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Long Waves, Technology Diffusion, and Substitution

Arnulf Grübler and Nebojša Nakićenović

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Preface

There is an urgent need to drastically reduce adverse environmental impacts resulting from prevailing economic activities. Even more important is the question of the future direction of economic development and technological changes. In this paper the authors argue, from a historical perspective, that this process will remain discontinuous and spatially heterogeneous, as a result of diverse policies and strategies.

The authors illustrate empirically the argument that the process of economic growth and technological change is not smooth and continuous. They demonstrate that various phases of economic expansion are driven by the diffusion of a host of interrelated clusters of technologies and that the timing of the transition from one dominant cluster to another is consistent with the pattern of Kondratieff long waves.

The paper also illustrates that we are currently moving away from the old, materials- and energy-intensive development trajectory to a new future. There is a need to progressively close the industrial-ecology cycle and there are indications that this may indeed be possible, given the promotion of a range of carefully selected technological and policy measures for achieving sustainable development. One of the main goals of the Environmentally Compatible Energy Strategies (ECS) Project at IIASA, is to point out such promising technological and policy alternatives.

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*Long Waves, Technology Diffusion, and Substitution**

Arnulf Grübler & Nebojša Nakićenović

INTRODUCTION

Much of the long wave debate is centered around the issue of whether long-term regularities in economic development exist, and whether there are associated fluctuations of relevant indicators, such as prices, profit rate, employment, innovative activity, trade, investment, and other pertinent measures. For example, research has often concentrated on the questions of to what extent the fluctuations in price levels are cyclical, whether there is synchronization, and whether the variations are only limited to monetary indicators or can also be extended to physical measures of output, materials, or employment. We will attempt to describe the long wave phenomenon as a process of structural change that goes beyond the question of the extent to which prices and some other monetary indicators might portray inflationary tendencies over a period of a few decades which are followed by periods of disinvestment. We will try to show that periods of growth and expansion in economic activities are punctuated with phases of fundamental changes in the structure of the economy, the technological base, and many social institutions and relations.

Freeman and others (Freeman, 1983; Freeman & Perez, 1988) have characterized such periods as times of paradigm shifts—times in which the dominating techno-economic paradigms that have led

* This paper is based on a presentation at the conference "The Long Wave Debate," Brussels, January 12-14, 1989.

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to previous upswing phases reach the limits of their validity and begin to saturate. The development trajectories (Dosi, 1983; Nelson & Winter, 1982) under the old techno-economic paradigms often reach the limits of social acceptability and environmental compatibility, and sometimes, very simply, the demand for goods and services begins to saturate. As Schumpeter (1935; 1939) pointed out, during these periods innovative activities blossom. However, it is not the innovative activities themselves that have structural impact but rather the diffusion of new technologies and institutions that emerge from innovative activities. To a large extent this is a social process, since the new technologies and institutions are mediated by society, and can become accepted or blocked. We will briefly document the diffusion of important technologies that have been pervasive in the sense that they have led to the development of a whole cluster of new activities that are associated with each Kondratieff upswing and its technoeconomic development trajectory. Pervasive techno-economic systems diffuse not just in one sector; they alter many economic and social activities (typical examples include steam, mass production methods, or electricity; see, e.g., Freeman, 1989).

The evidence is phenomenological; we will not make any attempt in the present discussion to establish causality. We will illustrate that the diffusion of new systems evolves from emergence to growth to saturation, and we will show how the diffusion of pervasive technologies is related to the fundamental structural changes and development associated with each Kondratieff upswing.

The effect of the pervasive diffusion processes can be described in the contexts of technological change, the transformation of economic relations, and changes in the associated institutions. We will focus on documenting the growth of new technologies and the substitution of old technologies by new ones during each of the Kondratieff upswing phases. This process results in increasing performance that can be measured in terms of efficiency and other techno-economic characteristics, such as costs and prices.

The results of the analysis of these diffusion processes indicate regularity, correlation, and recurrence within each cluster of interrelated technologies. It should be noted here that the discontinuities between different clusters of techno-economic development are not sharply focused, nor is the clustering phenomenon very rigid. Nevertheless, the beginning of pervasive diffusion processes and the onset of saturation are, to a large degree, correlated with the turning points in the long wave.

The clustering of innovations during Kondratieff lower turning points does not appear to be as pronounced as originally indicated by Mensch (1975), although more recent research, based on an analysis of the dating and frequency of innovations by Kleinknecht (1987), has given a more differentiated view, a view based on the statistically significant evidence of the discontinuities in the innovation rate. In fact, there is stronger evidence of confluence in the saturation–rather than in the emergence–of the diffusion processes.

In this sense, the diffusion processes can be seen internationally as Schumpeterian bandwagons, that is, as a family of related systems that emerge, albeit with some time lags, in different parts of the world. The time span between the beginning of the diffusion of new pervasive systems–that is, between the leaders and the laggers–tends to decrease as the diffusion progresses, so that the process appears much more focused towards the saturation phase. Thus, we can speak of a visible catch-up effect in the diffusion of pervasive techno-economic systems throughout the world. While most of these results are based on the analysis of technology diffusion, we have been able to document similar phenomena in the spread of some social and institutional innovations.

PRICE FLUCTUATIONS

Figure 1 shows one of the widely used indicators for the turning point in the long waves, that is, fluctuations in price levels (a measure already analyzed by Kondratieff in his famous 1926 long wave paper). With hindsight we see the occurrence of almost one full Kondratieff wave since the 1930's. The two price series, starting in the 1800's, give the indices of wholesale and fuel prices in the United States. The three upper turning points occurring in the 1820's, 1860's, and 1920's are clearly visible in the raw data. For comparison we show in Figure 1 also the price (in nominal terms) of the three major fuels: coal, oil, and natural gas. There is a sustained inflationary trend starting in the 1940's, reaching a peak of energy prices and other basic materials in the early 1980's, after which the curve portrays deflationary tendencies during the last few

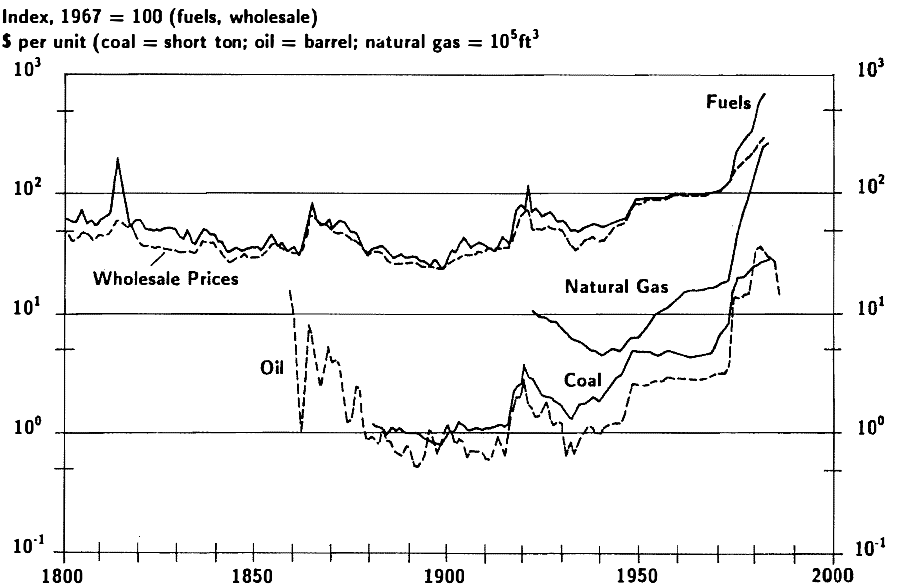

Figure 1. Energy Prices and Fuel and Wholesale Price Index, U.S.

years. In the meantime, oil and natural gas prices have returned to their pre-1970 levels in real terms. Despite many turbulent events and acute crises, and the complete transformation of the United States from an agrarian to industrial society over the last two centuries, the long term price trends have been surprisingly stable, with the exception of the four pronounced flares during the Kondratieff turning points.

Figure 2 emphasizes this remarkable long term stability of energy prices. It gives the price of oil since 1863 in constant 1958 dollars per kilowatt year. The second curve shows the composite price of all energy sources in the American economy, weighted by their relative shares in total primary energy for each period. The figure clearly demonstrates that the price flares since the OPEC oil embargo have been deflated back to historical levels. Thus, in spite of the recurring brief episodes of extreme price volatility, crude oil (and energy in general) has shown rather remarkable price stability in real terms over its more than century-long history as one of the major world commodities. With the exception of three prominent price flares in the 1860's, prior to the Great Depression and after

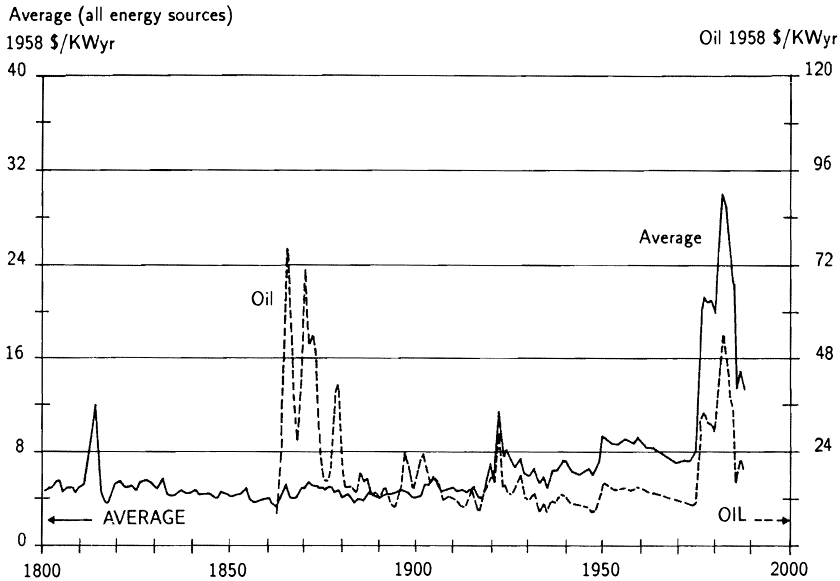

Figure 2. Real Composite Energy and Crude Oil Prices, U.S.

