V

Society as a Learning System:

Discovery, Invention, and Innovation Cycles Revisited

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Cesare Marchetti

The problem

Logistic* market-penetration analysis has been successful in describing long-term behavior of energy markets and submarkets. This success has stimulated theoretical attempts to reduce the empirically efficient logistic relationship to more basic and already-accepted scientific axioms.[1] A remarkable effort was made by Peterka, who demonstrated that, under constant productivity differentials, competing industries win and lose the market following logistic paths.[2]

Fleck considers market penetration as a diffusion process in which the buyer is a scattering element in a Markov chain.† From the properties of this microelement, Fleck can reconstruct the macroscopic behavior.[3] This is an interesting form of reduction, although the properties of the microelement cannot yet be established a priori—nor, consequently, can the parameters of the logistic equation be calculated before the penetration process starts. Fleck still limits his consideration to man as an economic animal.

The problem is how we predict economic behavior. Are purely economic analyses sufficient?

1. C. Marchetti and N. Nakicenovic, *The Dynamics of Energy Systems and the Logistic Substitution Model*, RR-79-13 (Laxenburg, Austria: International Institute for Applied Systems Analysis, December 1979).

2. V. Peterka, *Macrodynamics of Technological Change: Market Penetration by New Technologies*, RR-77-22 (Laxenburg, Austria: International Institute for Applied Systems Analysis, November 1977).

3. F. Fleck, "Regelmässigkeiten bei Marktdurchdringungsprozessen als Folge des individuellen Nachfrageverhaltens" (Diss., Universität Fridericiana Karlsruhe, Technische Hochschule, Fakultät für Wirtschaftswissenschaften, 1980).

The hypothesis: Society learns

I would like to go one step further, in abstraction and simplicity, and assume that *society is a learning system;* that learning is basically a random search with filters; and that random searches are characterized by logistic functions.[4] The most natural way to proceed is through examples of increasing complexity from which some abstractions and deductions can be drawn.

No, something else is at work—a social interaction called learning.

4. N.S. Goel, S.C. Maitra, and E.W. Montroll, "On the Volterra and Other Nonlinear Models of Interacting Populations," *Review of Modern Physics* 43 (1971): 231; and R.R. Bush and F. Mosteller, *Stochastic Models for Learning* (New York: Wiley, 1955).

**A logistic curve is a logarithmic relation of a given quantity to its growth over time. In this paper a logistic curve represents an exponential growth within a limited context, e.g., a product market.*

†A Markov chain refers to a process whose states succeed each other according to fixed probabilities. The probabilities do not tell us the details of the process, but they do permit us to know the basic "laws" governing what is going on. From the gross observable manifestations of the chain we may infer an overview of the process, even if the details are unknown to us.

The first and most important link in all human chains and feedback loops* is man. It is interesting to see him at work—for example, as a child trying to master an intricate structure like a language. To monitor the progress I examined the extension of vocabulary under the child's control. The result is given in Figure 1.

Learning by trial and error is a social equivalent of biological evolution...

