched paper-tape data input. However, it was designed only for code breaking and could not be used for any other purpose. A larger version was built the following year. However, the UK gradually fell behind in later years. The first commercial electronic computer, UNIVAC I (1952), was the direct descendent of ENIAC and EDVAC.

The transistor, introduced in 1948, required only a few more years to reach the stage where it could be produced in quantity. It finally displaced the vacuum tube in computer logic circuitry in the mid-1950s. One of the first transistorized computers was the Philco 2000 (1954). The solid-state magnetic core memory was first introduced in the MIT "Whirlwind" (1951). It was adopted for commercial computers in the late 1950s. The Control Data 6600 (ca. 1965) was the first computer designed to utilize integrated circuitry. (IBM's 360, introduced about the same time, used hybrid circuitry.) The memory chip with 1,024 bytes of storage capacity was introduced by Intel Corp. in 1969, followed by the first silicon microprocessor the following year. Those were the innovations that made the personal computer possible and began the fifth technological transformation, which is now under way.

The computer found many unexpected success in the market even in its earliest years. It has made IBM one of the world's largest and richest corporations in only 20 years. Yet there are still surprising doubts as to exactly what service the computer has performed up to now – apart from its obvious use for scientific computation and for such bookkeeping and accounting functions as keeping track of airline reservations, customer accounts, payrolls, and taxes. The gross revenues of the computer industry and the semiconductor industry are already approaching those of the auto industry, and will certainly surpass them soon. Yet the long-expected convergence of computer technology with telecommunications technology – computers linked into enormous open (public) networks and moving massive amounts of information back and forth with minimum human intervention – has not yet occurred on a significant scale.

5.4. Aircraft and air transportation [9]

As mentioned earlier, the aircraft industry, like the auto, is in some sense an outgrowth of the development of the bicycle and the internal-combustion engine. The growth of the auto industry depended very much on the availability of cheap steel and steel-manufacturing technologies. Likewise, the aircraft industry only became a commercial success with the development of the all-metal (aluminum) plane. Thus, the long period between 1903, when the Wright brothers first demonstrated powered flight, and 1926, the advent of the first commercial airliner (Ford Trimotor), was technologically driven. Rich dilettantes provided a small amount of venture capital and some prize money, but young adventurers provided the energy and "sweat-equity." Military services financed much of the early development, especially just before and during the first world war.

The Wrights were hardly the first to fly, even in a heavier-than-air machine. (Flight in balloons already had a long history, which need not be recapitulated here.) Otto Lilienthal made 2,000 flights in his hang glider between 1891 and 1896 before being killed in a crash. Hiram Maxim (better known as the inventor of a machine gun) built a steam-powered aircraft that rose a few inches off the ground (1894). Samuel Langley's pilotless steam-powered *Aerodrome* flew 4,200 feet over the Potomac River in 1896. With a $50,000 grant from the US Congress, Langley continued to work toward powered flight, and he was perhaps unlucky not to have made the decisive breakthrough in 1903. Having realized that steam power did not offer sufficient promise, he shifted his attention to internal-combustion engines. Langley's pilot, Charles Manly, designed and built a rotary engine that generated 52 hp with a weight of only 151 lb. But, because it was designed with insufficient attention to controllability in flight, *Aerodrome* failed to take off in two attempts. The Wright brother's biplane, by contrast, had a much less powerful engine but a better and more controllable aerodynamic design. Their experience as bicycle racers and builders may have been decisive (Crouch, 1987). Their critical contribution was the recognition that the pilot must exercise active control over motions in all three independent degrees of freedom, *viz.*, pitch, roll, and yaw.

In fact, the science of aeronautics lagged behind the practice. Pilots were actually flying for several years before theory could explain the phenomena of stall and spin, for example (Wegener, 1986). Even when the basic theory caught up (ca. 1910), the critical problems of flight control could only be solved by trial and error. Many pilot errors resulted in fatal crashes. Not until the mid-1920s did a combination of accumulated experience, improved theoretical understanding, and better instruments permit pilots to undertake long flights through less than ideal weather conditions with reasonable confidence of survival. When Charles Lindbergh flew alone from Newfoundland to Paris in 1927 his achievement gave him instantaneous world fame. It also created a climate of acceptance for air transportation.