1973, the price of crude oil fluctuated within the relatively narrow range of about $13/bbl (in 1987 dollars, or about $18/kWyr in constant 1958 dollars as shown in the figure). We have shown elsewhere (Nakićenović, 1988; Grübler, 1987) that periods of price volatility mark important turning points in the structural evolution in energy (and also other systems, such as infrastructures) in terms of the saturation of the predominant technological system, as well as in the introduction of new ones.

Against the background of this rather static indicator (despite the four pronounced flares around the stationary trend), we will now document the dynamic changes in the replacement of old by new pervasive technologies. We begin by describing the development of infrastructures.

GROWTH OF INFRASTRUCTURES

Figure 3 shows the increase in mileage of the three most important transport infrastructures: canals, railways, and paved roads. During the last 200 years the length of transport infrastructures in the United States has increased by almost five orders of magnitude. The development of canals started saturating in the 1850's and showed a clear disinvestment thereafter. The expansion of railways leveled off in the 1920's, and in the meantime the network has declined by a third of the maximum length. The growth rate of the road network has also been continuously declining over the last decade.

The sequences of the development of these three infrastructures appears in Figure 4 as a remarkably regular process when their size is plotted as a percent of the saturation level. The rapid expansion of canals lasted until 1836, and from then on the growth rate declined toward the saturation period. With the onset of the saturation of canals, railroad expansion began to grow exponentially until 1891. The development of paved roads is almost a recurrence of the expansion pulses in canals and railroads, with an inflection point in 1946 and with probable saturation towards the end of this century. It is interesting to note here that, measuring

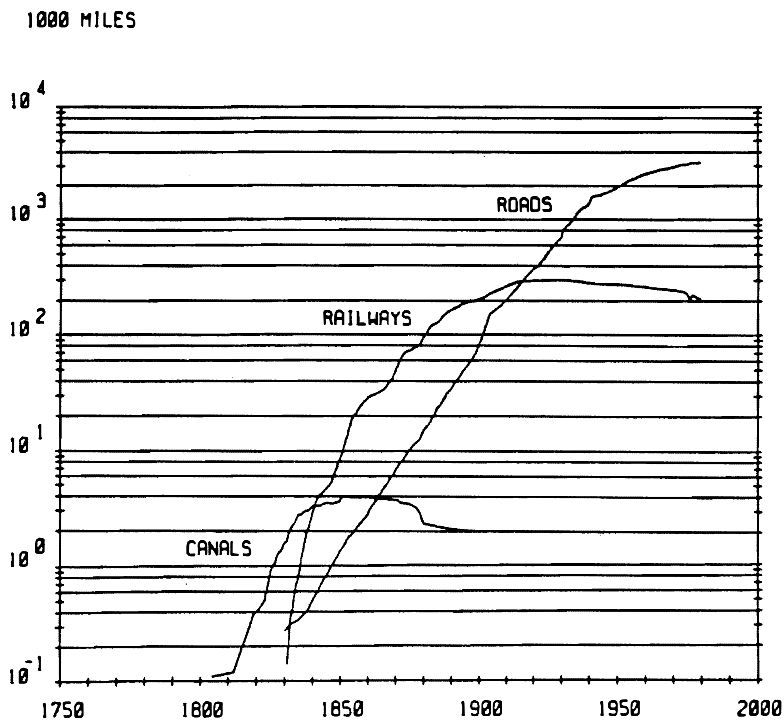

Figure 3. Growth of Length of Transport Infrastructures, U.S.

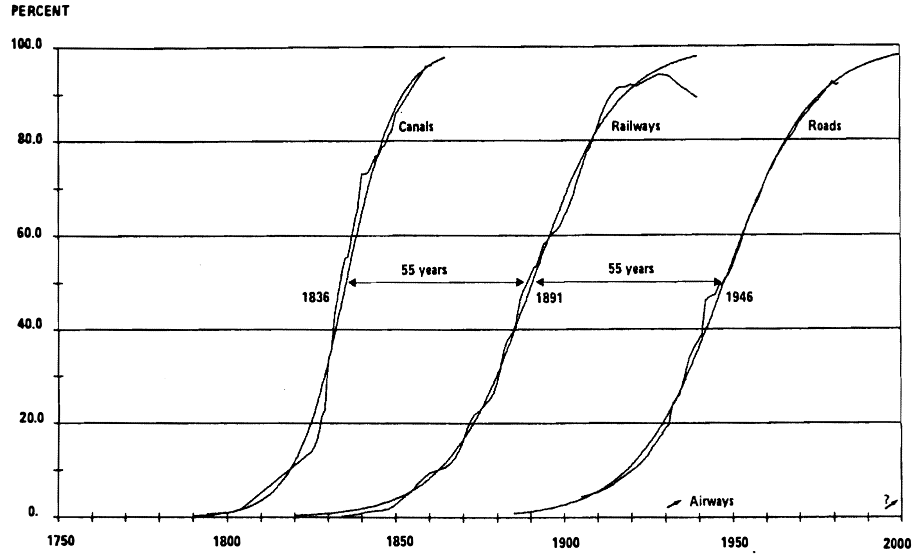

Figure 4. Growth of Transport Infrastructures as Percent of Saturation Level, U.S.

the distance between the respective inflection points, we see that the three growth pulses are separated in time by 55 years. The complete diffusion processes are rather lengthy, spanning more than six decades.[1]

Figure 5 gives the same data plotted on a logarithmic scale as the ratio of the growth level reached in a given year, divided by the amount of growth left to the saturation level.[2] This is a convenient way of presenting S-shaped diffusion processes as straight lines. For

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[1] The duration of the diffusion process is conveniently measured as the time that elapses between the achievement of 10% and 90% growth of the saturation level. We call this measure Δt.

[2] Historical data and fitted logistic curve are transformed as $x/(\kappa-x)$, where x denotes the actual infrastructure length in a given year and κ the estimated saturation level. The data and the estimated logistic trend are plotted as fractional shares of the saturation level, $f=x/\kappa$, which simplifies the transformation to $f/(1-f)$, the level of relative growth achieved divided by the remaining potential. Transformed in this way, the data appear to be on a straight line, which is the estimated logistic function. Without this transformation, the data and the trend curve would portray the same S-shaped growth as shown for the three transport infrastructures in Figure 4: canals, railways, and surfaced roads.

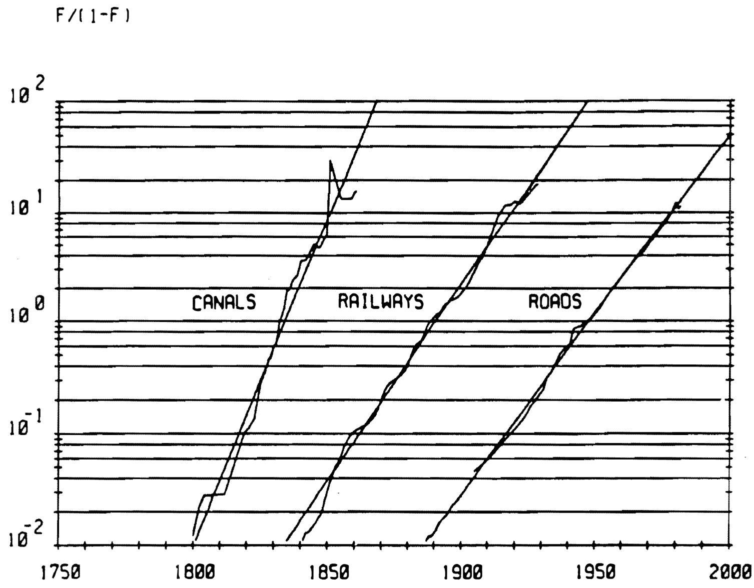

Figure 5. Logistic Growth of Transport Infrastructures, U.S.

purposes of clarity, only the expansion phases of the three growth pulses are shown, and the decline that follows is omitted.

