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Time for a Change: On the Patterns of Diffusion of Innovation

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A MEDIEVAL PRELUDE

The subject of this essay is the temporal patterns of the diffusion of technological innovations and what these patterns may imply for the future of the human environment.[1] But first let us set the clock back nearly one thousand years: return for a moment to monastic life in eleventh-century Burgundy.

Movement for the reform of the Benedictine rule led St. Robert to found the abbey of Cîteaux (Cistercium) in 1098. Cîteaux would become the mother house of some 740 Cistercian monasteries. About 80 percent of these were founded in the first one hundred years of the Cistercian movement; nearly half of the foundings occurred in the years between 1125 and 1155 (see Figure 1). Many traced their roots to the Clairvaux abbey founded as an offshoot of Cîteaux in 1115 by the tireless St. Bernard, known as the Mellifluous Doctor. The nonlinear, S-shaped time path of the initial spread of Cistercian rule resembles the diffusion patterns we will observe for technologies. The patterns of temporal diffusion do not vary across centuries, cultures, and artifacts: slow growth at the beginning, followed by accelerating and then decelerating growth, culminating in saturation or a full niche. Sometimes a symmetrical decline follows or a new growth pulse.

Over time the Cistercians also diffused in space. Their pattern of settlements shows significant differences in spatial density. The innovation origin, Burgundy, was home to the four major mother houses and hosted the highest spatial concentration of settlements. From there, daughter houses were founded ("regional subinnovation centers," in the terminology of spatial diffusion), from which

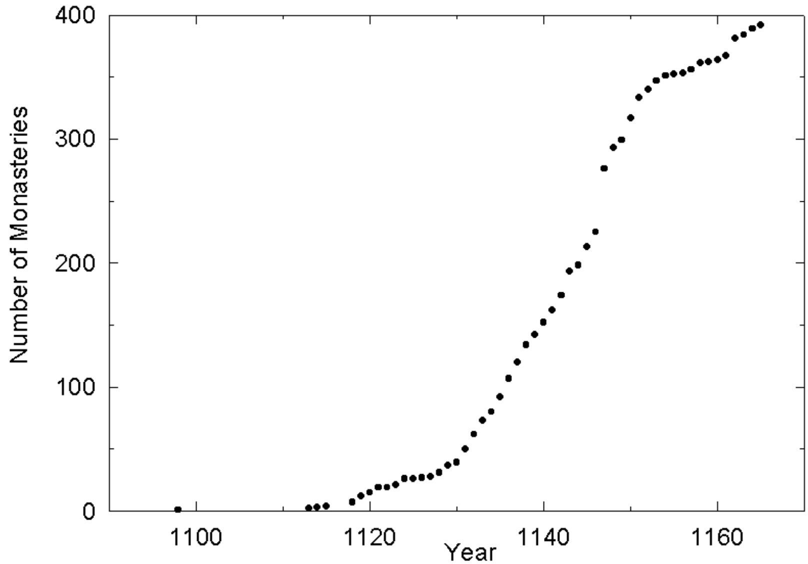

FIGURE 1 The initial diffusion of Cistercian monasteries in Europe. DATA SOURCE: Janauschek (1877).

Cistercians spread further into their respective hinterlands ("the neighborhood effect") and to other subregional centers, originating yet further settlements. The density of settlements decreased at the periphery, away from innovation centers, implying persistent regional diversity and disparities. The Cistercians also differentiated into "subfamilies," named after their respective parental houses. In fact, each subfamily followed its own pattern of settlements, regional specialization, and implementation of the Cistercian rule.

Some of the additions to the Cistercian rule were not genuine new settlements but "takeovers." For example, the existing Benedictine monastery of Savigny, with all its daughter houses, submitted to the rule of the Clairvaux Cistercians in 1147 and in turn became the mother house of all Cistercian settlements in the British Isles.

Despite distance and differentiation, all the monasteries communicated closely. The industrious Cistercians thus introduced and channeled influential innovations, including new agricultural practices and the water mill, throughout Europe in the thirteenth and fourteenth centuries. The British monks excelled in wool production. In fact, according to the Cistercian rule, settlements were to be located in remote, undeveloped areas. Thus, Cistercian monasteries became important local nodes for the colonization of land within Europe and, hence, for deforestation.

The Cistercian topology reveals a hierarchy of centers of creation and structured lines of spread. The patterns bear witness to the existence of *networks*. As we shall see, social and spatial networks, and their interactions, support and shape the diffusion process.[2]

INVENTION, INNOVATION, THEN DIFFUSION

In discussing the time for a change associated with a technology, it is necessary to consider invention and innovation as well as diffusion. Discourse now customarily distinguishes among these three concepts following the classic analyses made in the 1930s by the Austrian economist Joseph Schumpeter (1939). Invention is the first demonstration of the principal feasibility of a proposed new artifact or solution. Fermi's Chicago reactor demonstrated the feasibility of a controlled nuclear fission reaction (invention). In 1958, sixteen years after the inauguration of Fermi's pile, the Shippingport, Pennsylvania, reactor went into operation to generate commercial electric power (innovation). Some forty years later more than one hundred nuclear reactors now generate some 20 percent of the electricity in the United States (diffusion). Analogously, we might say St. Robert invented the Cistercian rule, St. Bernard innovated, and diffusion followed.

In fact, considering the Cistercian rule as a technology makes an important point. In the narrowest definition, technology is represented by the objects people make, axes and arrowheads and their updated equivalents. Anthropologists call them "artifacts"; engineers call them "hardware." But technology does not end here. Artifacts must be produced, that is, invented, designed, and manufactured. This process requires a larger system of hardware (machinery, a manufacturing plant), factor inputs (labor, energy, raw materials), and finally "software" (human knowledge and skills).