Development of aircraft between 1908 and 1918 was financed largely by the military. Although technological progress was considerable, especially during World War I, aircraft played only a peripheral role in the war. Primitive aircraft undertook duels (dogfights) with each other, but planes could not carry enough payload of bombs or ammunition, nor could they fly fast enough or far enough to have a significant impact on ground operations until the end of the war. By that time, however, the potential impact of air power on future wars was clear, at least to a few pioneers, such as Giulio Douhet and Billy Mitchell.

Actually, the first scheduled passenger service in the US was the St. Petersburg-Tampa Air Boat (1914). Dozens of other airlines opened, merged, and closed through the twenties. A London-Paris service was inaugurated in 1919. Airmail began in the US in the 1920s, partly as an indirect subsidy to the fledgling industry, but passenger service was unreliable and irregular. The situation began to stabilize when the Ford 5-AT Trimotor, the first all-metal plane (*Tin Goose*), was introduced (ca. 1926). It was followed in short order by the Boeing 247 (1933) - prototype of modern airliners - and the Douglas DC-3 (1935). The Douglas DC-3 was the most successful single aircraft design of all time. More than 10,000 DC-3s were eventually built, and some of them are still flying in the 1980s. Scheduled trans-Pacific service was initiated in 1935.

Aircraft size, power, and speed increased continuously as demand for passenger and freight service began to grow. Meanwhile, the capabilities of the piston engine began to approach natural limits in the 1930s. (The Rolls Royce Merlin engine, which powered the ***Spitfire, Hurricane,*** and ***Mustang*** of World War II, has never been improved upon in terms of power output per unit weight.) To achieve better performance a new type of engine was needed. That was the gas turbine, which took two forms: the turboprop and the turbojet. The former was a transitional engine; the latter is the primary source of power for all high-performance aircraft today.

The turbojet was first proposed (and patented) by Frank Whittle of the Royal Air Force (1928). The first working model was tested in 1937. A competitive German version built by Pabst von Ohain flew a few months later. The first military jet aircraft was the Heinkel He 178 (1939). The first UK jet fighter was the Gloster E28/29 (1941). The first jet used by a civil airline (1952) was the de Havilland *Comet*, which raised cruising speeds from about 300 mph for the DC-6 to about 470 mph. Unfortunately several of these planes crashed due to metal-fatigue failures attributed to poorly designed windows. The first really successful all-jet airliner was the Boeing 707 (1954). It raised cruising speeds to about 550 mph and became the workhorse of the world's airlines. It was also the progenitor of a series that still dominates the world's civil airways, including the 727, 737, 747, and 767. Interestingly, the first and only supersonic civilian airliner (the British-French *Concorde*) has been an economic failure, with no successor yet in sight. Meanwhile, the airline industry has grown into a giant, but the rate of technological change has slowed down significantly. Problems plaguing the industry today have more to do with moving people and baggage on the ground than in the air.

5.5. Conclusion

The fourth technological transformation has spawned other technologies, including nuclear power and rocketry. Nuclear weapons transformed warfare, and may have transformed global politics. But the civilian spin-off, nuclear power, is mostly notable for its failed promise of ultra-cheap energy. It now looks like the long-term costs of decommissioning nuclear power plants and disposing of their radioactive wastes are likely to be far higher than the economic benefits ever were. At this point, the unmanned space program has led to minor benefits (mainly direct-broadcast satellites and surveillance satellites). The manned space program seems to be justified mainly by political calculations (or miscalculations) in comparison with the meager scientific returns and large development costs to date. The possibility of great benefits in the long run cannot be ruled out, but they have not yet materialized.

The vast majority of the innovations during the fourth transformation were new materials or new products offering higher performance or greater utility to consumers than products or services available previously. This is particularly true of the various new and improved electric appliances available to consumers, from refrigerators to TVs. It applies also to the "wonder drugs" and synthetic fibers, and to some extent to plastics (e.g., new packaging materials). Some appliances, notably washers, dryers, dishwashers, and vacuum cleaners could also be classed as labor saving, even though most household work – then and now – remains unpaid. The net effect was, nevertheless, to allow more women to take paid employment, thus increasing the labor force. The advent of civil air transportation during this period also could be classified as labor extending, inasmuch as it saved travel time for businessmen. The vast extension and improvement of the US highway network that began in the 1930s (and accelerated in the 1950s) was a response to the growing importance of private automobiles. It had the effect, however, of facilitating long-distance truck transportation. The early impact of this was to weaken the competitive position of the railroads and trigger a significant disinvestment in rail transportation (in the US, but not in Europe or Japan). However, the long-run effect was to improve the efficiency of the distribution system in the US, permitting significant reductions in inventory and consequent capital savings.