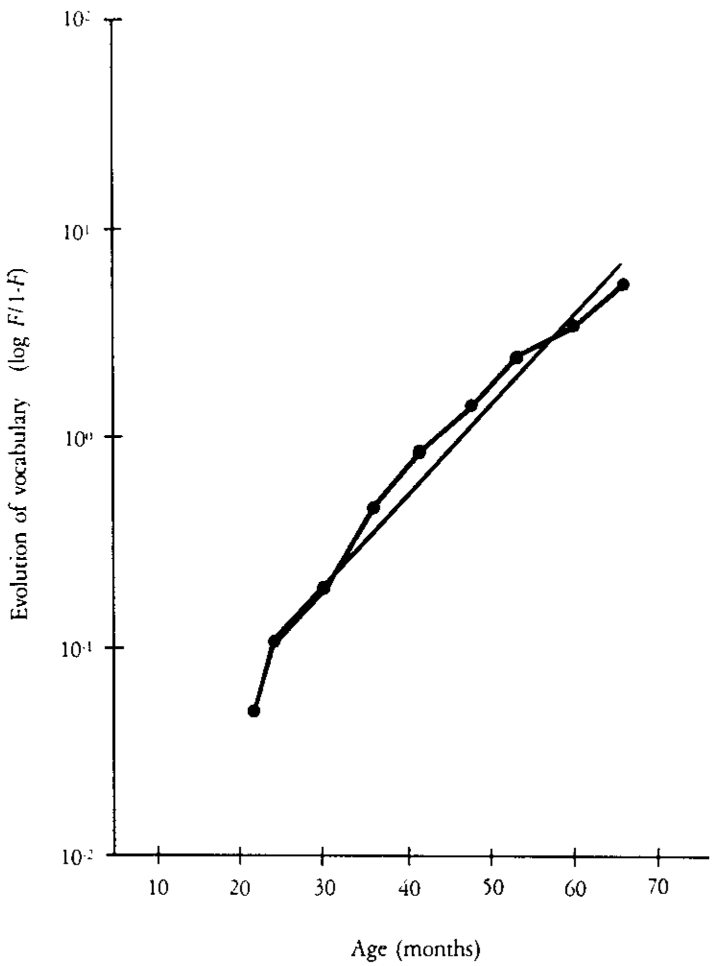

Figure 1

Log $F/1\text{-}F$ is a general logarithmic equation. It is used to standardize one set of data so that the set may be related to other sets of data taken from seemingly disparate sources of information. For example, in this essay the logarithmic expression $F/1\text{-}F$ is used to relate world energy production, vocabulary acquisition, and theoretical advances in chemistry.

Figure 1. Evolution of a child's vocabulary. The set of words currently used is about 2,500. The curve is a logistic written in the form of $\log (F/1\text{-}F) = at + b$ (where F is the fraction of the final vocabulary, t is time, and a and b are constants). Data from T.G. Whiston, "Life Is Logarithmic," in J. Rose, ed., *Advances in Cybernetics and Systems* (London: Gordon & Breach, 1974).

My second example of learning calls for a group of men interconnected by informational links (e.g., learned journals) and working on the common task of pounding molecules to pieces in order to separate the unbreakable components, the stable atoms. That game drove the chemists crazy in the period about 1750-1850, when some 50 stable elements were discovered. In Figure 2 the glorious progress in this task is reported. The child and the learned guild seem to behave the same way, or at least the same functional relationship takes care of the two cases.

...and a professional phenomenon. It deals with the processes of discovery, application, and refinement.

The third example (see Fig. 3) bears some similarity to the second; however, the objects indicated on the graph do not have a physical existence in the sense of words or chemical elements but belong to conceptual sets, as those in the Platonic world, where all ideas sit. Figure

**A feedback loop is a process in which a given quantity changes in response to information about its earlier states. A thermostatically controlled heating system, for example, is a feedback loop.*

