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Regularities in Technological Development: An Environmental View

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Forward, forward let us range;
Let the great world spin forever down
the ringing grooves of change.

Tennyson, "Locksley Hall," 1842

Accept for the moment that there are long-term regularities in technological development. Suppose that the evolution and use of both individual technologies and entire technological systems are sometimes tightly consistent and predictable over decades and generations. Then, we can know with confidence some important sources of future stress on the environment and, equally, what technologically based stresses may fade, largely through natural advancement of the industrial economy. The thesis of this chapter is that, in fact, there are such long-term regularities in technological development and that these deserve more attention for the important implications they have for environmental concerns.

Let me draw you back a century to a forgotten episode of environmental history. The photographs in Figure 1 show the key material in terms of bulk in the massive expansion of the railroads in the nineteenth century. It is not widely remembered that railroads, usually associated in our minds with coal and iron, were largely wooden systems in their early development. The "iron horse" was something of a misnomer. Fuel for locomotives was

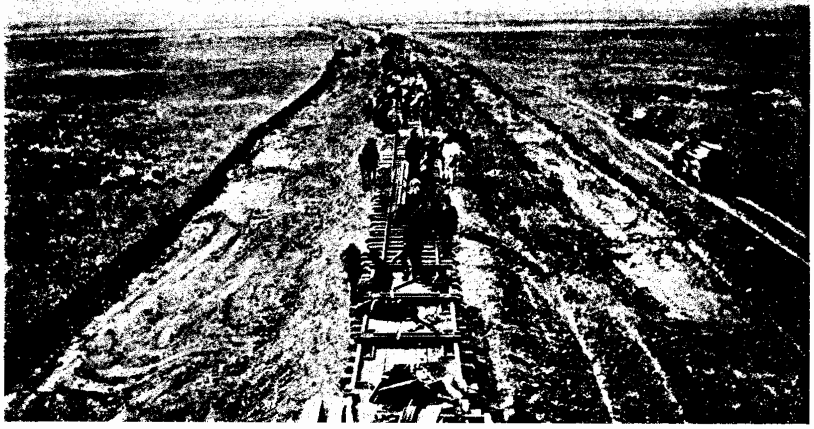


FIGURE 1 *Above*: track being laid in 1887 across the vast Montana Territory; *below*: close-up of track laying. Records of 8 miles per day were set by using huge volumes of wood, large labor forces, horses, and wagons. SOURCE: Burlington Northern Railroad Company.

wood, cars were wood, some of the rails were wood, trestles were wood and most important, crossties were wood. About the turn of the century President Theodore Roosevelt spoke as follows:

> Unless the vast forests of the United States can be made ready to meet the vast demands which this [economic] growth will inevitably bring, commercial disaster, that means disaster to the whole country, is inevitable. The railroads must have ties. . . . If the present rate of forest destruction is allowed to continue, with nothing to offset it, a timber famine in the future is inevitable.
>
> Speech to the American Forest Congress, 1905 (quoted in Olson, 1971, p. 1)

An industry leader in 1906 described the railroads as the "insatiable juggernaut of the vegetable world" (Olson, 1971). Such images were echoed in Argentina, India, the Middle East, and parts of Europe as railway networks were extended at the expense of local forests. In the United States, prevention of destruction of forests was proposed through a range of both supply and demand strategies. It was proposed to cover Kansas with a catalpa forest dedicated to supplying crossties. Railroad companies were asked to plant trees along the rail right-of-way to have a renewable stock of timber for ties. Better management of remaining forests was seen as urgent; in fact, the Forest Service was in large part built under Gifford Pinchot in this era in response to the railroad-induced crisis.

What eventually contributed most to averting the forecast crisis were, initially, creosote and other technologies for preserving crossties and, later, especially in Europe, replacement of wood by concrete ties. As is evident from Figure 2, around the time of the peak of the perceived crisis, a technological solution was already penetrating the market for crossties. Preservation technologies tripled the life of ties, and within a couple of decades, the juggernaut of the vegetable world was satiated. In fact, in the 1920s the railroad network itself reached saturation (see Figure 5), so that demand for both new and replacement ties decreased. Railroads today are almost always described as environmentally benign. So, in the railroad timber story, new technologies are both cause and cure of environmental problems. The new transportation system placed intense demand on natural resources, and innovations in turn alleviated the demand to the extent that today the issue is obscure or forgotten.

At this point it is necessary to make a brief methodological comment. A premise of this chapter is that, as suggested by Figures 3 and 4, sociotechnical systems, like biological systems, often grow according to basic patterns well-described by S-shaped curves, in particular, logistic functions (Hamblin et al., 1973; Lotka, 1956; Montroll and Goel, 1971; Volterra, 1927). In the simplest case, technologies, like biological organisms in constrained environments, proceed through a life cycle of early development through rapid growth and expansion to saturation or senescence. Often two technologies are in competition for an "econiche," that is, the market; then a logistic

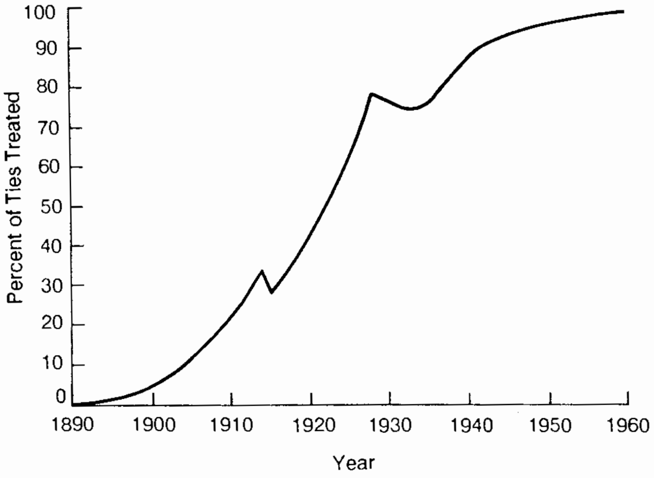


FIGURE 2 Percentage of crossties manufactured in the United States treated with chemical preservatives. It is interesting to note that the innovation penetrated the market in a characteristic S-shaped curve, disturbed only temporarily by world war and depression. SOURCE: After Olson (1971).

substitution model applies where a new technology replaces the old and the status of the system is described by the changing fraction or share of the market held by the technologies (Fisher and Pry, 1971). When more than two technologies are competing for a market, a generalized version of the logistic substitution model can be used (Marchetti and Nakicenovic, 1979; Nakicenovic, 1988, pp. 212–220).[1] Logistic functions and logistic substitution models are a compact way of presenting data on the history of technology and are used frequently in the following sections of this chapter. However, numerous methods exist to explore quantitatively the existence of patterns in sociotechnical phenomena (Montroll and Badger, 1974), and the method used most frequently here should be taken simply as indicative of the value of extending the search for regularities by using a variety of methods.