The introduction of plastics had no immediate effect on the design and construction of engineering products (e.g., automobiles) or buildings. Early uses were fairly specialized. One of the first substitutions of plastic for metal (except in packing) was the introduction of PVC in water-sewer pipes, which gradually began to replace cast-iron pipes. Plastics later began to replace die-cast zinc parts requiring little structural strength, and still later, stamped metal housings for small appliances and some auto parts. Plastics now account for around 10% of the weight of automobiles; their higher intrinsic material cost is increasingly compensated by reduced fabrication costs. During the current (fifth) transformation, the use of plastics in automobiles is likely to increase much further (resulting in sharply reduced use of steel and sharply reduced vehicle weight and fuel consumption). Thus, despite the high intrinsic energy-content of synthetic materials (and light metals as well), their long-term economic impact is quite likely to be resource extending.

Semiconductors have made possible dramatic increases in the performance of electronic devices. They have also allowed spectacular reductions in the size of electronic devices, from telephone switching systems to radios, TVs, and computers. One major impact has been the ability to economize on the materials and energy required to deliver information services. These services, in turn, have unquestionably extended or replaced human labor in a number of areas, including scientific computation, actuarial computation, bookkeeping, accounting, drafting, typesetting and composition, and word-processing. The fact that these developments have not yet resulted in increases in conventional productivity measures has puzzled economists. The leading hypotheses seem to be that the statistics themselves are faulty (i.e., we are measuring the wrong things), that the improved quality and other new services provided by computers swamps the (real) productivity effects, or that most users have not yet learned how to use computers competently, especially due to the information overload phenomenon. In this connection, it is increasingly plausible that the hierarchical structure of most major corporations interferes with effective information flow, and therefore with optimum use of computer and telecommunication technology. If so, smaller, less rigidly structured organizations will compete more and more effectively with large companies until the latter adapt. To date there is no compelling statistical evidence of either labor or capital savings attributable to the convergence of computer and telecommunication technology, but this may well be a key feature of the fifth technological transformation now under way.

6. The Fifth Technological Transformation 1975–?

The fourth transformation had neither a well-defined beginning nor a well-defined end. It does appear, however, that the rate of major innovations (as distinguished from revolutionary ones) began to slow down after 1950, while the economy as a whole forged ahead more rapidly. At any rate, there seem to have been fewer noteworthy innovations in the 1960s and early 1970s than there were in the 1930s and 1940s or since 1975. However, if there has been a recent speedup (or a prior slowdown), it will be difficult to confirm.

Clearly, a kind of "sea change" began around 1970, marked by a dramatic slowdown in the growth of the US automobile industry and the electric-power industry and an actual decline in domestic petroleum production and steel output. While growth has not necessarily ceased on a worldwide basis (i.e., production has, to some extent, simply moved to Japan or other countries in Asia), there is little doubt that consumption of a number of material-intensive and energy-intensive products has reached a point of saturation, not only in the United States but also in Europe.

The leading sectors of earlier decades have become lagging sectors. It is now widely recognized, and correctly so, that "high tech" is the leading sector of the 1980s. Within this decade, or early in the next one, the computer and telecommunications sectors are almost certain to overtake the auto industry and its satellites as the "locomotives" of the world economy. Already, computers and related automation equipment have become the dominant form of capital equipment, and software development and maintenance are becoming major sources of employment.

A revolutionary change in manufacturing appears to be well under way. The old approach to large-scale production, by maximum standardization of product and specialization of process, appears to be obsolescent. The problem is that the extremely specialized nature of mass production raises the costs of product change and therefore slows down innovation (Abernathy, 1978). The way out of this dilemma is to use programmable flexible automation – computers and robotics (Ayres and Miller, 1983; Ayres, 1984).

A revolutionary change in the design and use of computers is also in progress. The path of progress from 1945 to 1975 was to decrease the size and increase the power of centralized mainframes, and to service many users by means of time-sharing. The microprocessor and memory on a chip have changed