The third of these elements, which French scholars call *technique,* represents the disembodied aspect of technology, its knowledge base. Technique is required not only for the production of given artifacts but ultimately also for their *use,* both at the level of the individual and at the level of society. An individual must know, for example, how to drive a car; a society must know how to conduct an election. Organizational and institutional forms (including markets), social norms, and attitudes all shape how particular systems of production and use of artifacts emerge and function. They are the originating and selection mechanisms of particular artifacts (or combinations thereof) and set the rate at which they become incorporated into a given socioeconomic setting. This process of filtering, tailoring, and acceptance is technology diffusion.

Before discussing diffusion further, let us return to the prior processes, invention and innovation. In truth, a realistic history of social and technological innovations would consist mostly of nonstarters. The overwhelming share of inventions are ignored. And an analysis of several hundred major innovations over the past two centuries shows a typical span of about fifteen to forty years between invention and innovation (Mensch, 1975). Moreover, the existence of one or more possible innovations in itself hardly guarantees subsequent diffusion.

To appreciate the uncertainty in the early phases of technology development, let us look at a historical problem of technological hazard and environmental pollution from steam railways. In the early days of railroad expansion in the United States, sparks in the smoke from wood-burning steam locomotives caused a considerable fire hazard to both human settlements and forests (Basalla, 1988). Inventors and entrepreneurs registered more than one thousand patents on "smoke-spark arresters" during the nineteenth century in a futile search for a solution, which arrived finally not by an add-on technology but by the replacement of steam by diesel and electric locomotives. This large number of alternatives illustrates that diversity and experimentation are precursors to diffusion. Many are called, but few are chosen.

Moreover, what is chosen for diffusion is not necessarily the best. The selection of a particular technological alternative may not conform to *ex ante* or *ex post* judgments about optimality. Sometimes selection of a particular alternative stems from an accumulation of small, even random events, eventually "locking in" a particular configuration. Thereafter, positive feedback mechanisms yield increasing returns to adoption of the standardized alternative. We suspect that the standard gauge of railroads or the disk operating systems in use now in personal computers are not the "best" but simply prevailed at a certain time in history and therefore can only be dislodged with great difficulty (see Arthur, 1988).

What are the factors in setting the diffusion clock? One is simply opposition to change. Opposition to proposed and diffusing technologies always recurs. The most cited case is the Luddites, who destroyed knitting and other textile machinery between 1811 and 1816. A similar movement, led by Captain Swing, resisted the introduction of mechanical threshing in rural England in the 1830s. As shown in Figure 2, the opposition to the machines was itself an orderly diffusive process. The time it took for the craze to smash machines to spread—two weeks—shows that social interaction and communication were highly effective far in advance of modern transport and telephony. Although opposition causes uncertainty about the eventual fate of an innovation, it fulfills two important evolutionary roles. First, it can operate as a selection mechanism for rejecting socially unsustainable solutions or technologies. Second, it helps qualify technologies to respond to societal concerns, improving their performance and thus enabling further, even pervasive, diffusion.

In a classic article, Earl Pemberton (1936) provided many illuminating examples of curves of gradual cultural diffusion. The first country to introduce postage stamps was England in 1840. Such a good idea; yet it took close to fifty years for a sampling of thirty-seven independent states in Europe, North America, and South America to imitate. A more delicate idea, touching on the nature and

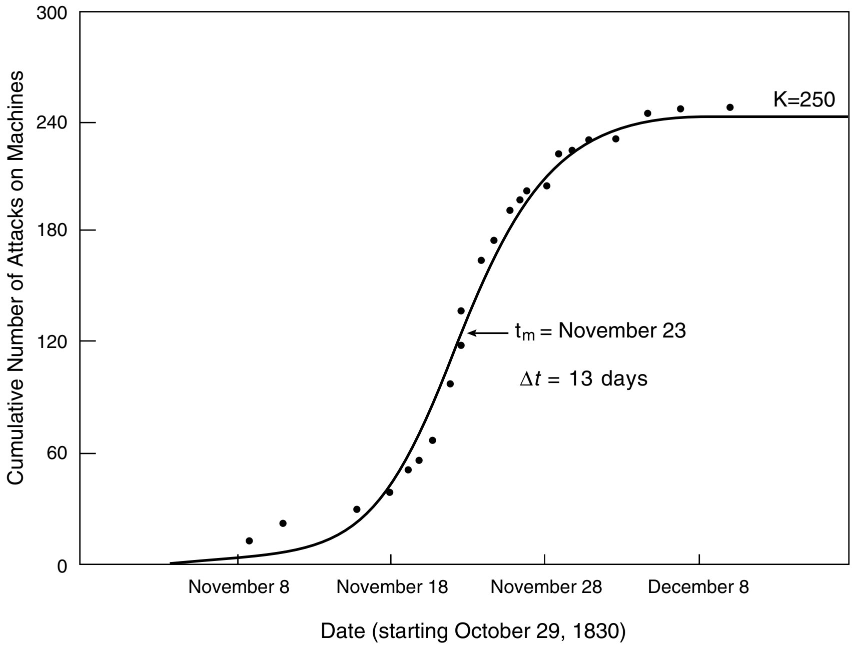

FIGURE 2 Resistance to technology as a diffusion process: number of threshing machines attacked during the Captain Swing Movement in England in 1830. NOTE: Actual data and a fitted three-parameter logistic curve. See endnote 5. DATA SOURCE: Hobsbawm and Rudé (1968).

control of the family, is the first compulsory school attendance law, enacted at the state level in the United States in 1847. It took fully eighty years, until 1927, for the last state then belonging to the United States to adopt similar legislation. These examples already emphasize that changes in technologies and social techniques are not one-time, discrete events but rather a process characterized by time lags and often lengthy periods of diffusion.