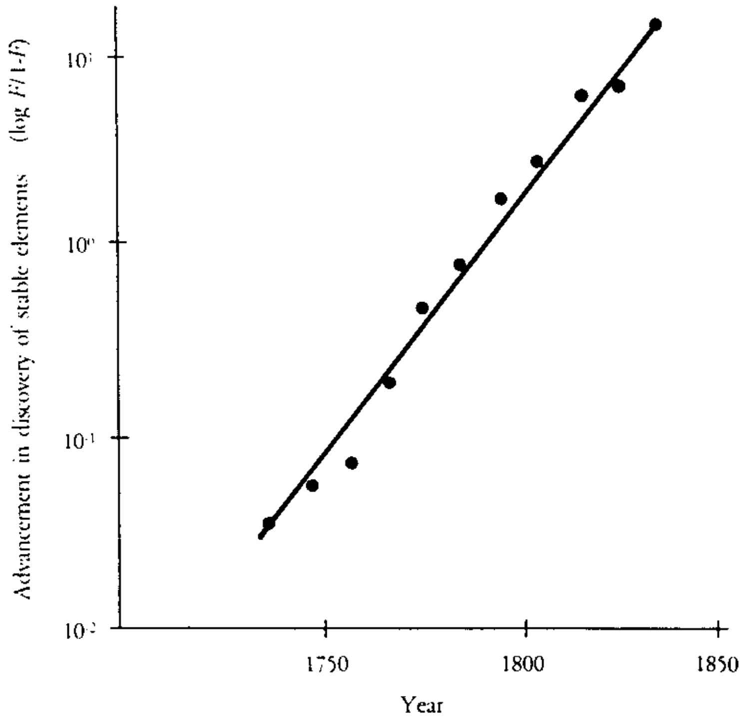

Figure 2. Discovery of the stable elements, ca. 1750–1850, as a learning process. The set consists of about 50 stable chemical elements accessible with then-current chemical technology; and $F(t)$ is the cumulative fraction of elements already discovered at time t. Data from *The World Almanac* (New York: Doubleday, 1971).

3 reports the evolutionary trends of three technologies (steam, artificial illumination, and ammonia production), embodied in machines of evolving performance. In a sense, inventors, wandering in the world of all possible machines, picked those which seemed best, and they were ready to throw them away for better machines, like Alice in Wonderland with her flowers. Here only one parameter was taken as an indicator of performance, but it was based on a very important and subtle notion: thermodynamic efficiency.

Social learning is the aggregate response of many individual learning experiences.

Inventors are not organized in a guild, and their stimulus and financing come from a wide variety of sources. They are, however, interconnected through literature and inspection of competing products. And they seem to behave like a single structure, operating toward a purpose, insensitive to historical trivialities like wars, pestilences, and economic crises.

Learning rates are stable over time. They are not perturbed by economic factors such as price and supply. Learning is more influential than economic factors in affecting the dynamics of social systems.

The fourth example of learning (see Fig. 4) refers to large industries capillarily interconnected with many strata of society—technical, economic, financial, political—which draw stimuli and constraints from these strata. Being processing industries, they may take thermodynamic efficiency as an indicator. As the statistical data show, the evolutionary pattern is exactly the same as before. Here, however, due to the visibility and strong coupling of these industries, the effects of war may be felt, perhaps through bombing or shortage of new equipment, as in the case of Great Britain's steel industry. It is remarkable, however, that some kind of internal clock keeps ticking, and finally the time lost is recovered in a well-adjusted dash. This elastic reabsorption of perturbations is a general and surprising feature of practically all the systems studied.

The last example of the series (Fig. 5) involves humanity as a whole and its behavior with respect to a very important item, the use of primary-energy sources during the last century or so.[5] As can be seen,