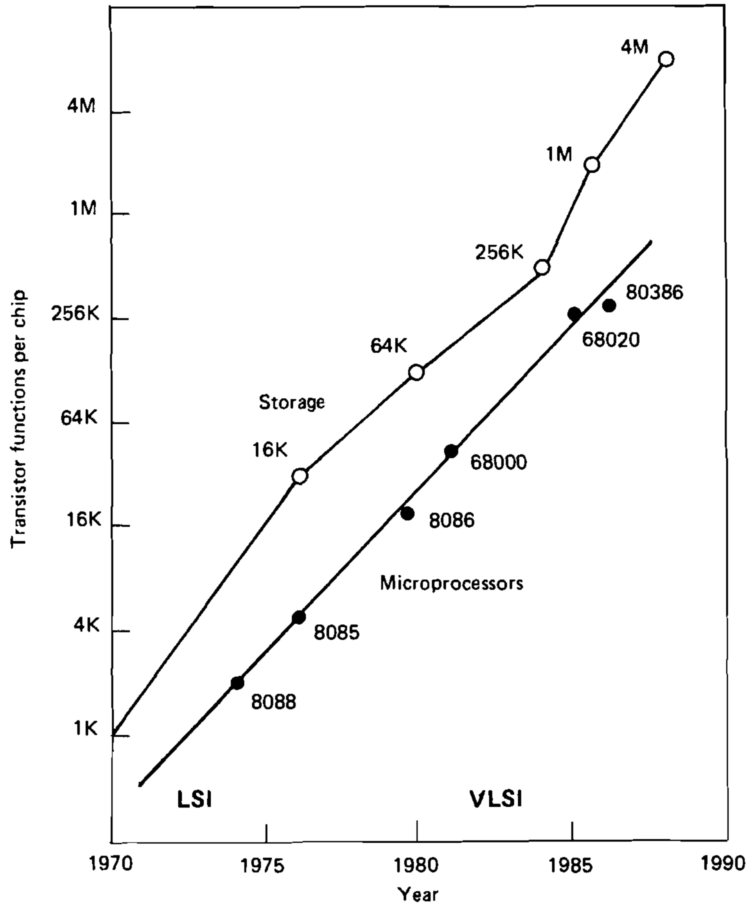

Figure 16. Development of memory and microprocessor chips. (Adapted from Bursky, *Electronic Design,* 1983.)

this. Mass produced personal computers and engineering work stations now offer more than ten times as much computing power per dollar as large mainframes. The latter are still needed, but only for systems involving huge databases and very complex software systems. The emergence of packaged software from firms like Microsoft and Lotus has further encouraged the shift away from time-sharing and toward networking.

The linking of public networks of personal computers (and other types of equipment, such as television sets) by means of optical fiber telephone lines or cable connections appears to be both technologically and economically feasible, and is, therefore, inevitable. As networks of this sort begin to expand (in the 1990s), a variety of new types of information and entertainment services will rapidly become available. These will be the most visible signs of the arrival of the long-awaited information age.

To be sure local area networks (LANs) are now in the news, and have recently become a recognized category of software. Currently, the term refers to

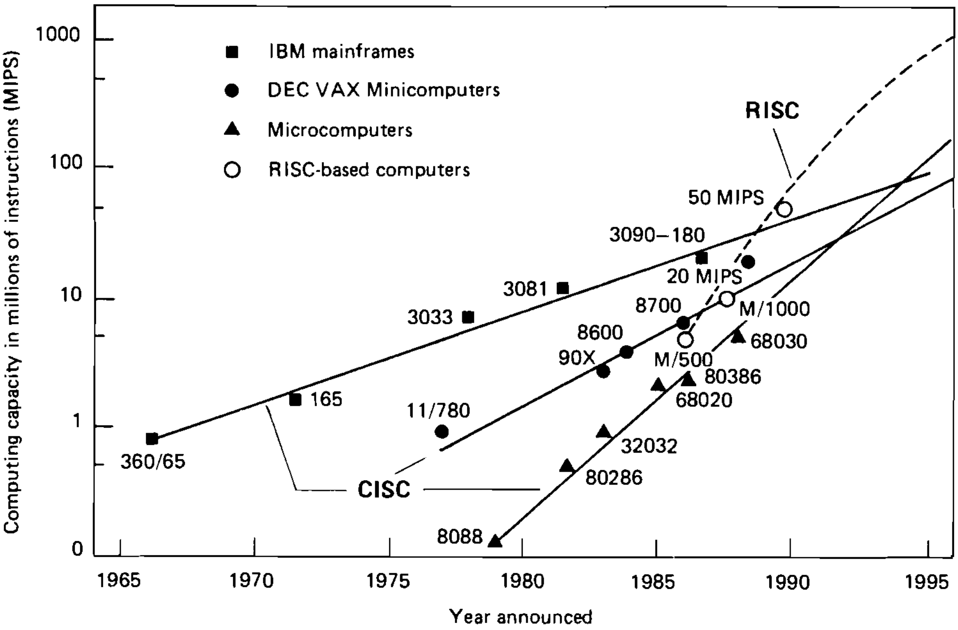

Figure 17. Efficiency of different computing architectures. (Adapted from *Electronic Design,* 7 January 1988.)