They also suggest that when diffusion succeeds, the forces and factors determining its speed and extent may change over time.[3] Performance, cost, fashion, and familiarity are among the considerations. Nevertheless, the diversity and complex interactions at the micro level appear often to lead to smooth, orderly behavior at the macro level, whether of Cistercians and Luddites, or, as we shall see, canals and passenger cars. Some theorists argue that orderly macroeconomic evolution requires such microeconomic diversity, which at first glance might instead seem likely to dissipate order (see Dosi et al., 1986; Silverberg, 1991; and Silverberg et al., 1988).

In addition to sociological and economic factors, straightforward, generic considerations appear to influence the speed of diffusion. The scope of technical change itself is a powerful one. We might distinguish four levels: 1) incremental improvements; 2) radical changes in individual technologies and artifacts; 3) changes in technology systems, that is, combinations of radical changes in technologies combined with organizational and managerial changes; and 4) changes in clusters and families of technologies and in associated organizational and institutional settings.[4] The latter levels of change, as well as larger system sizes, will likely entail longer times for diffusion (Grübler, 1991).

In sum, inventive and innovative activities provide the *potentials* for change. However, *diffusion* translates these potentials into changes in social practice. One abbey could not transform European agriculture; 740 did. Diffusive, largely imitative or repetitive phenomena are at the heart of the changes in society and its material structures, infrastructures, and artifacts. Thus, in the subsequent discussion, the analysis of time required for diffusion provides the central metric to analyze processes of social and technological change. Let us now try to grasp the main patterns.

THE DURATION OF DIFFUSION

We will consider an increasingly complex series of cases of technology diffusion, characterized by the environment in which diffusion processes operate. In the simplest case, an idea, practice, or artifact represents so radical a departure from existing solutions that it largely creates its own market niche. In practice, preexisting means for meeting basic social functions, such as transport and communication, are always present; nothing is truly new or free of competitors. Physicist Elliott Montroll (1978) called evolution a sequence of replacements. But clearly, some technologies enter much more accommodating environments than others.

The development of canals in the early nineteenth century offers a reasonable case of simple diffusion. In fact, the actual data on the growth of the canal network in the United States are approximated very well by a symmetrical growth curve, a three-parameter logistic equation in this case (Figure 3).[5] The estimated upper limit of the diffusion process, some 4,000 miles of canals, matches the historical maximum of 4,053 miles of canal in operation in 1851. The characteristic duration of diffusion (or Δt), defined as the time required for the process to unfold from 10 percent to 90 percent of its extent, is thirty-one years. The canals spread through the United States at about the same rate as the Cistercians initially spread through Europe. The entire canal diffusion cycle from 1 percent to 99 percent spans some sixty years. The year of maximum growth, or midpoint (t_m), occurred in 1835.

Subsequent major transport infrastructures, rails and roads, evolved along a dynamic pattern similar to canals, as Figure 4 illustrates (Grübler and Nakićenović, 1991). In the figure the sizes of individual networks have been

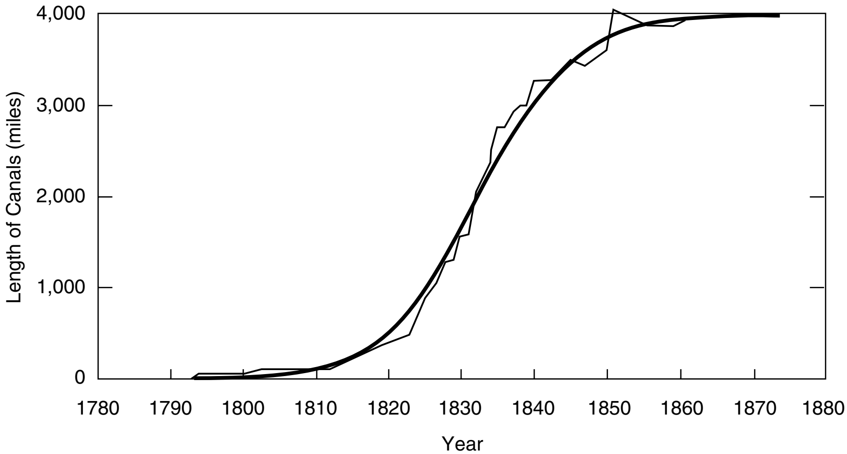

FIGURE 3 Growth of the canal network in operation in the United States. SOURCE: Grübler (1990).

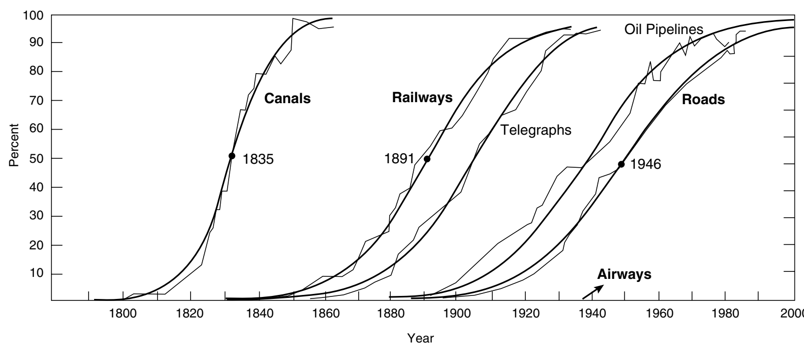

FIGURE 4 Growth of infrastructures in the United States as a percentage of their maximum network size. SOURCE: Grübler and Nakićenović (1991).

normalized for better comparability; in absolute extension, railways and surfaced road networks were one and two orders of magnitude larger, respectively, than canals at their maximum network length. Not surprisingly, the duration of the growth of railway and surfaced road networks is somewhat slower, Δt's of fifty-five and sixty-four years, respectively. Interestingly, we see the three major historic transport infrastructures spaced rhythmically apart in their development by a half century or so.