The next two figures document both the expansion and the decline phases of the railway network in six industrialized countries, in order to illustrate to what extent the development of railroads has converged internationally. Figure 6 shows the diffusion of railroads starting from top to bottom in the United States, the United Kingdom and Germany (Federal Republic of Germany after the Second World War). Figure 7 shows in the same sequence the expansion and contraction of railroads in the Austro-Hungarian Empire (Austria after the First World War) and France, and the two growth pulses of the railways in Russia and the Soviet Union. While the growth processes and construction phases differ both in slope and, to a lesser degree, in duration, there is no doubt that there is a high degree of synchronization in the ultimate saturation of railway networks in the industrialized countries during the 1920's. The most interesting cases are France and the Soviet Union, since they show departures from the development pattern of the other countries.

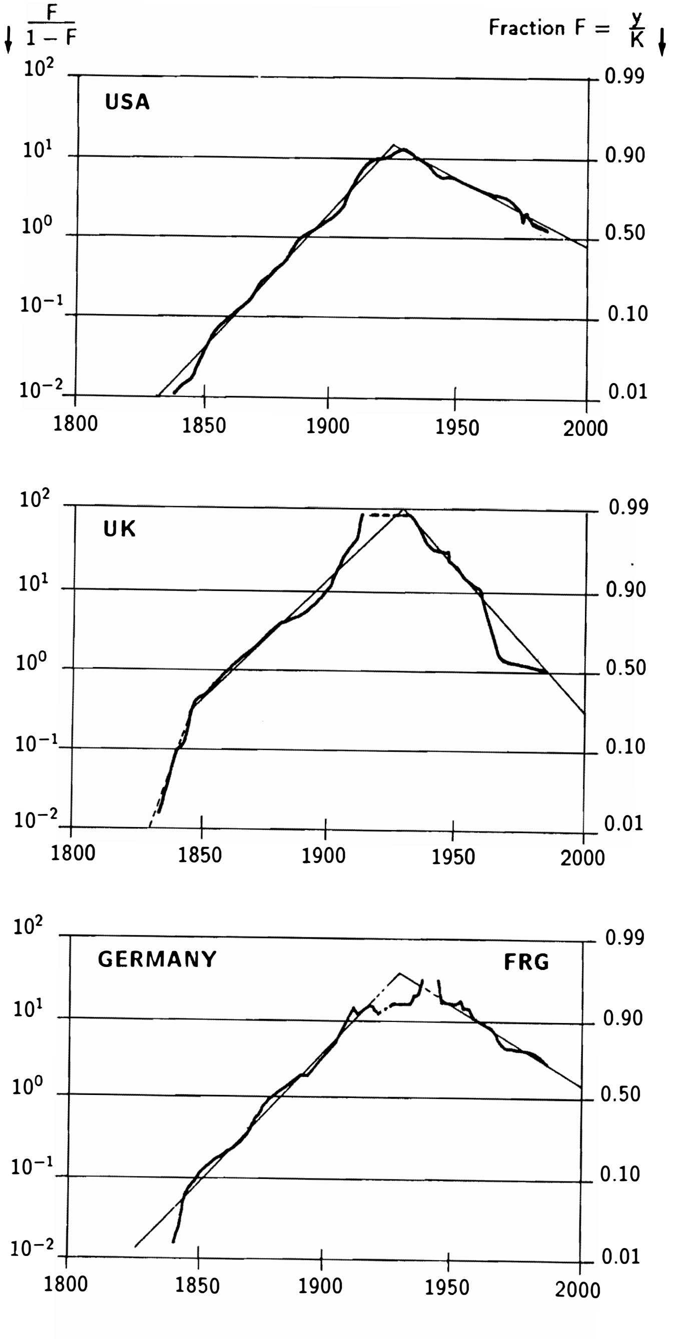

Figure 6. Growth and Decline of Railways, U.S., U.K. and F.R.G.

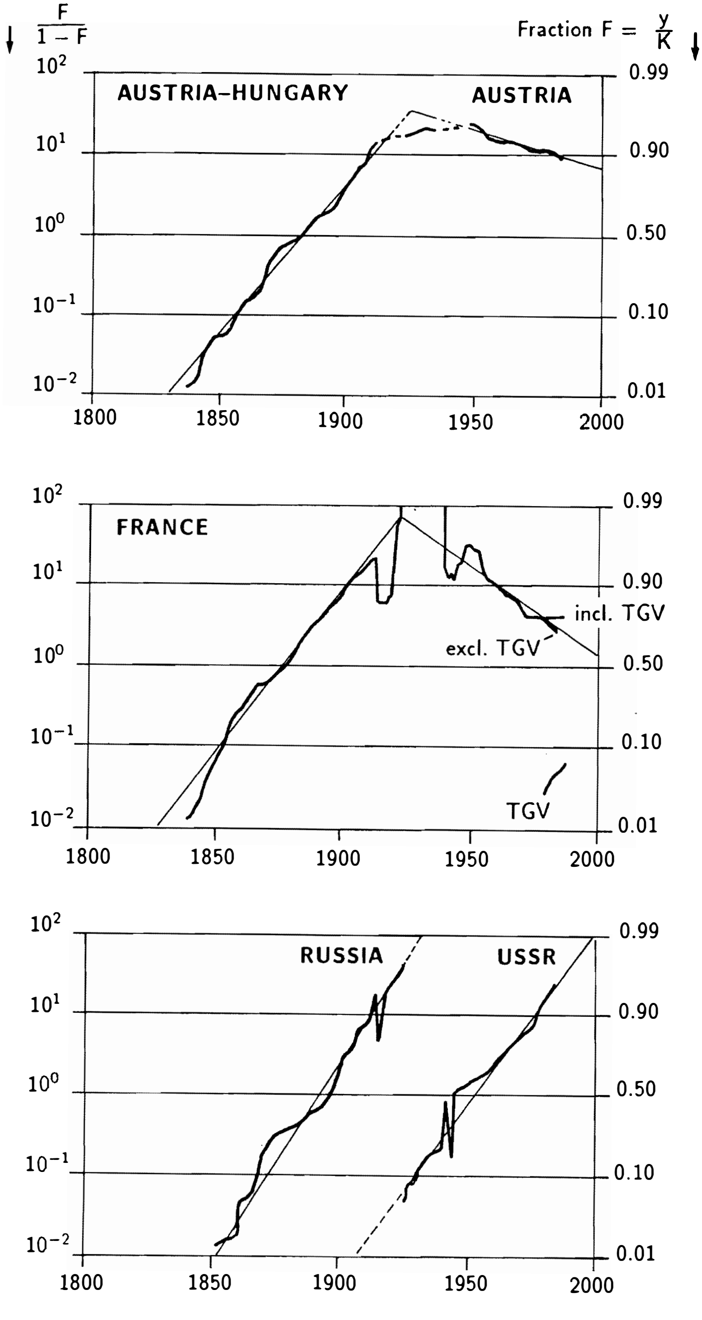

Figure 7. Growth and Decline of Railways, Austria, France and U.S.S.R.

In France there are two unusual features worth noting. The first is that the turbulence during the saturation phase is very large compared to other countries; second is the introduction of the TGV (*train à grande vitesse*) in the railway grid during the 1970's. Without the additional infrastructure dedicated to the TGV, the length of the French railway system continues to decline along the historical path, while the inclusion of the TGV links could indicate the beginning of a trend reversal. Thus, one could speculate whether the introduction of rapid rail transport systems does not, in fact, represent the beginning of a new transport infrastructure. In order to document this possibility, the growth of TGV lines is plotted in the lower right corner of the graph.

The development path of railroads in Tzarist Russia is almost identical to the patterns observed in the other five countries, until the onset of saturation in the 1920's. This period also coincides with the October Revolution. It is possible that the reconstruction period following the revolution is the reason for the further expansion of railroads in the Soviet Union. Thus, we see here two consecutive expansion pulses of the railway network. After saturation of the first pulse, the second followed a similar trajectory with a slightly longer duration and is now entering its own saturation phase.

These six examples clearly show that the development of a particular techno-economic trajectory follows similar paths in countries with fundamentally different social and economic relations, different technological bases, and, certainly, different initial conditions. In this sense we can speak of international bandwagons in the diffusion of pervasive techno-economic systems.

Figure 8 summarizes the spread of railroads and associated technologies in a number of countries, including the six examples given above. The first cluster of curves shows a rather narrow band in the growth of railway networks. The second band of trajectories shows another important innovation in the railway systems that diffused during the period when most of the world's railways were already declining: namely, the replacement of steel by diesel/electric locomotives. This development trajectory is also confined to a rather narrow band that is intersected with the major irregularity of this process, that is, the second growth pulse of the railways in the Soviet Union. For reasons of clarity, other associated technolog-

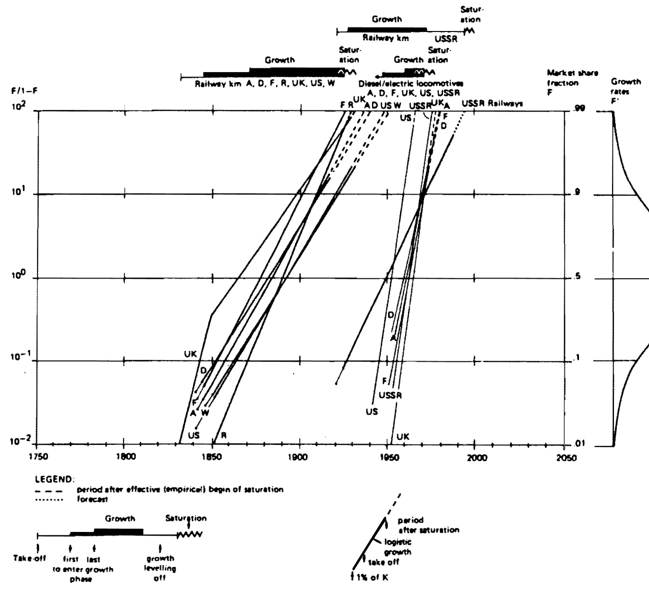

Figure 8. Diffusion of Railways and Replacement of Steam Locomotives, World.

ical changes in the spread of railways are not included, such as the replacement of wood by treated wooden ties, iron by steel rails, and numerous other innovations that made railroads one of the most important factors in economic development between the 1860's and the 1920's.