networks linking personal computers within companies or universities. There are two groups: the IBM compatibles (3 Com, Novell, Tandy, Gateway, 10-Net, IBM PC) and the non-IBM compatibles (Apple, Datapoint). As of 1988, it is estimated that 10% of the 19 million PCs are linked by LANs, but market studies suggest that more than 50% of the PC will be linked to LANs by 1992 (*NY Times,* 9 September 1988). However, the larger goal of allowing computers built by different manufacturers to communicate using software designed by others is still remote.

Two obstacles must clearly be overcome. First, there is an unsolved problem of data security. How can such networks protect proprietary data from computerized theft and computerized sabotage (e.g., "viruses")? The second major problem is the lack of uniform standards for software systems. Computers, like people, speak in different languages, and there exist no universal translators except in science fiction. Nobody knows just how to solve these problems. But, in any case, the major social and economic impacts of computers are still in the future. Enormous potential still remains for technological progress in the field. This is evident from the rapid progress demonstrated in several measures of performance over the past decades, which continues unabated (*Figures 16* and *17*). Computers have not yet had a major impact on manufacturing, for example, but the potential of computer-integrated manufacturing (CIM) is becoming clearer by the day. It will almost certainly turn out to be one of the leading sectors of the fifth technological transformation.

7. Conclusions

Two questions were raised at the outset, namely, Does the history of technology support the notion that clusters of innovations tend to occur during troughs in the Kondratieff long wave? and Do such clusters trigger the next round of fast economic growth? The power of technological innovation to stimulate growth cannot be doubted. However, while clusters do seem to occur, they appear to be technologically determined. Sometimes they follow major scientific or technological breakthroughs, not bearing any particular relation to overall economic conditions. In other cases (e.g., the auto, radio-TV, and aircraft) they result from the convergence or fusion of several independent lines of development.

In support of the thesis of technological determination, the major cluster of inventions that followed Marconi's venture into radiotelegraphy and especially De Forest's invention of the "audion" occurred during a period of extremely rapid economic growth but (otherwise) relatively slow innovation. This is also true of the development of the viscose and acetate processes for rayon, ammonia synthesis, Bakelite, and a number of other important innovations in the chemical industry. Again, the semiconductor and computer industries were highly innovative even as the general economy was rapidly expanding throughout the 1960s, despite a marked slowdown in most other areas of technology.

History also seems to support the notion that some major clusters of inventions and innovations tend to follow great breakthroughs, such as Bell's telephone or Edison's electric light and generating system, and that the timing of big breakthroughs is determined by technological conditions more often than by macroeconomic ones. It seems quite evident that clusters of technological innovations can (and do) stimulate economic growth. Nevertheless, it seems clearly evident – as Freeman (1983) has stressed – that periods of rapid growth are typically characterized by the *diffusion* of major technologies developed in earlier periods but not necessarily the immediately preceding trough. The fact that automobile-related technologies were the principal driver of growth after World War II should suffice to make this point.

The most difficult question to resolve is whether periods of slow growth are effective in stimulating technological innovation. This is where microeconomic conditions appear to be most relevant, but the evidence is thinnest. Some evidence supports such a link, especially if one contrasts the 1920s and 1930s. During the prosperous 1920s relatively few important new commercial products were introduced. After 1930, the rate of new product introductions increased dramatically. The depression was a major factor. General Electric and Westinghouse, for instance, experienced sharp cutbacks in their sales of power-generating equipment to utilities (also suffering from reduced demand). They responded by introducing a host of new or greatly improved consumer products to stimulate consumer demand for electricity and, of course, to keep their own factories and employees busy. Most of these consumer products could have been developed and introduced a decade earlier, at least from a technical perspective.

The rapid rate of introduction of new plastics, synthetic rubbers, and synthetic fibers by chemical companies beginning in 1930 was undoubtedly also due in part to cutbacks in demand for their commodity chemical products such as dyes for the textile industry. This is not to deny that some of the new products could not have been introduced earlier than they were because they had not yet been invented! But some of them could have been invented or commercialized sooner than they were, if the firms had been interested in producing them. There was a very rapid increase in the number of new plastics and synthetic fibers on the market through the 1960s, with an apparent slowdown in growth since then.