Transport infrastructures strongly influence nearly every aspect of daily life.[6]

Here we will comment only on their close relationship with other infrastructures. As Figure 4 suggests, the railway and the telegraph evolved together, as did the road network and the oil pipelines delivering the fuel for the cars on the roads. This synchronization illustrates technological interdependence and cross enhancement. Particular technologies and techniques do not diffuse in isolation but in a larger context, as we shall discuss below.

In fact, a new solution does not evolve in a vacuum but interacts with existing practices and technologies. One technology replaces or substitutes for another, with varying degrees of direct one-to-one competition. For example, after reaching its maximum size, the canal network declined rapidly because of vicious competition from railways. Looking at relative "market shares" of competing alternatives rather than at absolute volumes makes the interaction visible.

Probably the most famous case of technological substitution is motor cars for horses. In this case, the diffusion of one technological artifact, the passenger car, began simply by replacing another, the riding horse and the carriage. Looking at the absolute numbers of draft animals and cars in the United States (Figure 5), we see that the millions of horses and mules used for transport practically disappeared from the roads within fewer than three decades. Measured by a curve fit to a model of logistic substitution (for the model see Marchetti and Nakićenović, 1979), the duration of the replacement process (Δt) was only twelve years, fast enough to traumatize the oat growers and the blacksmiths (see Nakićenović,

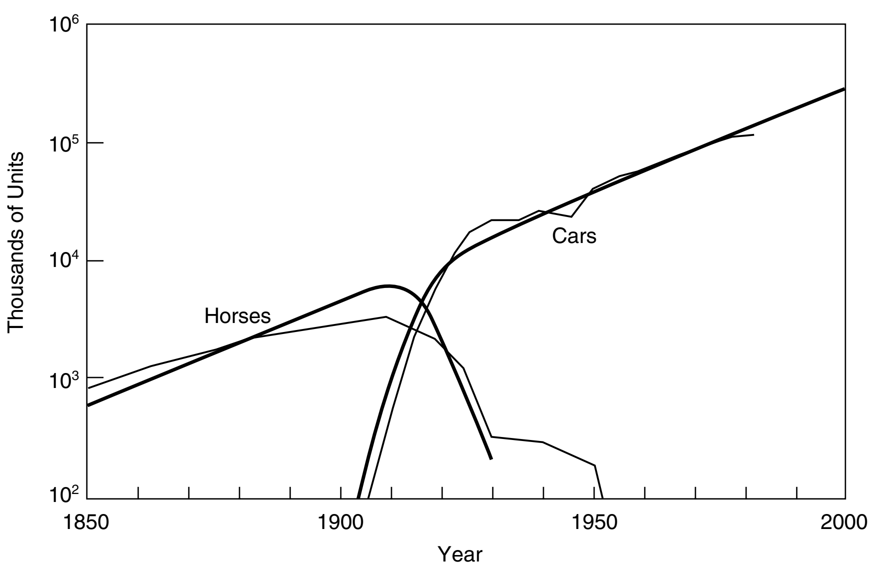

FIGURE 5 Number of nonfarm draft animals and automobiles. SOURCE: Nakićenović (1986).

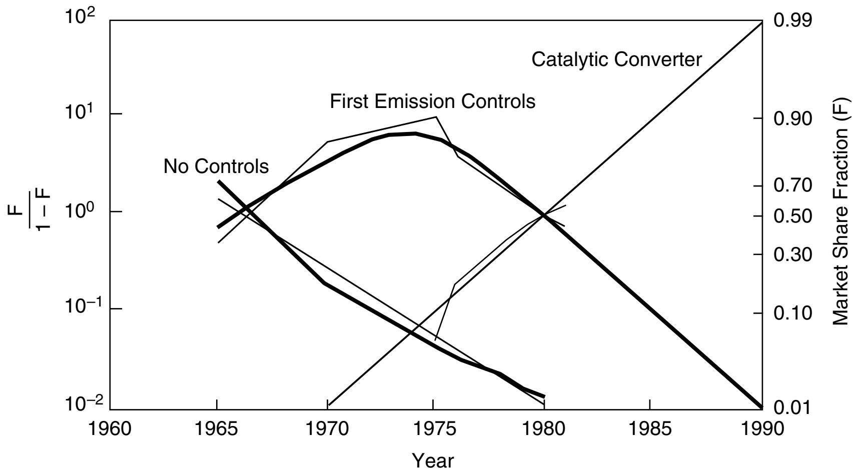

FIGURE 6 Diffusion of cars with first emission controls and catalytic converters in the United States, in fractional shares of total car fleet. SOURCE: Nakićenović (1986).

1986). Interestingly, the diffusion of a modern anti-pollution device, the catalytic converter, also occurred with a Δt of twelve years in the United States (Figure 6). The reason is probably that the lifetime of the road vehicle has not changed since the horse-and-carriage era; the working lives of horses and cars both last about ten to twelve years.