Some examples make the case for long-term regularities and also point out hazards in identifying them. Figure 5 shows the remarkably stable and parallel growth of three major systems of transport infrastructure in the United States: canals, railroads, and paved roads. For each of these transport infrastructures it would apparently have been possible relatively early in the life history of the system to make quite an accurate prediction about its eventual size and scope. Such vision in turn may be translated into conjectures about environmental problems and technological opportunities, indeed about technological necessity. For example, it could have been

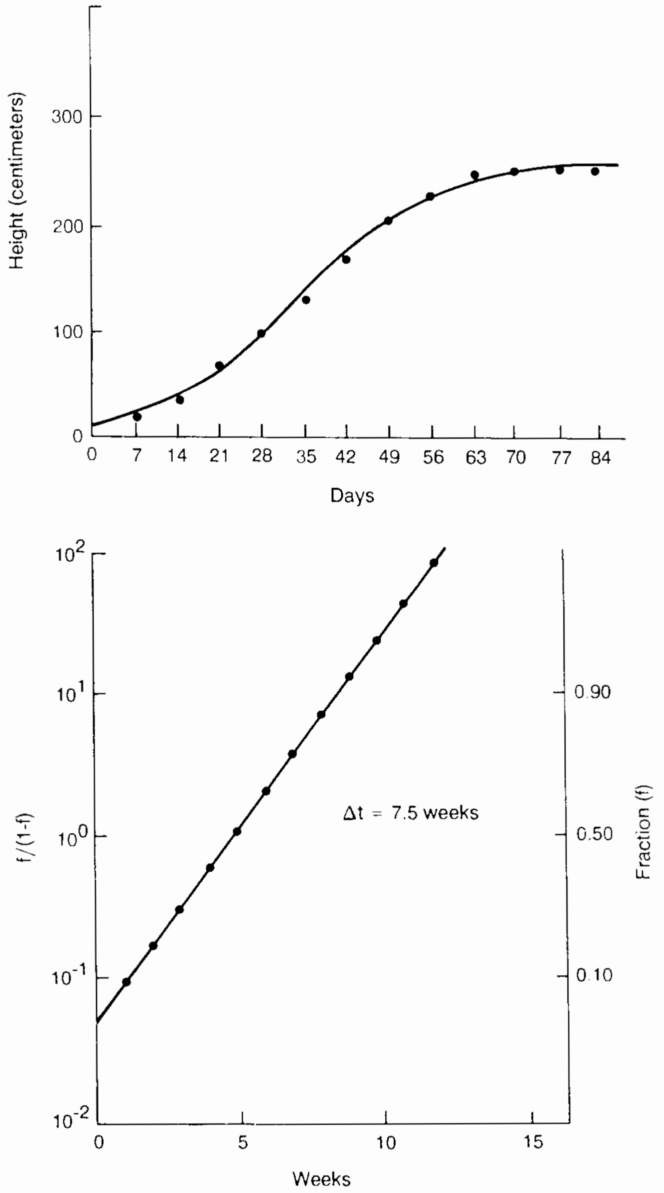


FIGURE 3 The upper panel shows the growth of a sunflower, measured in height, precisely charting a logistic curve (Reed and Holland, 1919). The lower panel shows the same data in linear transform, which is sometimes easier to employ for visual inspection and emphasizes the predictability of the process once established. For example, the ultimate height of about 260 centimeters could be estimated quickly with the linear transform. The "Δ *t*" refers to the time for the process to go from 10 to 90 percent completion, in this case 7.5 weeks (see Lotka, 1956; Marchetti, 1983).

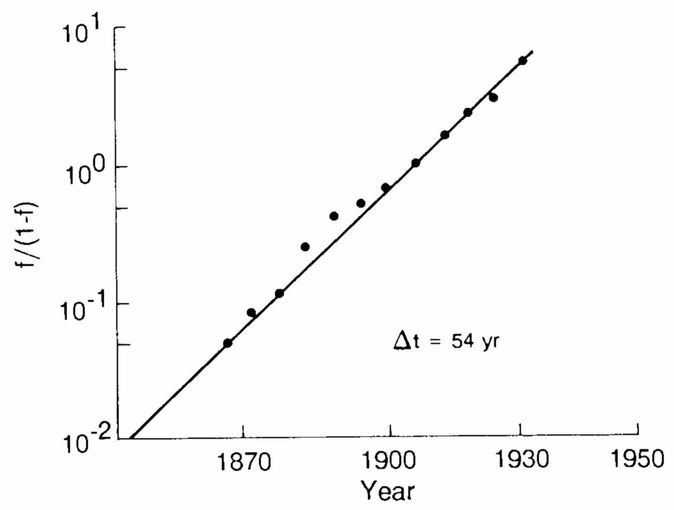


FIGURE 4 Growth of the length of wire for the U.S. telegraph system. Notwithstanding the battles involving Western Union and its predecessors and competitors, and all the associated economic and regulatory issues, the telegraph system spread its branches just as a sunflower plant grows. It is also interesting to note that the time the system required to reach its full extent (Δ t) was slightly more than 50 years. SOURCE: Marchetti (1988).