Of course, the upsurge in innovation after 1930 was also undoubtedly driven by other forces. Military needs prompted the rapid development of radar, sonar, the jet engine, the missile, and the atomic bomb. Military requirements, both during World War II and for two decades thereafter, provided both R&D support and initial markets for electronic computers. The needs of the aviation industry, civil and military, as well as resource scarcity (or its expectation), stimulated the innovation of continuous catalytic cracking.

On the other hand, the timing of the "miracle drug" innovations seem to have been unrelated to macroeconomic factors. The original discoveries of sulfa drugs and penicillin were serendipitous. Development proceeded relatively slowly until public interest was aroused by spectacular successes. Thereafter, the search for more such drugs was exceedingly well financed by profits. The slowdown in discovery in recent decades probably reflects the fact that the territory has now been fairly thoroughly searched. The recent breakthroughs in genetic engineering (ca. 1980) have already initiated a new burst of pharmaceutical innovations. The first wave of new products from this industry is already beginning to reach the market.

In summary, it appears that clustering of innovations is partly attributable to macroeconomic conditions and partly to wars. On the other hand, other causal factors are also operating. One such factor that has not been fully considered in this paper (for lack of space) is the possible relationship between long waves and the introduction of new energy sources and new energy conversion technologies, as suggested, e.g., by Volland (1987). Certainly, *Figure 18* and *Figure 19* suggest that the first technological transformation was, to a large extent, about new ways to create and use energy: the substitution of coal for charcoal in iron making and the addition of steam power to waterpower as a prime mover. The second transformation was, in effect, the practical application of steam power to transportation and its diffusion throughout the manufacturing sector.

In the case of the third transformation, the situation is more complex. A new primary source of energy appeared (petroleum), and this industry rapidly became one of the leading sectors. Moreover, the internal-combustion engine, a new type of prime mover arrived on the scene. Just as steam power plus iron provided the necessary conditions for the railroads, petroleum and the internal-combustion engine were two of the preconditions for automobiles. (Steel and sophisticated metal-working technology were the others.) Finally, electrification – perhaps the most far-reaching innovation of all – was fundamentally a new energy-conversion technology. In effect, steam power now reaches users in the form of electricity.

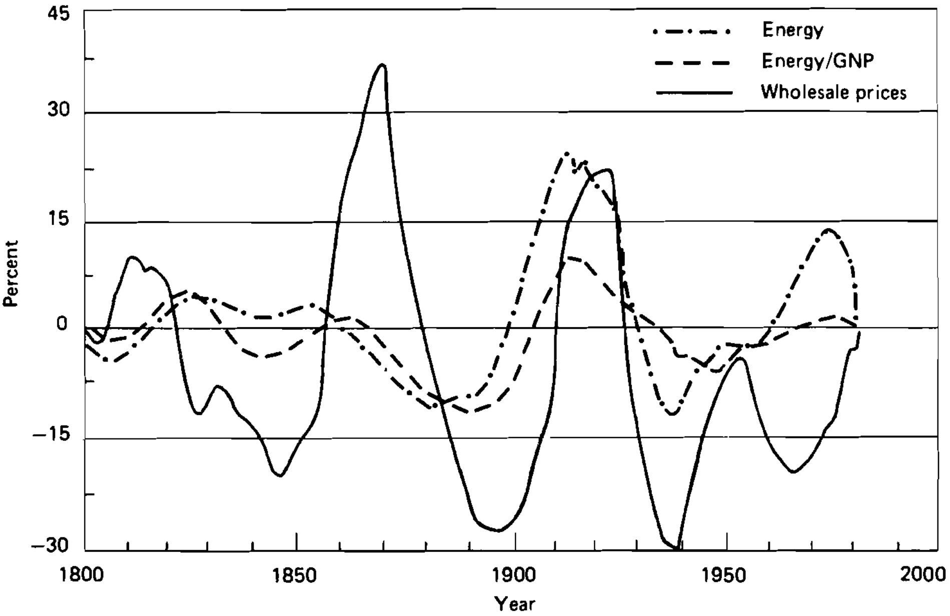

Figure 18. US energy, energy/GNP, and wholesale prices. (Source: N. Nakicenovic, IIASA, 1987.)