The continuing growth of the car population in Figure 5 illustrates another dynamic feature of technological evolution: growth beyond the initial substitution or field of application. Use of the car grew initially by replacing horses. After completion of that process in the 1930s, new markets were created. Higher average speeds, greater reliability in all weather conditions, and other features opened chances both for competition with trains for long-distance travel and for short-distance commuting that created suburbs, which in turn created more demand for cars. Currently some 150 million passenger cars are registered in the United States, about 0.6 cars per capita.

Mention of the sequence of horses, trains, and cars brings us to consider the most realistic process of technological change: multiple competing technologies. In steel manufacturing as many as four technologies have competed simultaneously with decreasing and increasing market shares (Figure 7). The diffusion trajectories of the processes are diverse, with Δt's ranging from less than two decades (replacement of the crucible process) to nearly seven decades (diffusion of electric arc steel). These changes in process technology not only enabled significant expansion of production but mattered greatly from an environmental perspective. They coincided with changes in energy supplies toward higher qual-

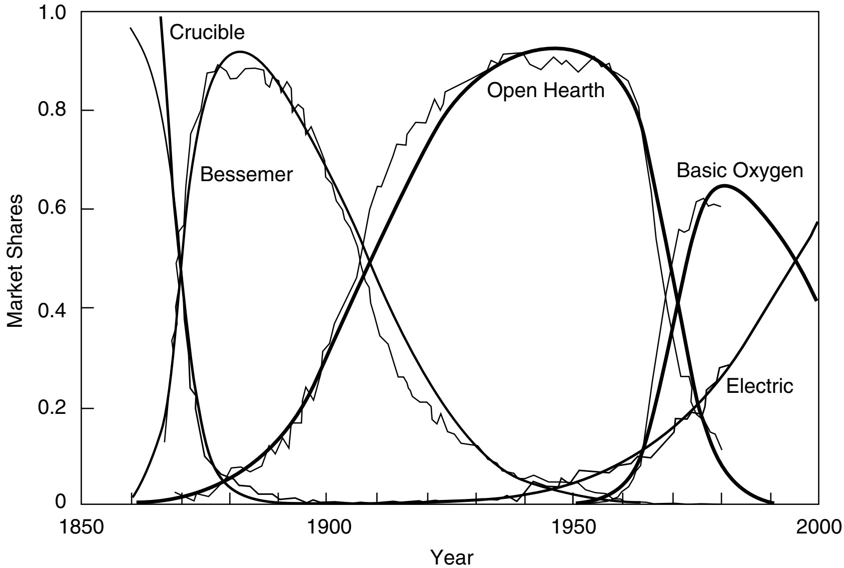

FIGURE 7 Process technology change in US steel manufacturing, in fractional shares of raw steel tonnage produced. SOURCE: Nakićenović (1987).

ity and cleaner energy carriers, consistent with the overall evolution of energy supply (see Nakićenović, this volume). Between 1800 and 1930 in the United States, one hundred million cords of hardwood are estimated to have been cut for charcoal for smelting iron (Reynolds and Pierson, 1942).

Let us now bring space back into our time picture. We have drawn examples so far from the United States. We commented at the outset about the patterns in space as well as the time of the diffusion of the Cistercian rule. Does the same hold true for a modern technology such as the motor car? Like Burgundy and its Cistercians, the United States was the earliest adopter of the car and has achieved the highest density of cars. Having started to adopt cars rapidly about the year 1910, America now has almost six hundred cars per thousand people. Having started in 1930, the United Kingdom now parks about four hundred cars per thousand people, while Japan parks about three hundred per thousand, having started the adoption process only in the 1950s. As Figure 8 suggests, empirical data from numerous countries show that later adopters manifest both an accelerated diffusion rate (shorter diffusion time) and a declining density of adoption as a function of the introductory date. The case of cars is corroborated by analysis of the declining adoption densities of "late-starters" in the railway development of the nineteenth century (Grübler, 1990).

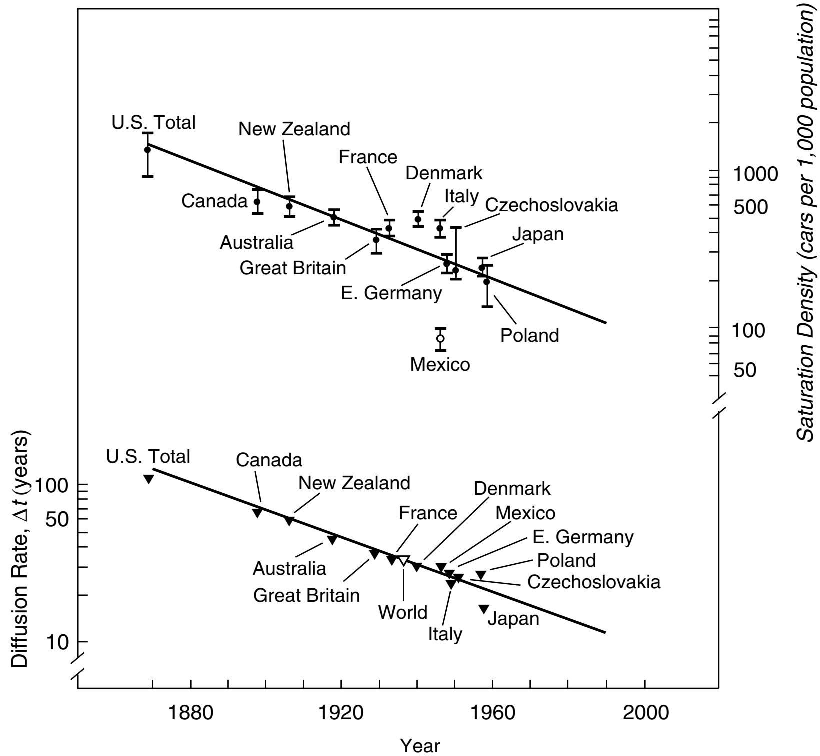

FIGURE 8 Passenger car diffusion at the global level: Catch-up, but at lower adoption levels. NOTE: Estimated saturation density and diffusion rates expressed as a function of the introduction date of the automobile. SOURCE: Grübler (1990).