This summary figure illustrates that the replacement of the rolling stock symbolized by the diffusion of diesel/electric locomotives was much faster than the development of the railroad infrastructures, with a Δt in the order of fifteen years, compared to a Δt for the expansion of railways of about seven decades.

This process was not only swift but it also represents another important feature of technological change—the substitution of old by new systems. According to Montroll, "*evolution is the result of a sequence of replacements*" (1978: 4633; italics added). Often, new technologies create new "niches" that lead to products and services hitherto unavailable. More frequently, though, successful innovations can preempt an established niche by providing improved technical and economic performance or the social acceptability of existing services through new ways of fulfilling them. Circumstantial evidence shows that many pervasive systems evolved through both of these evolutionary paths. First, they replaced older technologies, and then they created new and additional market segments that did not exist before. We will illustrate this feature of the diffusion of techno-economic systems by briefly sketching the spread of the automobile.

Figure 9 shows the "fleets" of road horses and cars in the United States. During the last century horse-driven vehicles were the predominant form of road travel. In the United States the number of road horses increased to more than three million by the 1920's, declining rapidly thereafter. After the advent of the horseless carriage towards the end of the last century, the spread of the automobile was very swift, until the 1930's, when a structural transition occurred in the growth path, followed by lower expansion rates.

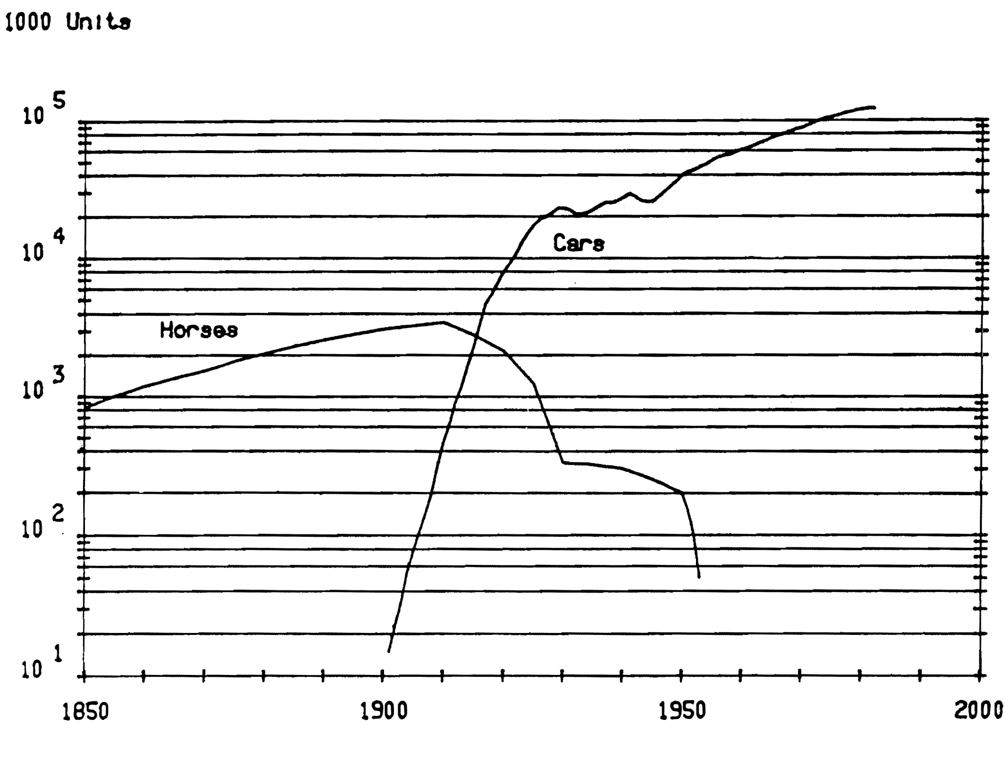

Figure 9. Population of Road Horses and Number of Cars, U.S.

Figure 10 indicates that this structural change was caused by the beginning of a new phase in the diffusion process of the automobile. The figure shows the shares of cars and road horses plotted on a logarithmic scale as ratios of one to the other.[3] By 1930 horses had virtually disappeared from American roads, indicating that this technological trajectory fulfilled the niche previously occupied by horses. Additional evidence is seen in the fundamental transformation of the vehicles themselves after the 1930's, and the numerous innovations in production methods and vehicle design that provided for higher performance, more comfort, and a lower price. A number of changes in other sectors also made the automobile more attractive and accessible to a wider public much beyond the relatively small circle of horse-driven carriage owners and users. Examples

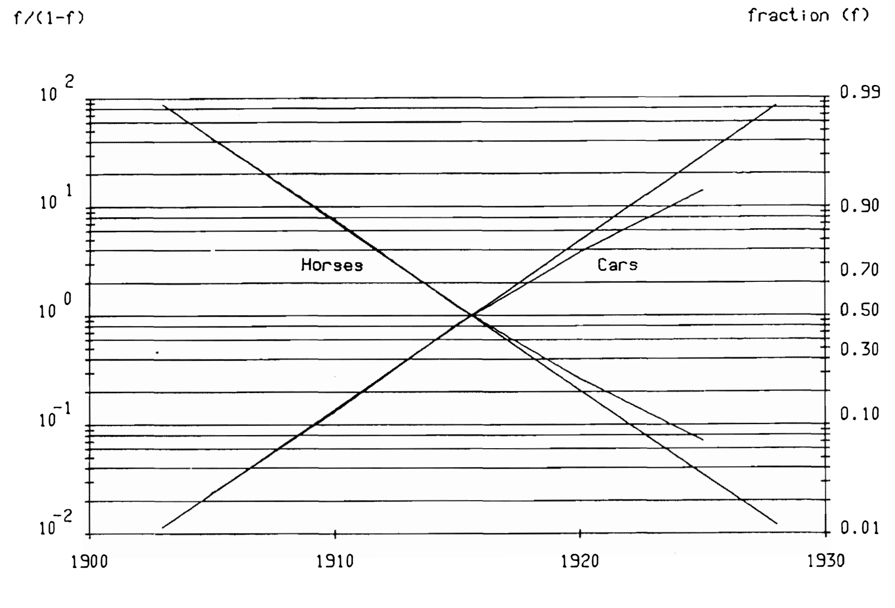

Figure 10. Replacement of Horses by Cars, U.S.

[3] The fractional shares, f, are not plotted directly but as the linear transformation of the logistic curve, i.e., $f/(1-f)$, as the ratio of the market share of cars (f) over the market share of horses ($1-f$). This form of presentation reveals the logistic substitution path as a linear secular trend. The model was formulated by Fisher & Pry (1971) and has been subsequently been applied in many case studies.

of these changes include innovations in the steel industry (higher quality alloys and wider sheet metal) and petrochemical industry (catalytic cracking and high quality rubber), and a host of other institutional changes which eventually even led to automobile compatible settlement patterns. Incidentally, the high usage of automobiles today has led to numerous environmental problems, but in a historical perspective the replacement of horses by cars alleviated one of the grave environmental problems of the cities of the last century, namely, horse manure in the streets.

The complete replacement of horses by cars lasted about 30 years in the United States (with a Δt of about fifteen years). Figure 11 shows the equivalent process in the United Kingdom for all road vehicles classified into two groups: (1) all horse-driven vehicles and (2) all internal combustion engine propelled vehicles. The complete replacement process lasted about as long as in the United States and also ended by 1930.

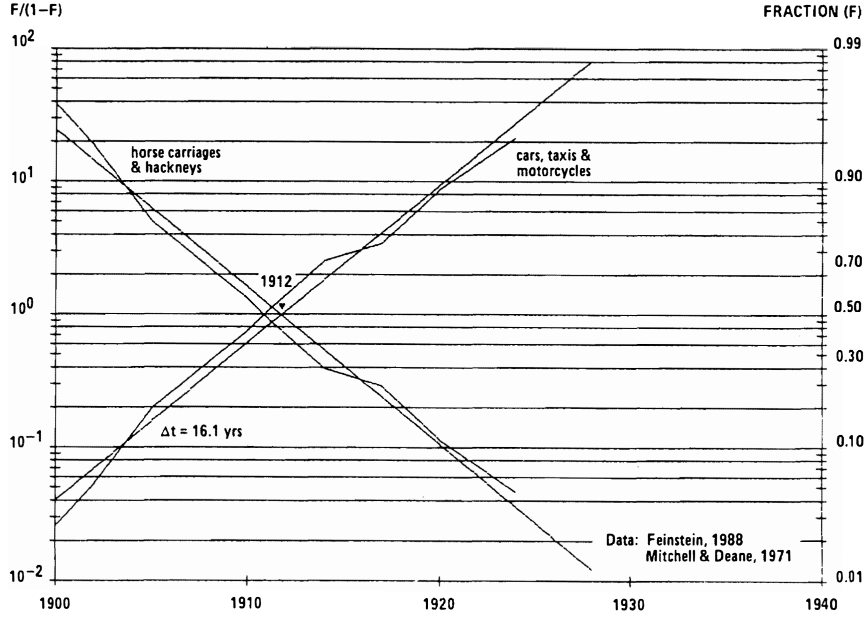

Figure 11. Replacement of Horse by Motor Vehicles, U.K.