In contrast, the fourth transformation had much less to do with energy per se and much more to do with mass production and mass consumption. Energy consumption per unit of GNP has been declining for most of this period, *Figure 20* – despite sharp increases in direct energy consumption by final consumers. To be sure, this period has also witnessed substitution for hydrocarbon liquids and gases for coal, reflecting the substitution of liquid fueled ICEs for solid fueled steam engines in transportation and the substitution of gas and electricity for solid fuels in households.

These substitutions, in turn, required a long period of transition because of the enormous infrastructures involved. Hundreds of thousands of miles of oil and gas pipeline had to be laid and hundreds of thousands of miles of highways had to be paved to facilitate the substitutions. During the phase of rapid buildup, a great deal of capital is required. There is anecdotal evidence, at least, that such infrastructures tend to be overbuilt in response to high returns on the earlier investment. As a result the return on the later phases of the investment are too low (or even negative). This has a depressing effect on subsequent economic growth, at least until demand catches up. In some cases demand never does catch up, with the result that a great deal of capital is effectively devalued. This occurred in the UK canal system after 1840; as canals began to lose business to railways, canal stocks began a rapid decline. In addition, railway companies acquired sections of the canal system and made their use difficult and

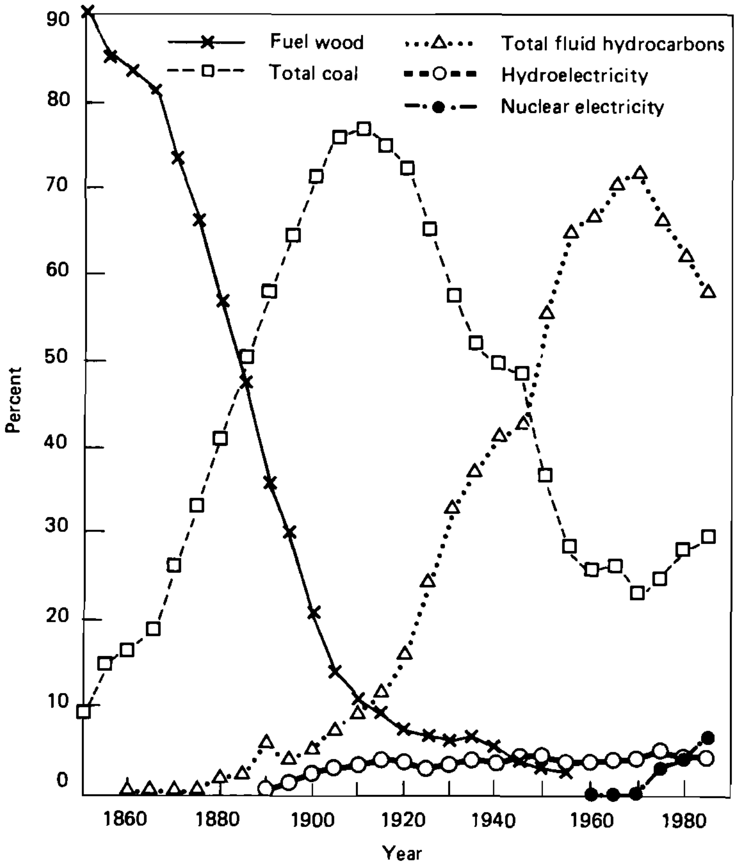

Figure 19. Sources of energy in the US. (Data taken from Schurr, Netschert *et al.*; USBOC.)

expensive (Taylor, 1942, p. 31). It is significant that this occurred before the major UK railway-building boom of 1845–1846.

A similar situation occurred in the US railway system, which reached a peak of 429,883 miles of track in operation in 1930 (USBOC, 1975). This total declined continuously thereafter; the 1970 figure was 360,330 miles. The decline is a direct result of competition from federally subsidized highways, which grew from 169,007 miles in 1923 (the first year of available statistics) to 895,208 miles in 1970. It is noteworthy that road building accelerated during the 1930s, doubtless to create jobs. However, some of the highway jobs "created" were certainly at the expense of railway jobs.