The spread of railway networks in fact clearly shows how both spatial densities and the temporal rates of the adoption of technologies remain diverse. In the United States, the early innovation centers for railways on the East Coast and around the Great Lakes achieved by far the greatest spatial density of networks. Railway construction reached the West Coast some fifty years after the East Coast, and network densities remained significantly lower. In Europe, rails spread from the north of England in the 1820s to the rest of England and also to Belgium. By 1836 independent innovation centers had arisen in the Lyons region of France and Austria-Bohemia. The railway innovation wave spread from the early continental centers to cover most of Western and Central Europe by the 1850s. By the mid 1870s all of Eastern Europe, as well as most of European Russia, southern Scandinavia, and part of the Balkans, were networked. The final European subinnovation center was Greece, toward 1900. Rails penetrated the Albanian region almost a century after England. Starting first, England built a network (with attendant costs and benefits) one-third denser than Germany, almost twice the density of France, and ten or more times denser than other countries that might have appeared comparable at the outset of the railroad era.

In this light, we can ask, is the United States a likely guide for future mass-motorization globally? According to our understanding, no. Instead, the high density of cars in the United States results from specific initial conditions, including high individual mobility before the advent of the automobile and a long period of diffusion, which created precisely the conditions in life-style, spatial division of labor, and settlement patterns of an "automobile society." As Figure 8 indicates, heterogeneity in rates of diffusion and thus levels of adoption follows orders and thus is likely to persist, not only for railways and autos but in general for systems that diffuse globally. This perspective leads to lower-than-usual estimates of future demand for transport energy for China, for example (Grübler, 1992).

SEASONS OF SATURATION

We have noted that clusters of radical innovations and technology systems, interdependent and mutually cross-enhancing, give rise to families of technological innovations with associated new institutional and organizational settings. For example, the development of the automotive industry was contingent on developments in materials (high-quality steel sheets), the chemical industries (oil refining, in particular catalytic cracking), production and supply infrastructures (exploration and oil production, pipelines and gasoline stations), development of public infrastructures (roads), and a host of other technological innovations. The growth of the industry was based on a new production organization (Fordist mass production combined with Taylorist scientific management principles), yielding significant real-term cost reductions that made the car affordable to more social strata, thus changing settlement patterns, consumption habits of the population, and leisure activities. In turn, the automobile is just one artifact among many consumer durables now standard in every household in industrialized countries. These linkages multiply the effects of such techno-institutional clusters on the economy and society and account for their pervasive impact.

To quantify the emergence of technology clusters, I analyzed the history of a large sample of technologies for the United States (Grübler, 1990, 1991) Consistent with the definition of technology adopted here, the sample used in the analysis was not taken from the hard technology field alone. The cases included diffusion of energy, transport, manufacturing, agriculture, consumer durables, communication, and military technologies, as well as diffusion of economic and social processes, such as literacy, reduction of infant mortality, and changes in job classes. Two samples were analyzed. The first consisted of 117 diffusion cases that my colleagues at the International Institute for Applied Systems Analysis and I had studied ourselves (see Grübler, 1990; Marchetti, 1980; Marchetti and Nakićenović, 1979; and Nakićenović, 1986). The second sample was aug-

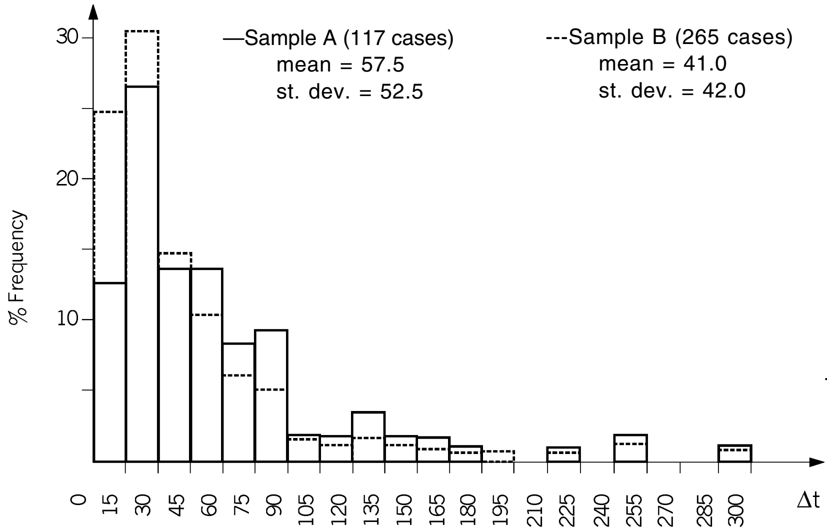

FIGURE 9 Histogram of diffusion rates of samples of 117 and 265 processes of technological, economic, and social change in the United States. NOTE: The Δt equals the time in years for a process to extend from 10 to 90 percent of its duration. St. dev. = standard deviation. SOURCE: Grübler (1990, 1991).

mented by additional, well-documented cases with a quantification of diffusion parameters that we found in the literature. This sample totaled 265 cases of innovation.