5. Marchetti and Nakicenovic, *Dynamics of Energy Systems*.

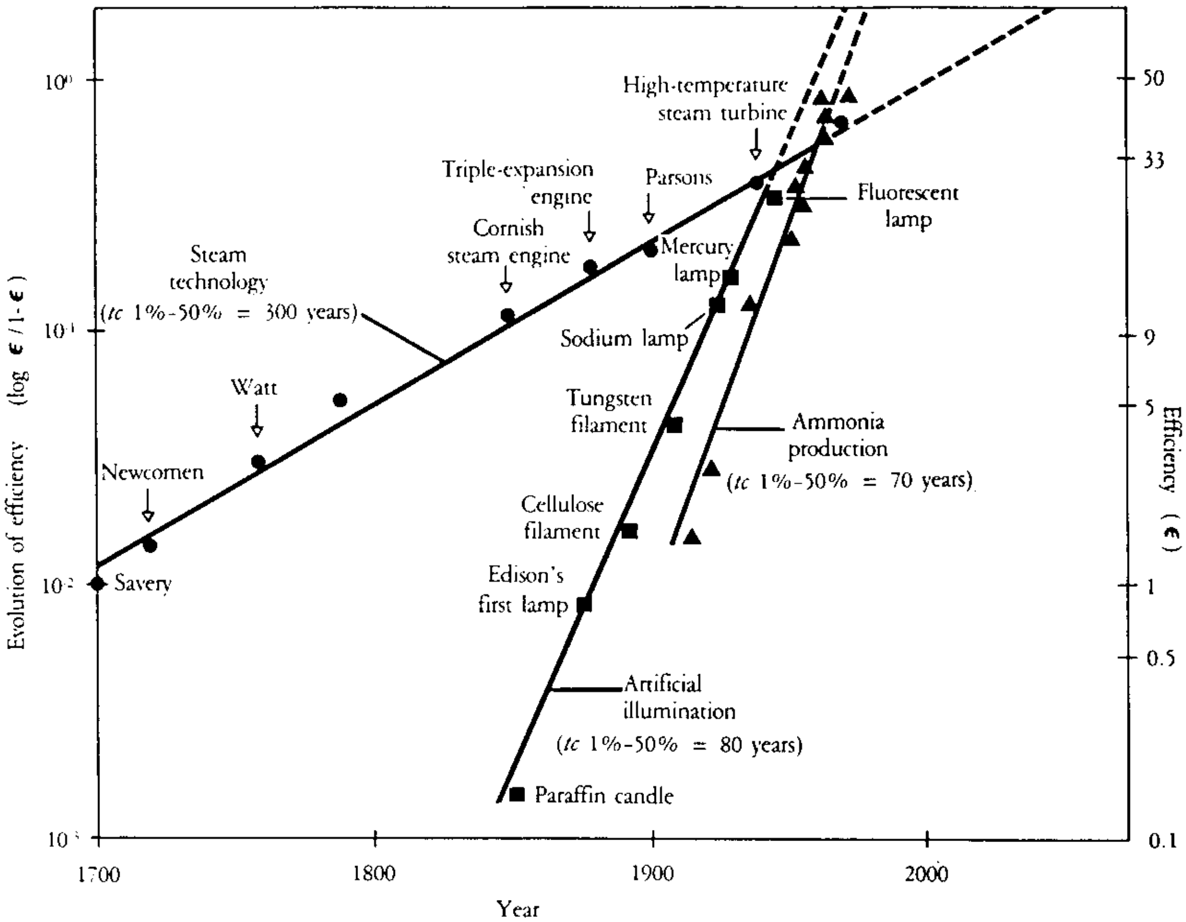

Figure 3. Historical trends in thermodynamic efficiency ε for three technologies since 1700. Evolution of efficiency is reported by comparing the performance of the best commercial machine (at a given time) to the maximum efficiency that is thermodynamically possible using the specific fuel. Thus steam-engine efficiency does not refer to Carnot's machine but to free energy in the fuel. The slope given as the time required to go from 10^{-2} to 10^0 (1% to 50% efficiency) is *tc*. The data are fitted with a logistic equation expressed in terms of $\varepsilon / 1 - \varepsilon$; ε is efficiency, the Good, and $1 - \varepsilon$ is obviously inefficiency, the Evil. (I have nicknamed this figure "the yin-yang plot.") Adapted from C. Marchetti, "Energy Systems: The Broader Context," *Technological Forecasting and Social Change* 14 (1979): 191-203.

Figure 3
In the development of steam technology, Thomas *Savery* invented a machine to lift water—the first engine to provide mechanical power by harnessing steam (1698). Thomas *Newcomen* improved on Savery's machine with a steam engine that could pump water (ca. 1711). In 1769 James *Watt* devised further, major improvements on the steam engine. The triple expansion engine in 1871 was the first engine to use three cylinders successively in the conversion of steam to mechanical energy. The year 1897 saw the marine application of Sir Charles A. *Parson's* revolutionary steam turbine, which was capable of driving generators to produce electricity.

the match between the statistical data and their logistic fitting is very snug over this long period of time. Humanity too seems to behave like an interconnected system that is learning its way toward an objective, at extremely stable rates. Incidentally, the concepts of prices and of resources do not appear necessary for the description of the system. Prices appear in response to the working of deeper physical mechanisms.