At this stage the contribution of the overbuilding mechanism to an integrated theory of the long wave cannot be fully evaluated. It is one of several mechanisms considered by the systems dynamics group at MIT (Forrester, 1976, 1979, 1981; Sterman, 1983, 1985). In fact, the only definite conclusion it is

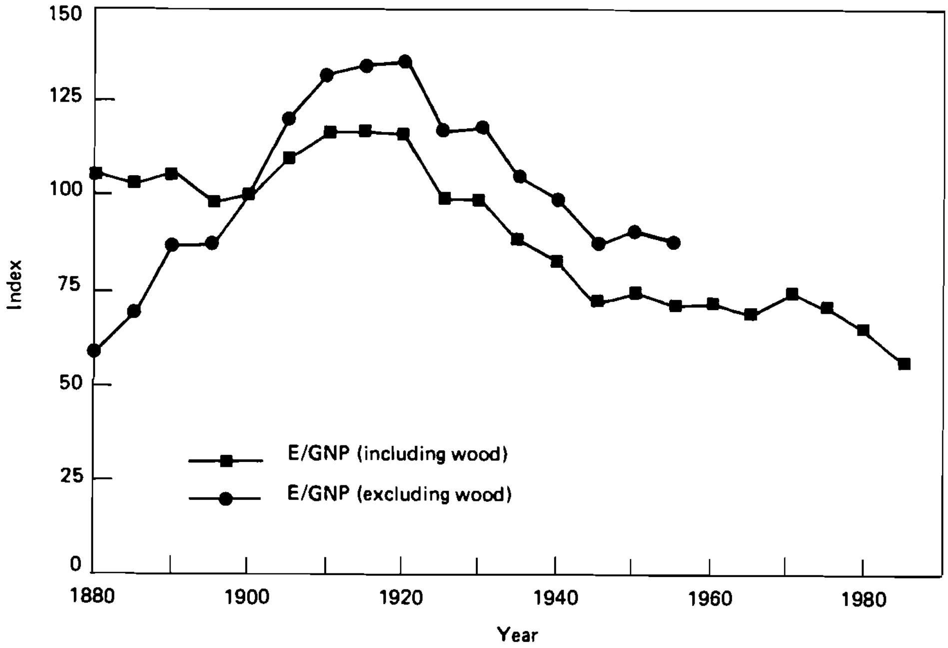

Figure 20. The US energy/GNP ratio. (Sources: Schurr and Netschert, 1960; EIA, 1986.)

possible to reach at present is that technological change is an important determinant of the long wave. Beyond that, much more empirical historical research on technological change is needed before it would be safe to venture a comprehensive theory of the long-wave phenomenon.

Notes

[1] I am indebted to Luc Soete for this comment (Soete, 1988). I am not aware of any detailed study of the historical data with respect to this issue.

[2] The idea of the moving assembly line can be traced back to the mechanized "disassembly" lines of the meat-packing industry in Cincinnati (1870s) and in principle to Oliver Evan's automatic flour mill of 1804 (Griedion, 1948, p. 86).

[3] That the market must be "sending a message" was, of course, Holy Writ to most bankers and financiers (and the academic economists who advised them). Some, such as Andrew Mellon, took the message to be that speculative excess must be "purged" by a harsh dose of financial discipline and "tight money." Some critics have charged that the Federal Reserve triggered the slump by reducing the money supply. For whatever reason, some 9,000 banks failed by 1933, with predictably adverse effects on all sectors of the economy. Others suggest that the evidence of federal actions points the other way, if anything (e.g., Temin, 1976). But other actions of the government may have contributed. For instance, the protectionist Smoot-Hawley Tariff (1930) added to a wave of retaliatory actions that sharply cut world trade.

[4] The major sources for Section 5.1 are Jewkes *et al.* (1961), Enos (1962), and *Encyclopedia Brittanica* [Rubber, Sulfa Drugs (1955)].

[5] The major sources for Section 5.2 include Jewkes *et al.* [case histories for radio, radar, and television (1961)], Finn (1967), Shiers (1969), and Lewis (1985).

[6] The major source for Section 5.3 was Shurkin (1984).

[7] Actually punched paper rolls were first developed by Basile Bouchon to control a draw-loom (used in the silk-weaving industry of Lyons) as early as 1725. Punched cards were introduced shortly thereafter by Falcon. An improved version of Bouchon's loom was built by Jacques de Vaucanson (1741) but then neglected for half a century (in Paris' Musée des Arts et Metiers) until Joseph Marie Jacquard was asked to rebuild it in 1800. He made minor improvements, primarily reverting to Falcon's punched card scheme, and successfully commercialized it (Burke, 1978).

[8] In Germany, starting in the late 1930s Konrad Zuse also developed several electromechanical computers with speeds comparable to Aiken's machine. The Z-4 was used to make aircraft design calculations in 1944. However, the German government withdrew support, and Zuse was unable to resume his work until after the war.

[9] Sources for Section 5.4 include *Encyclopedia Brittanica* (1955), Jewkes *et al.* (1961), and Wegener (1986).

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