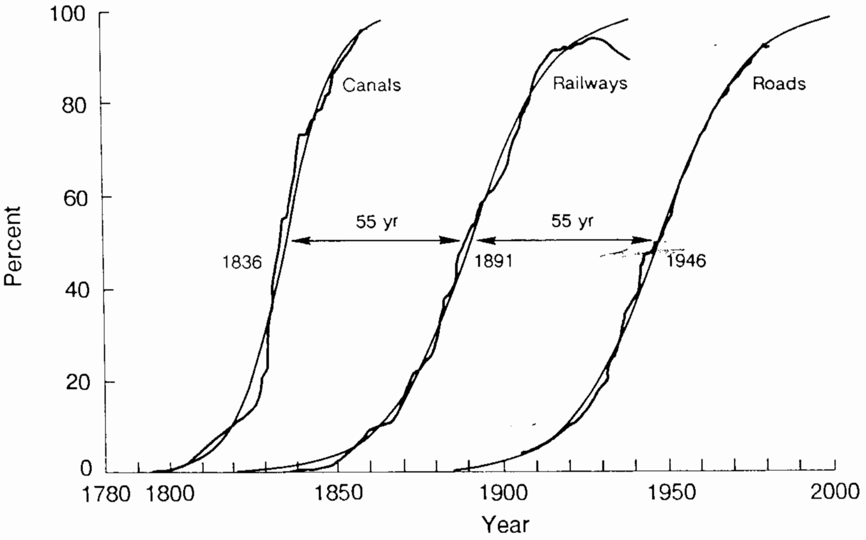


FIGURE 5 Growth of major transport infrastructures in the United States in terms of percentage of length of final saturation level. Both actual data and best-fit logistic curve are shown. The midpoint of the growth process is also shown. SOURCE: Grübler (1988).

TABLE 1 Vehicular Pollution

Means of Transport	Pollutant	Emissions (grams per mile)
Horses	Waste, solid[a]	640
	Waste, liquid[b]	300
Automobiles[c]		
	Hydrocarbons	0.25
	CO	4.7
	NO_x	0.4

[a] Calculation based on an average production of 16 kg of solid waste per day and a range of 25 miles per day.
[b] Calculation based on an average production of 7.5 kg of liquid waste per day and a range of 25 miles per day.
[c] 1980 U.S. piston engine standards.

clear early on that a rail system of predictable dimensions would be unsustainable as a predominantly wooden technology and required innovations in materials and other areas to reach forecast dimensions. Agendas for research and for entrepreneurship might have stemmed from this analysis.

A similar argument can be made about the system of paved roads. This system was initially designed for horses and horse-drawn vehicles, preceding the widespread use of the automobile. From an environmental perspective, a road system of the dimensions that began to be built could have been catastrophic if the traffic were horses. Table 1, based on calculations made by Montroll and Badger (1974), shows that, from an environmental point of view, cars were a marvelous technological innovation, at least when they were not much more numerous than horses.

Figure 6, showing the substitution of cars for horses, emphasizes the continuity of the demand for personal transportation service and the fact that technologies or modes compete to meet such demand. When considering the intensity of problems of urban air pollution in places such as Denver, Los Angeles, and Mexico City, the time may be at hand when an improvement almost as radical as that of substituting cars for horses is needed to accommodate growth in transportation demand. It is sometimes suggested that methanol fuel or electric cars will do the trick, but methanol has few obvious advantages over gasoline used in conjunction with a catalytic converter, and a versatile and wide-ranging electric car may not be available for decades. Methane and hydrogen cars are already technologically feasible and could meet stringent new environmental constraints, but they demand

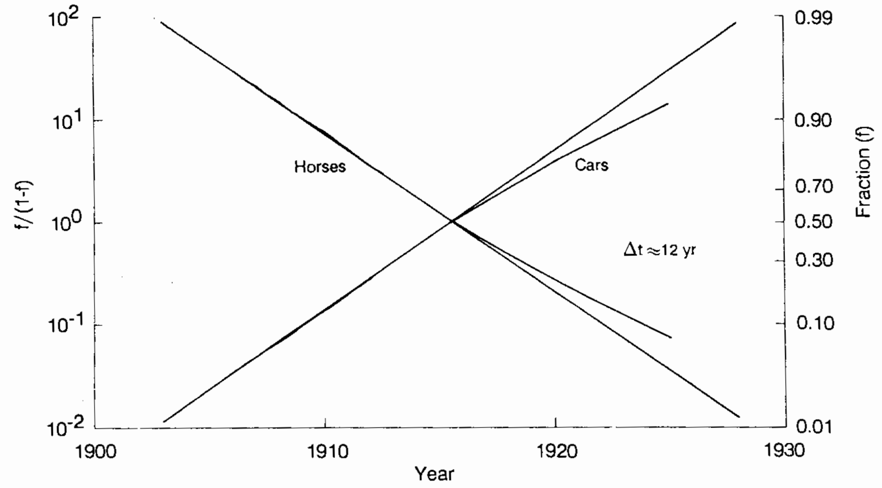


FIGURE 6 Replacement of horses by automobiles in the United States. Irregular lines are historical data; smooth lines are best fit and extrapolation. SOURCE: Nakicenovic (1988).

emergence of a substantial infrastructure of supporting service that so far is not evident. Will a breakthrough come and, if so, when?

The abrupt replacement of horses by cars shows one of the shortcomings of the type of framework presented here, namely, the difficulty of anticipating system bifurcations and fluctuations. Although the growth of overall demand for transportation as represented by horses or cars between 1900 and 1930 appears consistent in Figure 6, within 20–30 years a radical change occurred in the way that demand was met. Diesel technologies conquered steam with equal rapidity, and jets replaced propeller aircraft in about the same time. Could the timing of the introduction of such new technologies have been foreseen on the basis of a sound and transferable logic? How many in policy positions in government or industry would have believed that transformations of the transport system could occur so rapidly? Many might have recognized in 1900 that the horse-powered system was environmentally unsustainable and foreseen the concomitant need for technological solutions. I suspect that these solutions would more commonly have been believed to be incremental, for example, the breeding of horses that would be more powerful for their size (more fuel efficient) or somehow generate less waste.