The profile of the diffusion rates, or Δt's, was quite similar for the two samples. The rates ranged from very short-term processes of only a few years to processes that extended over two to three centuries. The mean value ranged between forty and sixty years, with a standard deviation of about equal size (Figure 9). The largest number of diffusion processes in our samples have characteristic durations, Δt's, of between fifteen and thirty years.[7] If our diffusion studies had documented more of the seemingly numerous short-term phenomena such as clothing fashions, the profile of the histogram in Figure 9 would likely approach a "rank-size" or Zipf distribution in which the frequency of diffusion rates would be highest for fast processes and decline as the rates became slower.[8]

The good news for the human environment from our analysis is that the majority of artifacts and practices can be replaced within a few decades. However, some key processes have demonstrably long durations. For example, the global quests for improvements in the thermodynamic efficiency of prime movers and for the decarbonization of the energy system both clock in at about three hundred years (see Ausubel and Marchetti, this volume; Nakićenović, this volume). In general, pervasive transformations take time. The transformation of the US population from a society of farmers to manufacturers to service workers took some two hundred years (Herman and Montroll, 1972). Societies starting the move from brown to blue and to white collars later may accordingly move faster, but such all-embracing processes will never collapse to weeks and months.

We might summarize by saying that at any time, change in a society can be decomposed into a large number of diffusion (or substitution) processes with great variety in their rates. We can then ask whether aggregate measures exist for the average diffusion rate over time for the whole socioeconomic system and whether it changes. For such a measure, I calculated the average diffusion rates of the innovation samples, that is, the sum of the first derivatives of the diffusion (or substitution) trajectories at each point in time divided by the number of diffusion processes then occurring. This indicator is the diffusion equivalent of the annual GNP growth rate. The resulting measure rates the average annual technical (and economic and social) change at the country level (Grübler, 1990, 1991).

For the United States since 1800, the calculated average diffusion rate portrays clear peaks and troughs, which vary by a factor of two or more. The process of change is not gradual and linear but is instead characterized by long swings and discontinuities. In addition, rates of change tend to increase over time. This rise may reflect that the closer we approach the present, the more processes are included in the sample. However, the rising average rate of change could also result from the cumulative nature of technological change. Even though no individual diffusion process may proceed faster when compared to the past, the number and variety of artifacts (particularly those with faster turnover rates) are in fact much larger today than earlier. This could increase the average rate of change. In other words, while no individual technology or artifact diffuses faster than it did in the past (other things being equal), many more technologies and objects are in use, and thus more change. In any case, the analyses show pronounced discontinuities and also a decline in the diffusion rate in the decades after 1970, indicating an increase in saturation phenomena in the United States since then.

The fluctuations and discontinuities in the long-term rate of sociotechnical change result from the complex dynamics of the discontinuous rates at which individual innovations appear and from the different rates of absorption of these innovations in the socioeconomic system. Periods of accelerating rates appear to indicate the emergence of a technology cluster in which a large number of interrelated innovations diffuse into the economic and social environment. These in turn contribute, by means of backward and forward linkages, to prolonged periods of economic growth.

Periods in which progressively more and more innovations enter their saturation phase of diffusion follow the growth periods. Thus, each major peak in the average rate of change characterizes the start of saturation of a corresponding cluster or family of diffusion processes. This “season of saturations” results in a significant decline in the average rate of technical and social change and, through market saturation and a decrease in investments, also contributes to a slowdown in economic growth.

Presumably many inventions of the past few decades now await their chance to become successful innovations. Were they included, these could reverse the recent downward trend in the rate-of-change curve by the late 1990s. Then the successful innovations, after a slow initial diffusion, would enter into the rapid, indeed exponentially growing part of their life cycle.

The turning points in the rates of diffusion of technological and social innovations coincide with the turning points of so-called long-waves of economic growth as identified by several researchers (Marchetti, 1980; van Duijn, 1983; Vasko, 1987). In the analysis of US data, the peaks—the maxima in the rate of sociotechnical change and the onset of leveling off and saturation phenomena—occurred in 1840, 1912, and 1970, respectively. Troughs, maxima of saturation periods and the slow beginning of a new phase of accelerated sociotechnical change, occurred in 1820, 1875, and 1930. Appropriately, these troughs correspond to periods of pronounced recession, even depression, in the economic development of the United States.

From a historical perspective we can associate four technology clusters with this statistical pattern and speculate on the emergence of a fifth. The clusters may be identified by their most important economic branches, infrastructures, or functioning principles. Extending to the 1820s, we find textiles, turnpikes, and water mills; extending until about 1870 we find steam, canals, and iron; extending until about 1940 we find coal, railways, steel, and industrial electrification; extending to the present we find oil, roads, plastics, and consumer electrification (Grübler, 1994). Currently we appear to be in transition to a new era of industrial and economic development. We can speculate that it will be characterized by natural gas, aviation, "total quality control" of both the internal and external (or environmental) quality of industrial production, and the massive expansion of information handling.

These observations add up to an essentially Schumpeterian view of long-term development. Major economic expansion periods appear driven by the widespread diffusion of a host of interrelated innovations—a technology cluster—leading to new products, markets, industries, and infrastructures. These diffusion processes are sustained by, in fact are contingent on, mediating social and organizational diffusion processes. The growth or diffusion of a dominant cluster cannot be sustained indefinitely, however.