Figure 12 summarizes the replacement of horses by automobiles in a number of countries as a rather quick and focused substitution path, starting around the turn of the century and ending by 1930. Thereafter a slower diffusion phase was initiated, as illustrated previously for the United States. This second pulse in the spread of automobiles was less swift and is not yet completed, although there are indications of a beginning saturation phase in most countries. Overlaid over this diffusion cluster is the development of associated infrastructures, such as oil pipelines, surfaced roads, and motor ships. The cross enhancement that characterizes the pervasive nature of these systems, or whole families of related systems, was an important aspect of the last Kondratieff upswing.

Up to now we have described two important features of the diffusion processes: growth and the replacement of old by new. Often, however, we not only observe a succession of growth pulses (for example, the two development phases of the railroad system in Russia and the Soviet Union) or the two different modes in the spread of the automobile, but also a succession of substitution processes. Rarely are only two technologies, production processes, goods or services competing in a market. More often the variation is much larger. Figure 13 illustrates for the United Kingdom a typical example that has been documented in a number of countries: that of the successive replacement of sailing ships by steamers and, later, motor ships, measured by tonnage of ships registered in each class. The dynamics of the process is quite long, with a Δt in the order of 70 years (comparable to the duration of the diffusion of railroads), with steam ships saturating in the 1930's.[4]

[4] The fractional shares, f, are not plotted directly but as the linear transformation of the logistic curve (see note 3). The presence of some linear trends in Figure 14 indicates where the fractional substitution of the three classes of merchant vessels follows a logistic curve. In dealing with more than two competing technologies, we must generalize the Fisher & Pry (1971) model, since in such cases logistic substitution cannot be preserved in all phases of the substitution process. Every competitor undergoes three distinct substitution phases: growth, saturation, and decline. This is illustrated by the substitution path of steam ships, which curves through a maximum from increasing to declining market shares (see Figure 14). In the model of the substitution process, we assume that only one competitor is in the saturation phase at any given time, that declining technologies fade away steadily at logistic rates, and that new competitors enter the market and grow at logistic rates. As a result, the saturating technology is left with the residual market shares (i.e., the difference between 1 and the sum of fractional market shares of all other competitors) and is forced to follow a

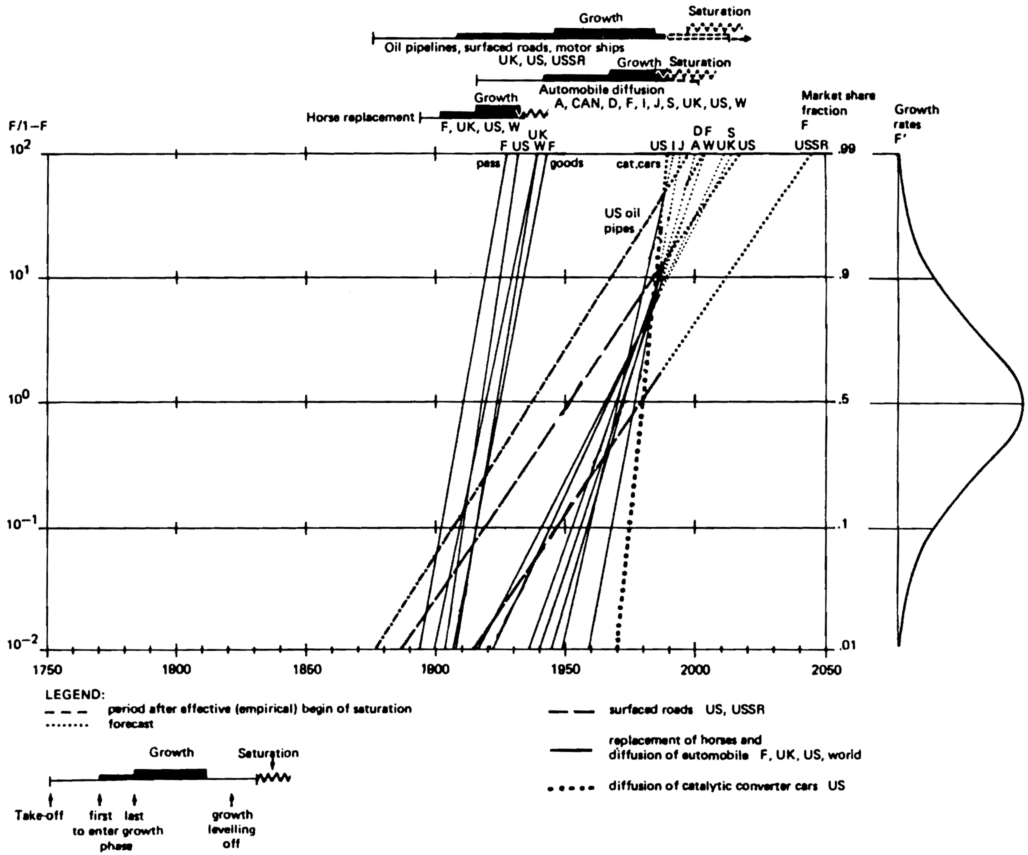

Figure 12. Replacement of Horses and Diffusion of Cars, Oil Pipelines and Paved Roads, World.

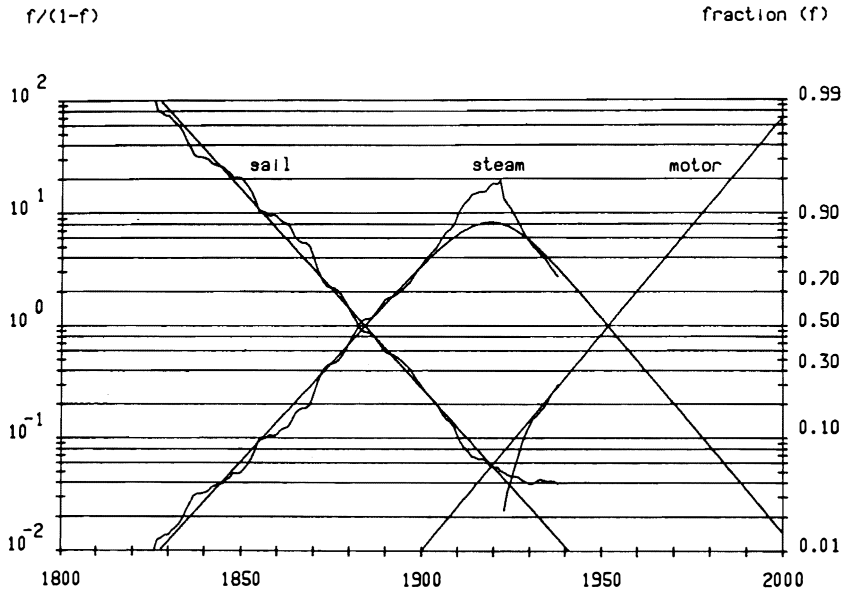

Figure 13. Substitution of Sailing, Steam and Motor Ships, U.K.

The next example in Figure 14 shows an even higher degree of complexity, that of the replacement process in five different steel production methods in (the Federal Republic of) Germany. Again, this is indicative of the technological changes in the steel industries of other countries, although the substitution processes in other countries are more regular. The process is rather irregular, with Δts varying from one steel production method to another. Nevertheless, there is a recurring pattern of structural discontinuities in the evolution of this system: saturation of the puddle steel production process around 1860, Bessemer and open hearth processes by the 1930's and the saturation of the basic oxygen process during the 1970's (Grübler, 1987). The sustained increase in the electric arc furnaces parallels the higher demand for recycled high quality steel.

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nonlogistic path that joins its period of growth to its subsequent period of decline. After the current, saturating competitor has reached a logistic rate of decline, the next oldest competitor enters its saturation phase, and the process is repeated until all but the most recent competitor are in decline. A more comprehensive description of the model and assumptions is given in Nakićenović (1979).