It is also interesting to note long-term regularities within the automobile system, where technologies specifically employed for environmental improvement have followed typical patterns of substitution and diffusion. Figure 7 shows the adoption of emission-reducing technologies and then

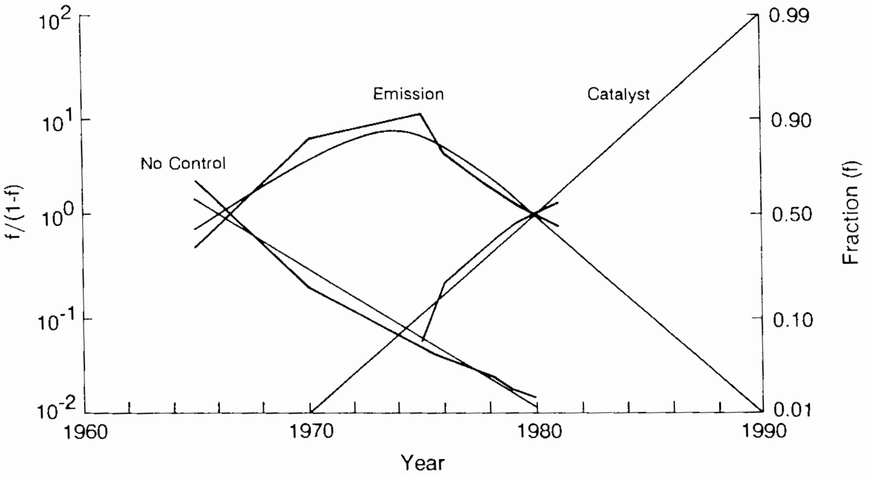


FIGURE 7 Substitution of emission controls in the U.S. vehicle fleet. The category "emission" refers to crankcase, exhaust, and fuel evaporation controls. SOURCE: Nakicenovic (1985).

catalytic converters. Identification of historically characteristic rates of such substitutions might help in setting feasible targets for future fleet improvements.

More examples of the implications of long-term regularities in technology for environment are found in examination of the transport system in its entirety (see Figure 8). If the road system is considered, it seems clear from Figure 8 (and Figure 5) that the challenge over the next many decades is maintenance and repair of a large, mature system. The road system is in fact fully grown and decreasing as a proportion of the length of the total transport system. However, we just seem to be coming to grips with environmentally sound operation and maintenance of the system that has been built. For example, with current practices and technology, the amounts of salts (close to 400 pounds per capita in the United States in 1980; Hibbard, 1986) and other chemicals that might be used for the next 50 or 100 years to keep the system ice-free are staggering. Their accumulations almost certainly pose worrisome problems for soils and water. Under the auspices of the Strategic Highway Research Program of the National Research Council (1988), technological alternatives are beginning to be explored. Accumulations of chemicals connected either with fuels that will wash off the roads or with the wearing out of tires (see Ayres, this volume) might be another issue that is now being underestimated.

Conjectures can also be offered about pressures on environment from the air transport sector. Since concerns faded in the early 1970s about

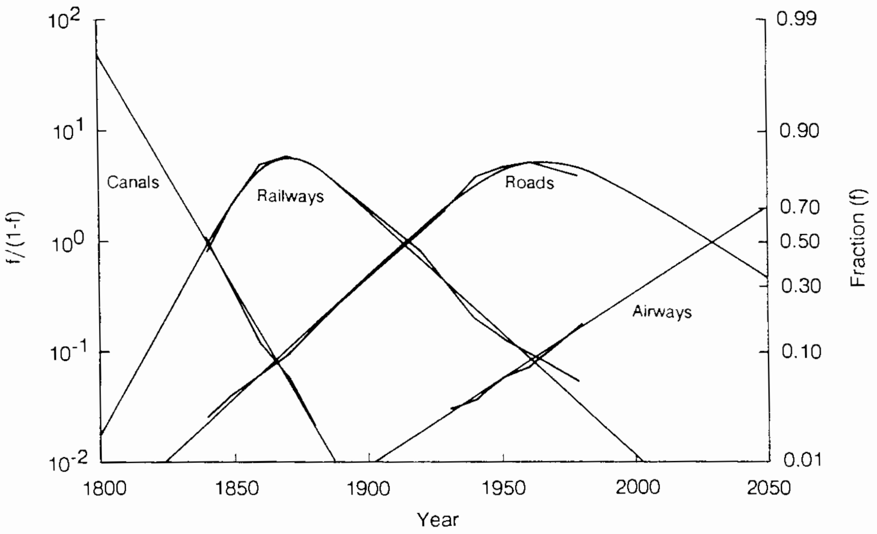


FIGURE 8 Shares of total operated intercity route mileage of competing transport infrastructures. SOURCE: Nakicenovic (1988).

stratospheric effects of fleets of supersonic transport planes (SSTs), little attention has been paid to environmental aspects of aviation. Noting the tremendous growth projected for the air transport system, one may wonder if concerns lie ahead, either in the stratosphere with a large fleet of second-generation SSTs or perhaps in a more straightforward manner in the troposphere. Could tropospheric ozone be significantly enhanced if growing emissions of nitrogen oxides (NO_x) by aircraft are considered? Changes might be looked for in the main travel altitude region near 10 kilometers, especially in the northern hemisphere where most air traffic occurs (Bruehl and Crutzen, 1988).

The long-term regularities identifiable in adoption of transportation technologies are paralleled in the closely related energy sector. To a considerable extent, the history of environmental and safety issues is simply the underside of the history of energy development (and agriculture). On an urban scale, 700 years of this history are recounted in *The Big Smoke* (Brimblecombe, 1987), which chronicles London air pollution since the Middle Ages and describes how improvements in technologies for burning wood and coal and for ventilation helped population density to increase and morbidity to decline.

In energy, as in transport, what is most striking is the overall consistency and stability of the evolution of the technologies favored, as illustrated in Figure 9, which shows consumption of hydrocarbon fuels—wood, coal, oil,

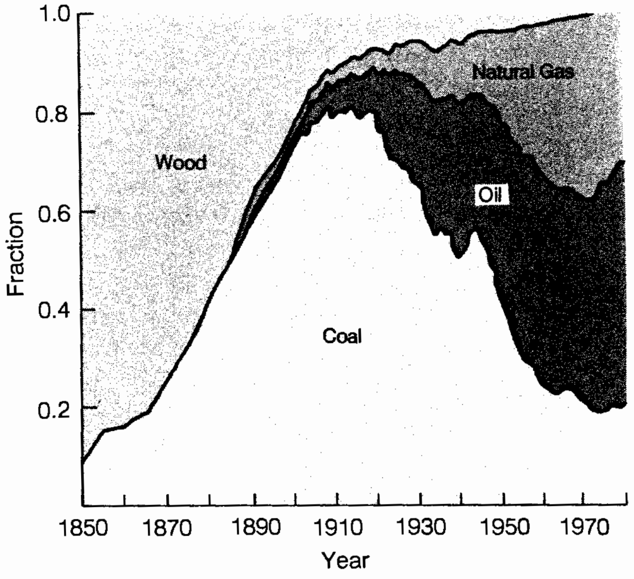


FIGURE 9 Hydrocarbon fuel consumption in the United States, fraction by fuel type, 1850–1980. SOURCE: National Research Council (1986).

and gas—for the United States in terms of market shares going back to 1850. The pattern carries with it a great deal of environmental history, for example, the deforestation that came with large-scale use of wood. Also implicit are the rise of sulfur emissions, which reached a peak in the 1920s at the apex of the coal era, and the rise of NO_x emissions associated in large part with oil and the use of the automobile.