Market saturation, the dwindling improvement of possibilities for existing process technologies, managerial and organizational settings, and an increasing awareness of the negative (specifically, environmental) externalities involved in the further extension of the dominant growth regime pave the way to a season of saturations. During such periods, opportunities arise for the introduction of new technological, organizational, and social solutions, some of which may have been latent but were barred from market entry by the dominance of the previous growth paradigm. Even when such innovations are introduced successfully, their penetration rates in the initial phase of their diffusion life cycle are rather slow, and a matching new social and economic mediating context has still to emerge. In the phase-transition period, the old is saturating, and the new is still embryonic. Only after such a period of transition, crisis, and mismatch does a prolonged period of widespread diffusion of a new sociotechnical "bandwagon" and thus of growth become possible.

CONCLUSIONS

Empirical examination of diffusion processes, as illustrated in this essay, highlight the following observations:

(1) No innovation spreads instantaneously. Instead, a typical S-shaped temporal pattern seems to be the rule. This basic pattern appears invariant, although the regularity and timing of diffusion processes vary greatly.

(2) Diffusion is a spatial as well as temporal phenomenon. Originating from innovation centers, a particular idea, practice, or artifact spreads out to its hinterland by means of a hierarchy of subinnovation centers and into the periphery, defined spatially, functionally, or socially.

(3) The periphery, while starting adoption later, profits from learning and the experience gained in the core area and generally has faster adoption rates. As the development time is shorter, however, the absolute adoption intensity is lower than in innovation centers or in core areas (spatial or functional) proximate to them.

(4) Although diffusion is essentially a process of imitation and homogenization, it clusters and lumps. The densities of application remain discontinuous in time and heterogeneous in space among the population of potential adopters and across different social strata. In fact, overall development trajectories appear necessarily punctuated by crises that emerge in transitional periods. As such, diffusion and its discontinuities may be among the inherent features of the evolutionary process that governs social behavior.

Nevertheless, appropriate incentives and policies may nurture the development of more benign technologies and their diffusion, and many changes can be implemented over a time frame of two to three decades. However, sectors and areas will also remain in which changes will occur much more slowly, particularly those related to the long-lived structures of our built environment: for example, infrastructures for transport and energy as well as housing stock. Here rates of change and diffusion constants ranging from several decades to a century are typical and will be costly to accelerate. Therefore, the efficiency with which existing systems are used merits attention.

In essence we have two strategies in light of diffusion. One focuses on incremental changes, for example, environmental add-on or "end-of-pipe" technologies. Such policies can bring quick changes but tend to reinforce the dominant trajectory, blocking more systemic and radical changes. A second strategy opts for more radical departures from existing technologies and practices. However, these strategies, such as the development of fuel cells and hydrogen for energy, although more effective in the long run, require much more time to implement because of the multiplicity of forward and backward linkages between technologies, infrastructures, and forms of organization for their production and use.

The interdependence between individual artifacts and long-lived infrastructures creates our dilemma. Within two to three decades the United States could in principle change its entire fleet to zero-emission vehicles. In fact, 99 percent of vehicles now on the road will be scrapped in this interval. Yet, this interval is too short for the diffusion of the required associated energy supply, transport, and delivery infrastructures, which will inevitably distend the rate of diffusion of end-use devices. Thus, key technologies that we can already envision to raise the quality of the environment probably must await the second half of the twenty-first century to become widespread and influential.

Historically, technology clusters have been instrumental in raising productivity and also in alleviating many adverse environmental effects. The emergence of a new cluster could hold the promise of an environmentally more compatible technological trajectory. But it will take time. There are times of change and times for change, and unless our individual and collective behavior is modified, these times will remain to frustrate and excite us.

NOTES

1. For an extended version of this essay, see Grübler (1995).

2. On the spatial diffusion of Cistercians, see Donkin (1978). For a general overview of diffusion theory, see Hägerstrand (1967), Morill (1968, 1970), and Rogers (1983). For a more recent overview of diffusion theory, see Grübler and Nakićenović (1991). On the role of networks, see Kamann and Nijkamp (1991).

3. For an overview from sociology and anthropology, see Rogers (1983); for an overview from economics, see Mansfield (1961, 1968). For industrial innovations, see Nasbeth and Ray (1974) and Ray (1989).

4. For a more detailed discussion, see Freeman and Perez (1988) and Grübler (1992).

5. The equation to which the data are fitted has the form $Y = k/(1 + e^{(-b(t-t_m))})$, where Y(t) represents the sigmoidal growth through time of a population or process, Y. This is often referred to as the logistic model. Three parameters control the shape of the sigmoidal growth trajectory: b controls the steepness (or diffusion rate) of the model; k denotes the asymptotic limit (or saturation level); and t_m denotes the middle or inflection point. The inflection point occurs at k/2, where the growth rate (dY/dt) is at a maximum. Note that k is sometimes also referred to as the "carrying capacity." A convenient notation for the diffusion rate (b) is Δt, where Δt is the time it takes for the process to grow from 10 to 90 percent of the saturation level, k. Approximately the same length of time is required for the process to grow from 1 to 50 percent. Through simple algebra, it can be shown that $\Delta t = \ln(81)/b$.

6. For an account of the dynamic interactions in US transport infrastructure development, see Nakićenović (1988). For a discussion of the impacts of transport infrastructure development on economic growth and discontinuities in economic development, see Berry et al. (1993), Grübler (1990), and Isard (1942). Berry (1990) also provides a good account of their impact on urbanization.

7. Starr and Rudman (1973) suggested a doubling time of twenty to thirty years for the technological component of economic growth, an estimate that our data sample corroborates.

8. For discussion of such distributions, see Montroll and Badger (1974).

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