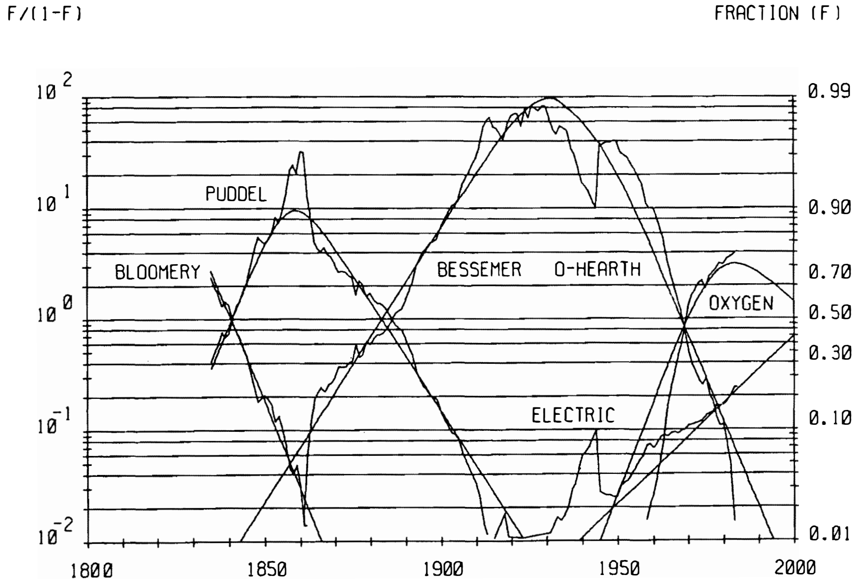

Figure 14. Substitution of Steel Production Methods, Germany (F.R.G.).

Figure 15 shows the substitution pattern in primary energy sources in the United States. Similar paths of technological change can be found in other countries, although the advantage of using the United States as the main example is that the historical records include consumption rates of older energy sources, such as fuelwood and the energy equivalent of the feed required by working animals. Energy substitution is portrayed by very long time constants with a Δt of about 90 years in the United States and 100 years at the global level. The saturation periods of each consecutive energy source in the substitution process are separated by about five decades and coincide with the upper turning points usually attributed to the Kondratieff long wave. The animal feed requirements saturate in the 1870's, coal around 1920, and oil around the time of the OPEC energy embargo of the early 1970's. Furthermore, during each of these three saturation periods a new energy source passes the 1% market share level: oil in the 1870's, natural gas in the 1920's, and nuclear energy during the 1970's. These periods coincide with the decades of extreme energy and oil price volatility noted in Figure 2.

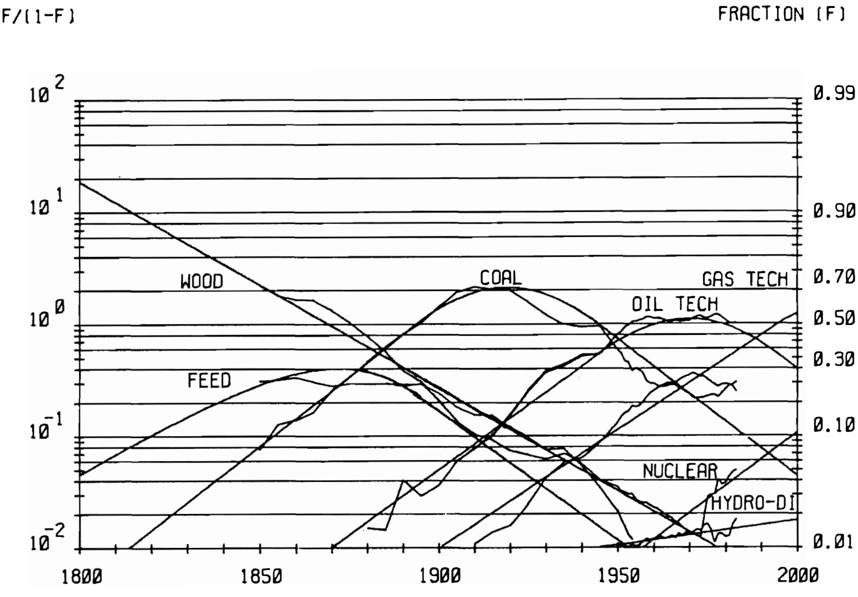

Figure 15. Substitution of Primary Energy Sources, U.S.

SEASONS OF SATURATION

Figure 16 shows a schematic representation of energy substitution paths, with the three saturation periods indicated in the figure. The upper curve shows three more conventional indicators of the long wave: fluctuations around the long term trend in wholesale prices, energy intensity (expressed as the ratio of primary energy supply divided by GNP), and the flares in energy prices referred to earlier. It should be noted that the four energy price flares each lasted about two decades and coincided with the saturation phases in energy substitution. This perhaps indicates the major disruptions and misadjustments that eventually lead to an increasing reliance on a new family of energy and other related systems.

Figure 17 shows a similar synchronization in the saturation phases of the three expansion pulses of transport infrastructures in the upper curve with the price flares underneath. The dashed curve labeled rate of change will be explained below. Both of these examples show a significant degree of synchronization in the diffusion of transport and energy systems with the fluctuations in price levels that

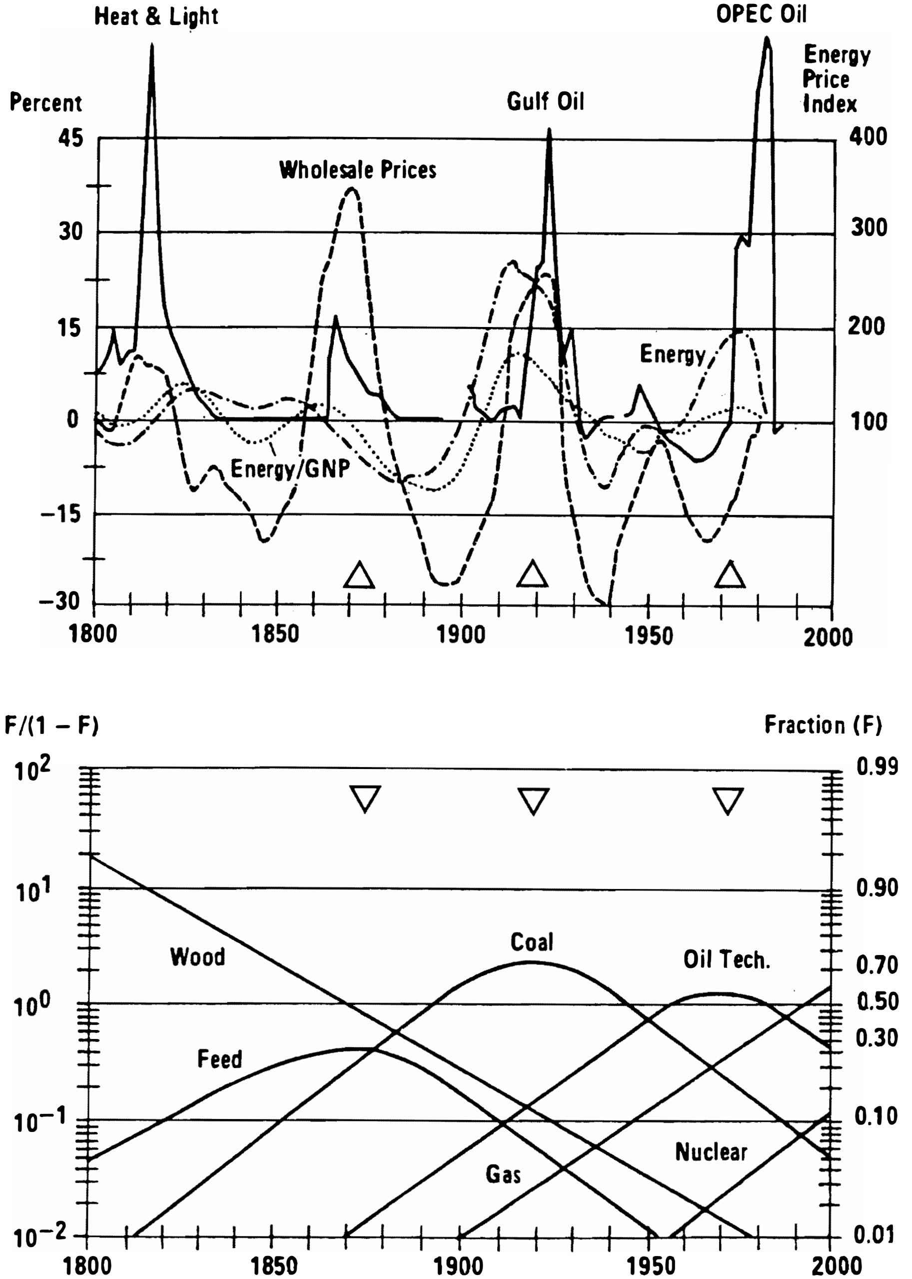

Figure 16. Energy Substitution Paths and Fluctuations in Prices and Energy Intensity, U.S.