The data: Historical views of invention and innovation in world industry

Armed with the working hypothesis that all sorts of societal subsets may operate in this way, I revisited a stimulating collection of data referring to waves of innovation in world industry during the last several hundred years (Fig. 6).[6]

Contrary to current perception, innovations do not, in fact, come as a trickle from science to technology to industry, with a lag that keeps decreasing in time. Historical analysis shows that innovations develop and peak with a certain rhythmic regularity. They come in season, much

6. Gerhard Mensch, *Das technologische Patt* (Frankfort on the Main: Umschau Verlag, 1975); also published as *Stalemate in Technology* (Cambridge, Mass.: Ballinger, 1979). These books provide a good bibliography on research on the innovation process. The German edition is preferable for details on how the data have been selected. See also A.K. Graham and P.M. Senge, *A Long-Wave Hypothesis on Innovation*, Workshop on National Innovation Policy and Firm Strategy (Laxenburg, Austria: International Institute for Applied Systems Analysis, December 1979).

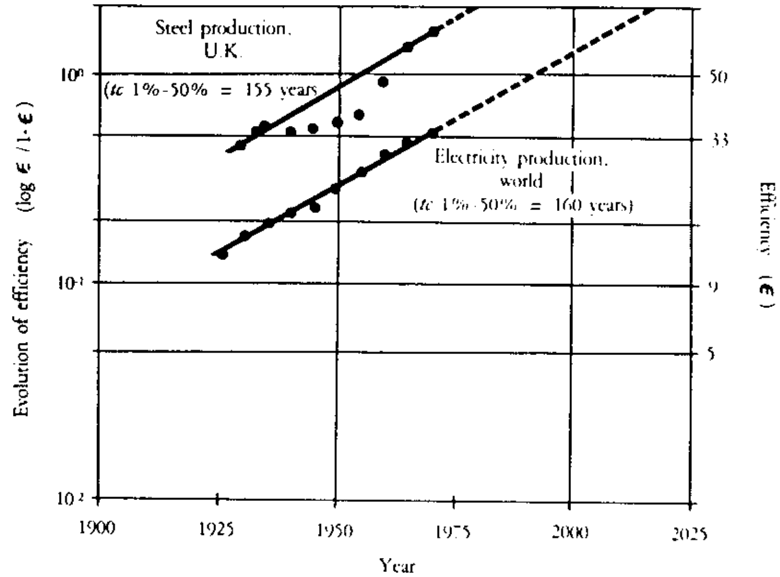

Figure 4. Historical trends in thermodynamic efficiency for production of steel in Britain and world electricity since 1900. This graph is comparable to Figure 3. The efficiency for electricity production is defined as electrical energy/fuel energy. The assumption for fossil fuels—that free energy and enthalpy of combustion coincide—is adequate. With nuclear energy the definition should perhaps be revised. Adapted from Marchetti, "Energy Systems."