If the historical data are employed in a logistic substitution model of the kind mentioned earlier, projections of future market shares emerge (Figure 10). In this model, natural gas soon becomes the leading source of primary energy. Increasing reliance on natural gas would be a most interesting development from an environmental perspective, significantly alleviating acid rain problems. It would substantially lessen, but not eliminate, concerns about the greenhouse effect as well (Ausubel et al., 1988). Broadly speaking, we need to think about opportunities for the improvement of environmental quality offered by the possibility, indeed the likelihood, of a large role for natural gas.

At a more abstract level, one of the most interesting and best-established trends in the energy area is the substitution of hydrogen for carbon in the chemical soup that has been used to generate most energy for the past 150 years. If wood, coal, oil, and gas are all examined simply as mixtures of carbon and hydrogen atoms, then, as Figure 11 shows, global

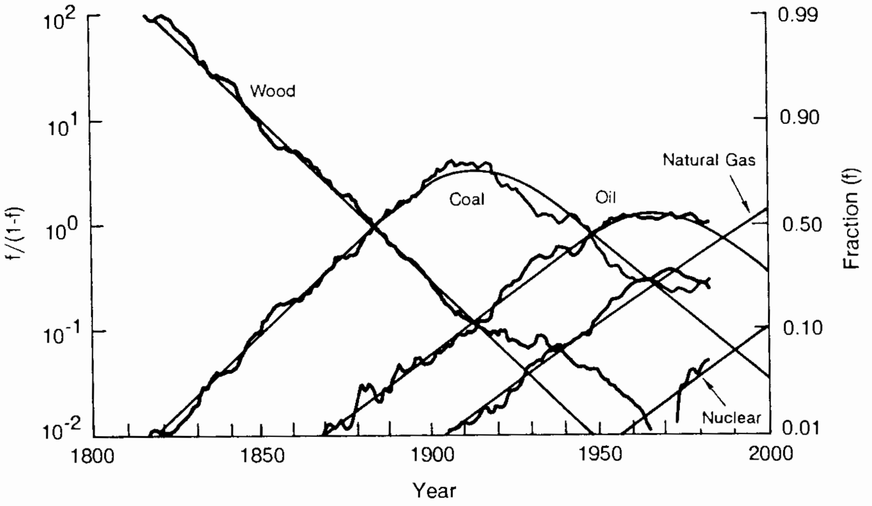


FIGURE 10 Primary energy substitution in the United States, expressed as "market share" according to the logistic substitution model, 1820–2000. The natural gas curve refers to gas resources not associated with oil exploration. SOURCE: Grübler and Nakicenovic (1988).

society has been moving steadily toward an economy running on natural gas and eventually on hydrogen. As discussed by Lee (this volume), the opportunities to evolve in the next decades beyond hydrocarbon fuels appear timely.

So far no reference has been made to "long waves," the cycles of about 50 years that seem to have characterized the world economy for the past 200 years (Freeman et al., 1982; Grübler, 1988; Nakicenovic, 1984; Schumpeter, 1939; Van Duijn, 1983). There is much disagreement about the strength of the signal that emerges in analyses of long time series of data of technological and economic phenomena that may be indicative of long waves. Figure 5 does show that a sequence of major transport infrastructures emerged at roughly 50-year intervals. Figure 9 shows that the characteristic time required for a major energy technology to capture or lose a leading role in the energy marketplace is also about 50 years. Synchronization of the diffusion of several major technologies would logically lead to periods of especially aggressive transformation of the environment and equally to "seasons of saturation" (Grübler, 1988), when environmental management might revolve more around accommodating mature systems (such as the interstate highway system).

Analysis of the evolution of energy demand shows two pulses of growth, each lasting 40 years or more (Ausubel et al., 1988; Stewart, 1988). Figure 12, which shows these pulses, may be seen as a pair of logistic curves, the second surmounting the first. From an environmental point of view,

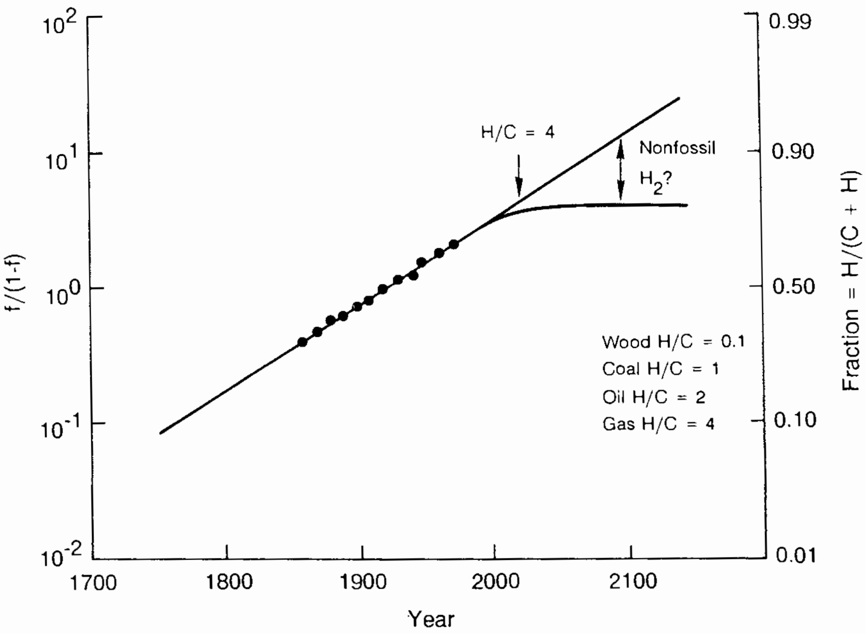


FIGURE 11 Evolution of the ratio of hydrogen (H) to carbon (C) in the world fuel mix. The figure for wood refers to dry wood suitable for energy production. If the progression is to continue beyond methane, production of large amounts of hydrogen fuel without fossil energy is required (see Marchetti, 1985).

several conjectures are worthwhile. One is that it may be possible to match each pulse with a dominant energy supply technology, coal in the first case and oil in the second. During each pulse of growth, this form of energy supply may reach environmental constraints (and other constraints as well) that limit the overall growth of the energy system. In other words, a characteristic density may be all that is achievable or socially tolerable for each form of energy within the context of a larger industrial paradigm in which that form of energy dominates. To accommodate a further increase in per capita energy consumption, a society must shift each time to a form of primary energy that is not only economically sound, but also cleaner and in some ways more efficient, especially in terms of transport and storage.