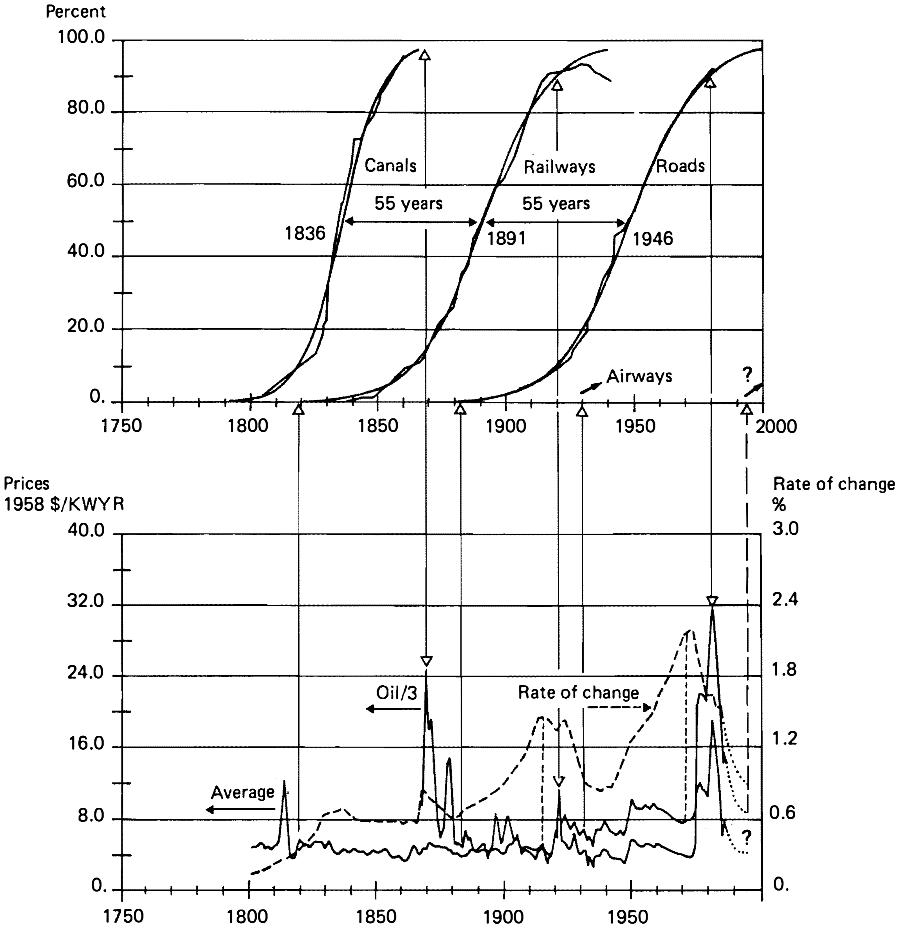

Figure 17. Growth of Transport Infrastructures and Fluctuations in Prices and Average Rate of Change, U.S.

have often been used to mark the turning points of the long waves. In our opinion this denotes major techno-economic paradigm shifts; the upswing phases are first potentiated by initial social acceptance of new technologies and institutions belonging to a given cluster, but they are driven by the subsequent pervasive and widespread diffusion.

CLUSTERS AND FAMILIES

In the introduction we argued that diffusion clusters can be documented internationally and not in just a few selected countries or sectors. Figure 18 summarizes our findings from the illustrative examples given above and other case studies. We have shown the international diffusion bandwagons of railways and automobiles, and they are also reproduced in Figure 18, together with the development of canals that peaked two centuries ago in a number of countries. Given below each area denoting a diffusion cluster is a list of the various growth processes that belong to it. As mentioned earlier, the focusing is not very pronounced, and there is a high degree of overlap among the various bandwagons due to differences in the time constants (Δt) among individual diffusion processes. Nevertheless, three rather clear clusters can be distinguished. The first saturates around 1865, the second around 1930, and the third is centered a few years away in 1995. Each cluster is converging toward the saturation period. The focusing increases as the diffusion cluster matures. In other words, the introduction of innovations is associated with great lags between the early and late adopters. However, the latecomers appear to achieve faster diffusion rates than the original innovators. We can speak of a pronounced catch-up effect that is convergent toward the saturation, indicating three distinct seasons of saturations that coincide with the Kondratieff upper turning points. The first one dates to the second half of the nineteenth century, indicating that technology diffusion was an international phenomenon even before the days of multinational corporations and technology transfer and before the advent of global communication.

We have observed some evidence, however, that the extent of the absolute diffusion level is much lower for the laggers toward the end of the cluster. The saturation density of railroad networks of a particular country is lower if the diffusion rate is higher. In

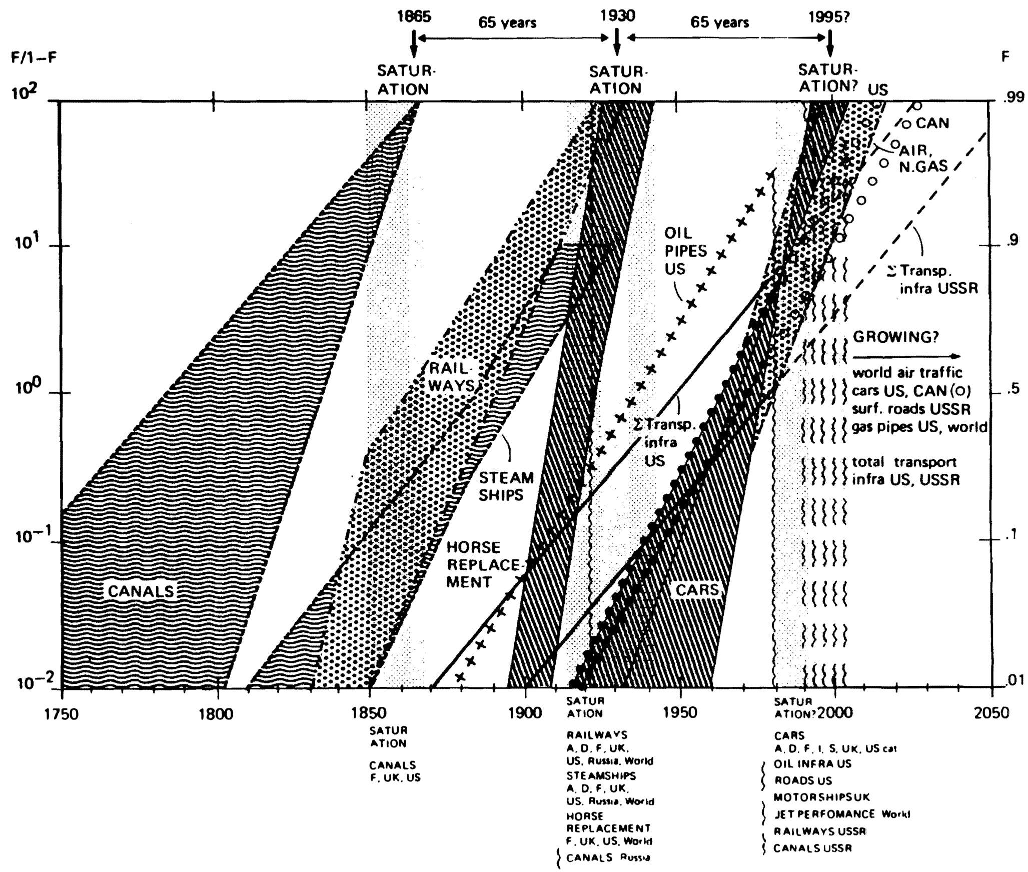

Figure 18. Three Clusters of Interrelated Diffusion Processes, World.

other words, the ultimately achieved railroad density is in general higher the earlier the railroads are introduced; leaders achieve the highest diffusion levels. We have observed the same phenomenon in the spread of motorization in different countries, the early innovators, such as the United States, have the highest per capita density, and the achieved density decreases in proportion to the lag in the automobile introduction in other countries.

In this sense each Kondratieff long wave portrays a barrier to diffusion. Most processes saturate during the end of the inflationary period and the onset of the disinvestment phase in the Kondratieff wave. Very few diffusion processes can tunnel through this barrier. If it is true that this marks the beginning of paradigm shifts, it is not surprising that the further diffusion of systems associated with the old techno-economic development trajectory is blocked to make way for the new. It is the disruptive crisis of the old that provides the fertile ground for new systems to develop.

Our working hypothesis is that the diffusion processes within each cluster constitute families of interrelated systems that enhance each other and promote the pervasiveness of each of the three successive diffusion clusters. In other words, each diffusion cluster is a network of interrelated families of socio-technical systems that reinforce and build upon each other. Classification or a taxonomy of each individual innovation, required to make the whole cluster viable, would probably reveal a hierarchical system with one successful diffusion having a positive feedback and catalytic effect on the development of many others within the whole cluster. In this sense clustering of these families is the inevitable and endogenous phenomenon resulting from the interdependent network structure. As pointed out by Schumpeter, the clustering is not coincidental. We contend that it is the interdependence of individual diffusion processes that in time also focuses each of the three clusters.[5]

One evidence for this assumption is the empirical distribution

[5] This would also explain the observation of innovation clustering during the lower turning point in the long wave (see Kleinknecht, 1989). It should be observed that only the successful innovations tend to develop in a cluster, while all innovations (including the failures, namely, those that do not lead to a diffusion process due to the lack of acceptance) need not cluster. In fact, most of the innovation studies deal with the successful ones, although they are presumably only a small fraction of all innovative activities.

of Δts. We have analyzed two samples of diffusion processes in the United States. Sample A is based on 117 case studies performed at IIASA, and sample B includes an additional 148 case studies taken from the literature, totaling 265 individual diffusion processes. The lists do not include only technological, process, and product innovations, but also some social diffusion processes, such as the spread of literacy. Figure 19 shows the histogram of diffusion rates measured by Δts. As can be seen, they range in duration up to 300 years. But there are very few processes that last longer than a century, and thus very few span more than two Kondratieffs. The mean value ranges between 40 and 60 years with a standard deviation of about equal magnitude. It should be noted that the largest number of diffusion processes last on the order of between 15 to 30 years, some of which we have given for illustrative purposes above (e.g., vehicle fleets or steel production methods). In general, Δts have a long-tailed distribution similar to Pareto or rank-size distributions.

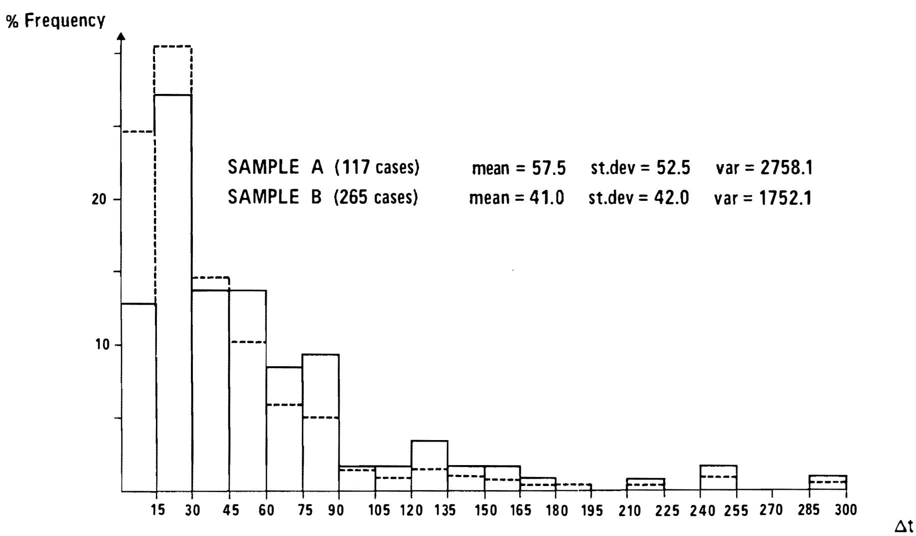

Figure 19. Histogram of Diffusion Rates for Two Different Samples, U.S.

The histogram gives one kind of summary about the distribution of diffusion process. Another possible aggregate measure is the average rate of diffusion for the whole economy. This indicator would be comparable to the growth rate of the Gross National Product. The average diffusion rate measures the pace of change in an economy. Figure 20 illustrates how the aggregate measure is derived. One possibility is to sum up the diffusion rates in a given sample of diffusions. The plot on the top of the figure gives two possible (idealized) diffusion processes that converge toward saturation, and the middle plot gives their diffusion rates (slopes). The lower plot illustrates the shape of the sum of the two diffusion rates and the dotted curve their average diffusion rates.

Figure 21 gives the aggregate diffusion rates of sample A with 117 diffusion processes. It portrays clear peaks and troughs, while the longer-term trend indicates an increase in aggregate level of diffusion. This could, however, be the artifact of the sample. There are simply more diffusion processes documented for the last hundred than the previous hundred years. Although we are taking averages, the higher number of overlapping processes in one interval could result in a higher aggregate diffusion rate. Each peak characterizes the beginning of the saturation of the corresponding cluster or family of diffusion processes. The reason why the curve tapers off on the right of the plot (after the present time) is that some diffusion processes with very long Δts could be assumed to continue in the future. Presumably, many innovations have emerged during the last decades that may turn out to be successful, and if they were included perhaps we could expect a trend reversal in the rate-of-change curve sometime after the mid-1990's. The turning points in the evolution of this new empirical measure of the long-term rate of change are consistent with some of the turning points identified by a number of long wave researchers (e.g., van Duijn, 1983; Goldstein 1988; Marchetti, 1983; Nakićenović, 1984; and Vasko, 1987).

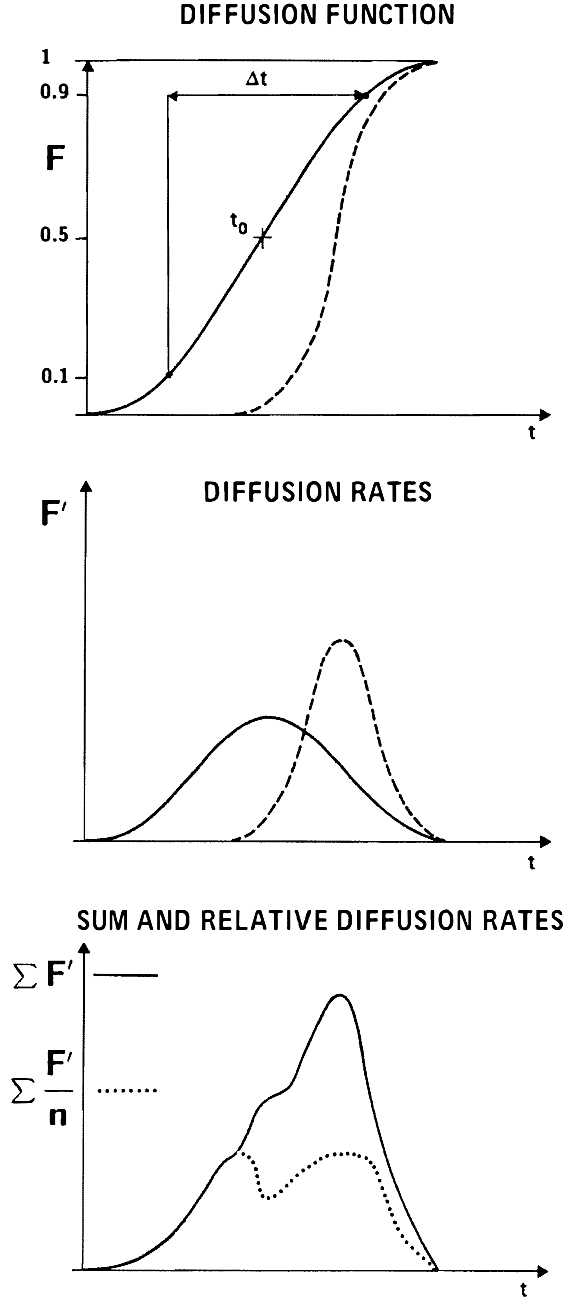

Figure 20. Aggregate Measures of Diffusion Rates.

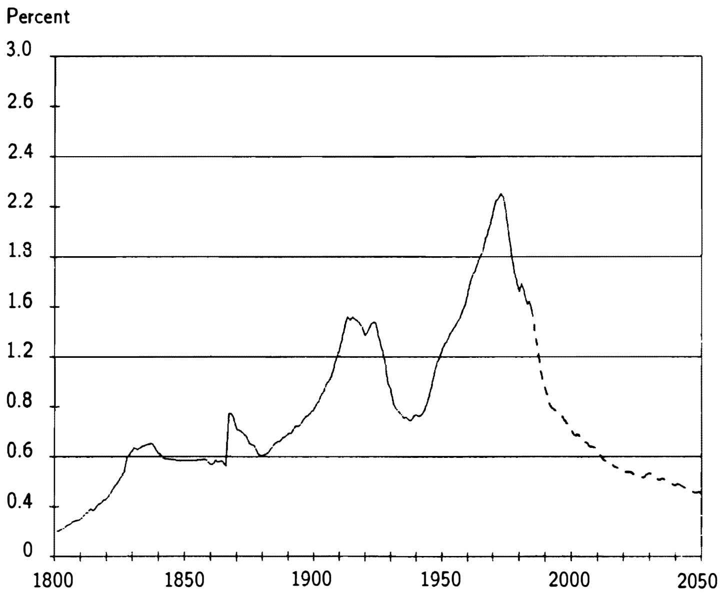

Figure 21. Average Diffusion Rates (percent), U.S.

CONCLUSIONS

The patterns of technological change and diffusion of innovations appear to be consistent with the hypothesis of long waves in economic development. We have noted a certain degree of regularity, correlation, and recurrence within each family of interrelated technologies, although the clustering or bundling is not very rigid. There is stronger evidence for the synchronization in the saturation of diffusion processes rather than in their emergence, so that the focusing increases as the systems mature. In other words, the time span between the beginning of the diffusion of new pervasive systems, that is, between the leaders and the laggers, tends to decrease as the diffusion progresses, so that the process appears much more focused toward the saturation phase. This visible catch-up effect refers only to the relative diffusion rates and not to the absolute levels of diffusion. The leaders usually achieve higher diffusion levels and the followers levels that are lower roughly in proportion to the lag in the introduction of a given innovation.

The results, however, cannot be conclusive before explicit linkages are established between the individual diffusion processes that constitute each of the three described clusters of techno-economic development. A taxonomy and establishment of hierarchies within each cluster could be a fruitful route toward determining the relationships and driving forces behind the clustering effect observed in our samples of innovation diffusions. This could perhaps answer some of the questions that emerge from the analysis. For example, why are the clusters more focused towards what we called the Kondratieff barrier? Alternatively, under which conditions could unbundling occur and perhaps lead to a more even pace of structural change? The overall development trajectory is punctuated by crises that emerge in the transition from an old saturating cluster to a new but uncertain development path, but this may simply be an inherent feature of the evolutionary processes that govern social behavior.

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