At a high hierarchical level, the cycle-adjusted view suggests that there are periods when the main orientation of the system is not so much growth as consolidation, with strong emphasis on squeezing more efficiency out of the system (a collection of technologies). At other times, the system seeks to expand rapidly and relies on introduction and diffusion of new technologies that may be "inefficient" when introduced.

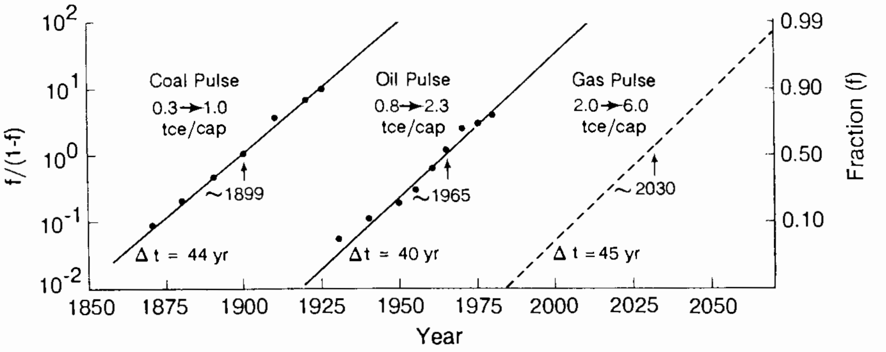


FIGURE 12 Growth pulses in world per capita energy consumption measured in tons of coal equivalent (tce). If historical discontinuities in per capita energy consumption persist, a new pulse of growth in world energy use would be expected to take off about the year 2000, which would triple per capita energy consumption from today's average world level of about 2 tce to about 6 tce (roughly half the current U.S. level). SOURCE: Ausubel et al. (1988).

It appears that we are nearing the trough of a demand cycle now. If strong demand for energy growth does not resume for another 7–10 years, as implied by the long-wave perspective, then improved energy efficiency looks like the most important near-term energy strategy, along with preparing the way for natural gas to accommodate another growth pulse (see Lee, this volume). This perspective also implies that the United States and other industrialized countries, almost all of which have sufficient capacity for electricity generation and other energy carriers in the near term, will face before the turn of the century a potential leap in energy consumption, not the steady state or low-growth world that many environmental advocates would like to see persist. To meet renewed rapid growth in demand in an environmentally sound way, gas must almost inevitably take the leading role, probably supported in particular niches by nuclear power.

It is useful to ask whether energy efficiency is always consonant with environmental improvement. At the level of particular functions such as lighting or refrigeration, it is clear that many engineering systems, indeed probably many biological systems, tend to follow steady trajectories over long periods of time toward higher efficiency (Figure 13). In most cases it may be supposed that increasing energy efficiency will also be environmentally beneficial. A counterexample is electricity. Its use is less efficient than more direct use of alternatives such as natural gas, oil, and even coal and yet is often environmentally preferred. Another counterexample, the lean-burn (Otto-cycle) engine, produces less carbon monoxide but much more NO_x than a less efficient engine with a catalytic converter, which

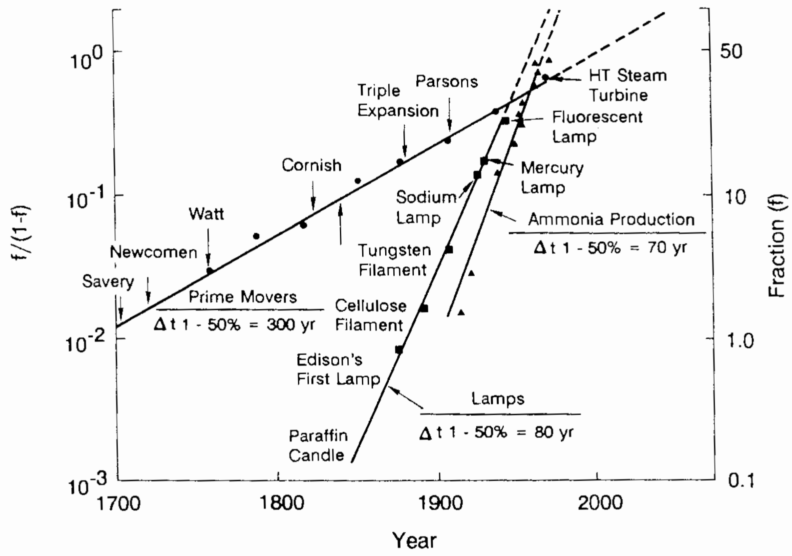


FIGURE 13 Examples of increasing energy efficiency. Prime movers, lamps, and ammonia production are measured as machines or processes for energy transformation according to the second law of thermodynamics. Original analyses are by L. M. Slesser, University of Strathclyde, Scotland. SOURCE: Marchetti (1983).

is currently more environmentally attractive at the cost of efficiency. Although the overall long-term evolution of energy systems appears to be in the direction of both efficiency and environmental compatibility, at various levels and times the system may not be optimizing for both of these objectives or they may be in conflict.

From transportation and energy, let us turn to materials, which figure prominently in the chapters by Herman et al. and by Ayres in this volume. Simple extrapolations of the kind used above have often been troublesome and unsuccessful as aids in projecting consumption of materials. As shown in Figure 14, past projections of demand for certain key materials remind us why studies such as those of Meadows et al. (1972) in the early 1970s foresaw extremely severe problems of both exhaustion of mineral resources and pollution associated with mineral use.

What happened to create the gap between the extrapolated trends and reality? Systems prove to be bounded in a variety of ways, so that exponential growth does not persist indefinitely. In the case of materials, several factors have been at work, including economic growth rates, shifts in the composition of economies from manufacturing to services, and resource-saving technologies. But most important may be smart engineering that made feasible the substitution of plastics, composites, ceramics, and optical

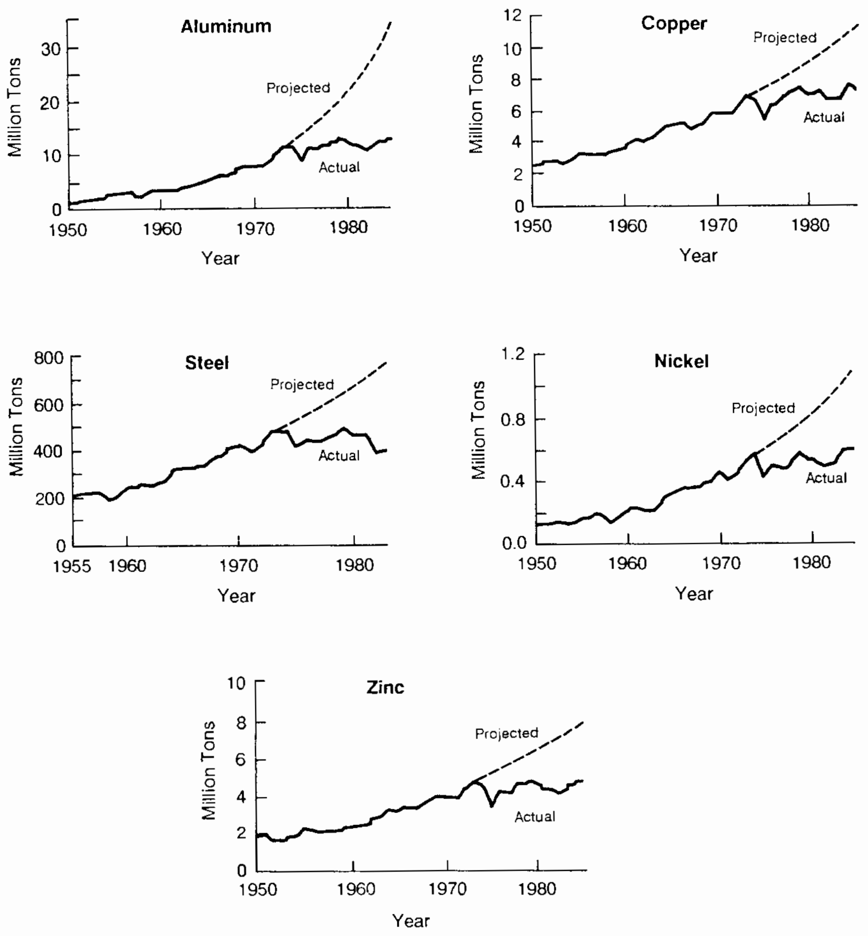


FIGURE 14 Actual materials consumption for five metals, 1950–1985, and projections made in 1970 for 1970–1985. SOURCE: Tilton (1987).

materials for metals, that is, the continuing replacement of metals with nonmetals and the associated overall decrease in metal needs.

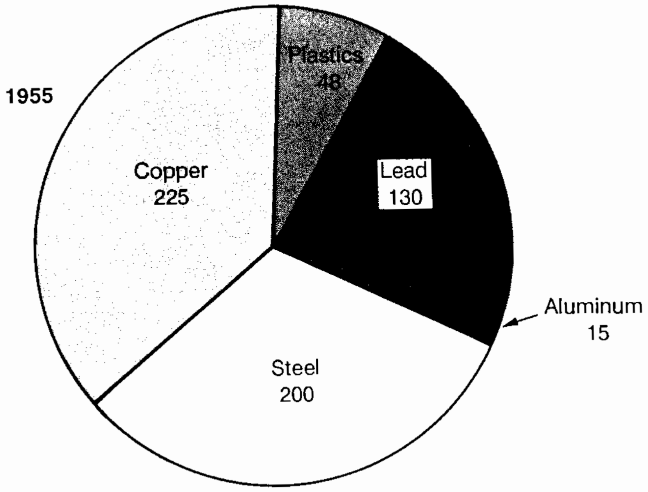
The telecommunications sector provides a vivid example (Figure 15). In 1955, telecommunications cables were made almost entirely of copper, steel, and lead. By 1984, close to 40 percent of the materials used were plastics. If substitution of lead by polyethylene for cable sheathing had not taken place, consumption of lead by AT&T alone might have reached a billion pounds per year, an amount to create considerable anxiety from the point of view of environment, given the toxic properties of lead. Herman et al. (this volume) have examined the possible "dematerialization" of the automobile. In considerable part, the phenomenon again has to do with the substitution of plastics for metals, as implied by Figure 16.

Overall, there appears to be a decreasing dependence on common metals, perhaps combined with greater need for less common metals (Hibbard, 1986). There is also growing use of metals in the form of composites, coatings, films, and artificial structures. As Ayres (this volume) suggests, use of metals in such areas as electronics may dissipate more broadly and rapidly because many of the uses are highly dispersed and thus also entail greater complexity in recycling.

The difficulty is that good data are not readily available, and may not exist, to back up such generalizations firmly. In 1976 Goeller and Weinberg sought to develop baseline information for what they termed the "age of substitutability." One of the notions they introduced was that of "demandite," the average nonrenewable resource used by human society. They defined demandite by taking the total extraction in moles of elements such as copper and iron and selected compounds (e.g., hydrocarbons) and computing the average hypothetical chemical composition of one demandite molecule (or average mole percent composition). Goeller and Weinberg excluded renewable resources, such as agricultural products, wood, and water, from demandite but looked at them in another portion of their study.

Table 2 shows the result for the United States and for the world, for 1968, the most current year for which Goeller and Weinberg were able to perform the calculation in the mid-1970s. The dominance of hydrocarbon is striking. It is interesting that in 1968 the United States had a more favorable hydrogen-to-carbon ratio than the world as a whole, partly offsetting from an environmental perspective the fact that U.S. energy consumption is so high. Broadly speaking, the need is apparent for developing and applying concepts like "demandite" on a regular basis. With steady monitoring, such approaches might serve as indicators that would alert us to substitution processes, improving projections and reducing the likelihood of the kind of erroneous projections shown in Figure 14.

At a specific level, it is evident that, just as some environmental concerns about metals use may be decreasing, more attention must be given to plastics and paper, as also argued by Herman et al. (this volume) and Ayres (this volume). Although according to one estimate per capita use of materials in the United States remained constant between 1974 and 1985 at about 20,000 pounds per year, use of paper increased by about 25 percent to about 650 pounds, and use of plastics increased by about 40 percent to 180 pounds (Hibbard, 1986). The latter figure is an obvious and essential part of the explanation for the recent widely reported concerns about the deterioration of environmental quality at beaches in the United States and Europe (see Lynn, this volume).



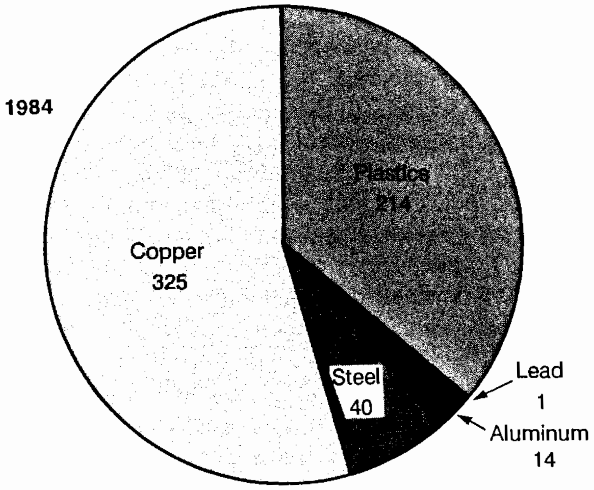


FIGURE 15 Use of materials for manufacture of telecommunications cables by AT&T Technologies, 1955 and 1984, in millions of pounds. SOURCE: Key and Schlabach (1986).

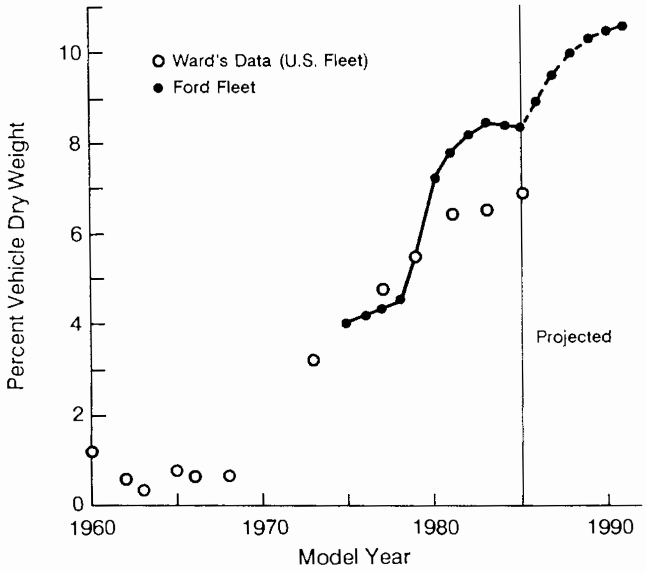


FIGURE 16 Trends in plastics content of U.S. passenger cars. Included is increased use of plastics in bumpers, fuel tanks, air cleaners, and wheel covers, but not in body panels, for which construction in plastic is also increasingly feasible. SOURCE: Gjostein (1986).

In the search for advanced materials, we may be creating materials that are virtually immortal. One wonders, for example, whether the new marvelously strong materials increasingly popular for heavy-duty envelopes are as readily recycled or biodegradable as old-fashioned paper. From an environmental point of view, electronic memory would indeed be a sought-after substitution for paper as a medium for storing information, if it could be made long-lived and reliably reproducible. Also attractive is the notion of replacing packaging itself; food irradiation, for example, may be environmentally desirable if it can significantly reduce the required volume of packaging materials.

To summarize, there is intriguing evidence of long-term regularities in the evolution, diffusion, and substitution of technologies. Understanding these regularities is of value for both environmental research and management. From numerous illustrations available in transport, energy, and materials it is evident that there is need to increase scrutiny of environmental problems and opportunities associated with growth of air transport; increasing reliance on natural gas; and disposal of plastics. Clear possibilities exist for the development of illuminating indicators, such as trends in the hydrogen-to-carbon ratio and the composition of demandite, connected to technologies and resources that would be valuable in our diagnoses

TABLE 2 Average Nonrenewable Resources Used by Man in 1968, "Demandite"

Resource	Atomic Percent	
	United States	World
$CH_{2.14}$	80.22	–
$CH_{1.71}$	–	66.60
SiO_2	11.15	21.17
$CaCO_3$	4.53	8.15
Fe	1.10	1.45
N	0.76	0.68
O	0.53	0.45
Na	0.53	0.45
Cl	0.53	0.45
S	0.23	0.23
P	0.08	0.07
K	0.07	0.07
A	0.11	0.07
Cu, Zn, Pb	0.04	0.04
Mg	0.04	0.04
X	0.08	0.08

NOTE: Here, X represents all other chemical elements: highest in order of demand are Mn, Ba, Cr, F, Ti, Ni, Ar, Sn, B, Br, Zr; others account for less than 100,000 tons per year worldwide or less than 30,000 tons per year in the United States. The term CH refers to the combination of coal, oil, and natural gas, which are all made up of carbon and hydrogen in different ratios. The subscript refers to the average hydrogen-to-carbon ratio.

SOURCE: After Goeller and Weinberg (1976).

and prognoses of environmental quality. We should not underestimate our technological ingenuity with respect to the environment nor the enormous dimensions of the systems requiring successful application of that ingenuity.

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NOTE

1. Mathematically, a logistic function may be denoted by $x/(\kappa - x) = \exp(\alpha t + \beta)$, where t is the independent variable usually representing some unit of time; α is a constant representing rate of growth; β is a constant for the location parameter (it shifts the function in time, but does not affect the function's shape); κ is the asymptote that bounds the function and, therefore, specifies the level at which the growth process saturates; x is the actual level of growth achieved; and $(\kappa - x)$ is the amount of growth still to be achieved before the saturation level is reached. Substituting $f = x/\kappa$ in the equation expresses the growth process in terms of fractional share f of the asymptotic level κ reached; that is, the equation becomes $f/(1 - f) = \exp(\alpha t + \beta)$, the Fisher and Pry (1971) model. Taking logarithms of both sides of the equation results in the left-hand side being expressed as a linear function of time, so that, when plotted, the secular trend of a logistic growth process appears as a straight line (sometimes with perturbations). The terminology employed here is used in the figures in this chapter.

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