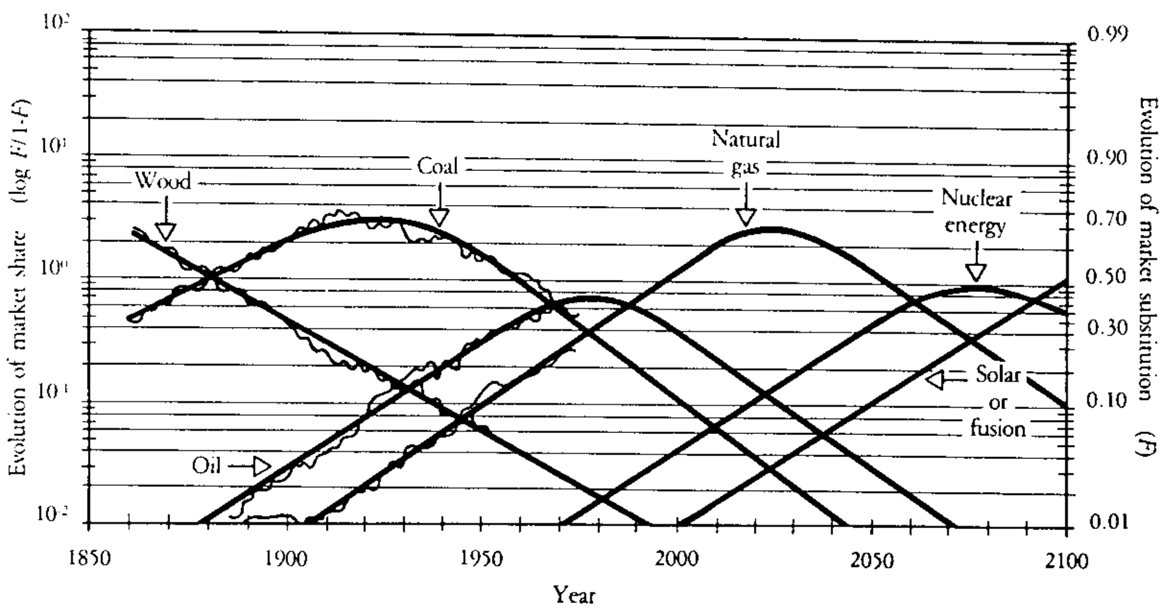

Figure 5. Worldwide use of primary energy sources since 1850. *F* is the fraction of the market (in energy units) taken by each primary-energy source at any given time. The wavy lines represent statistical data. Nuclear energy has not yet penetrated heavily, and the slope is therefore hypothetical. Solar or fusion is hypothetical for both slope and initiation point. Adapted from Marchetti and Nakicenovic, *Dynamics of Energy Systems.* NOTE: For nuclear energy, $F = 0.01$ in 1970 and 0.04 in 2000. For solar or fusion, $F = 0.01$ in 2000 and 0.04 in 2030. Values beyond 1970 are projected.

Invention is basic to the initiation of industries. Innovation is a process of application.

like agricultural crops. Following the harvest, for example, a fruit tree begins the slow nurturing process during winter and spring until its branches are ready to sprout, blossom, and produce for the next season's crop. Innovations in a social system are analogous; the system may be likened to the tree and the innovations to its fruit.

The analysis of the first cycle of invention and innovation in this col-

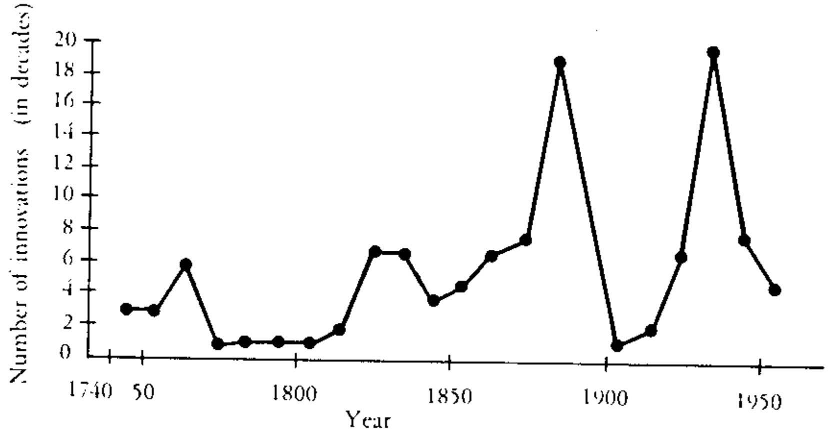

Figure 6. Frequency of basic innovations, 1740-1960. Adapted from Mensch, *Das technologische Patt*.

lection of data is reported in Figure 7. The information comes from Mensch, who also quotes other sets assembled by other authors claiming their sets do not differ substantially.[7] The inventions and innovations belonging to Figure 7 are listed in Table 1. (See also Table 2 for a closer focus on one industry.)

7. Mensch, *Das technologische Patt*.

I am using the term *innovation* (or *basic innovation*, if we go to finer distinctions) as *something that starts a new industry*. The phonograph, for example, is a basic innovation. Improvements in the process of manufacturing or in the quality of the products, which in the current language are also called innovations, are not considered here. *Inventions* refer to the *discoveries which are at the base of the innovations.*

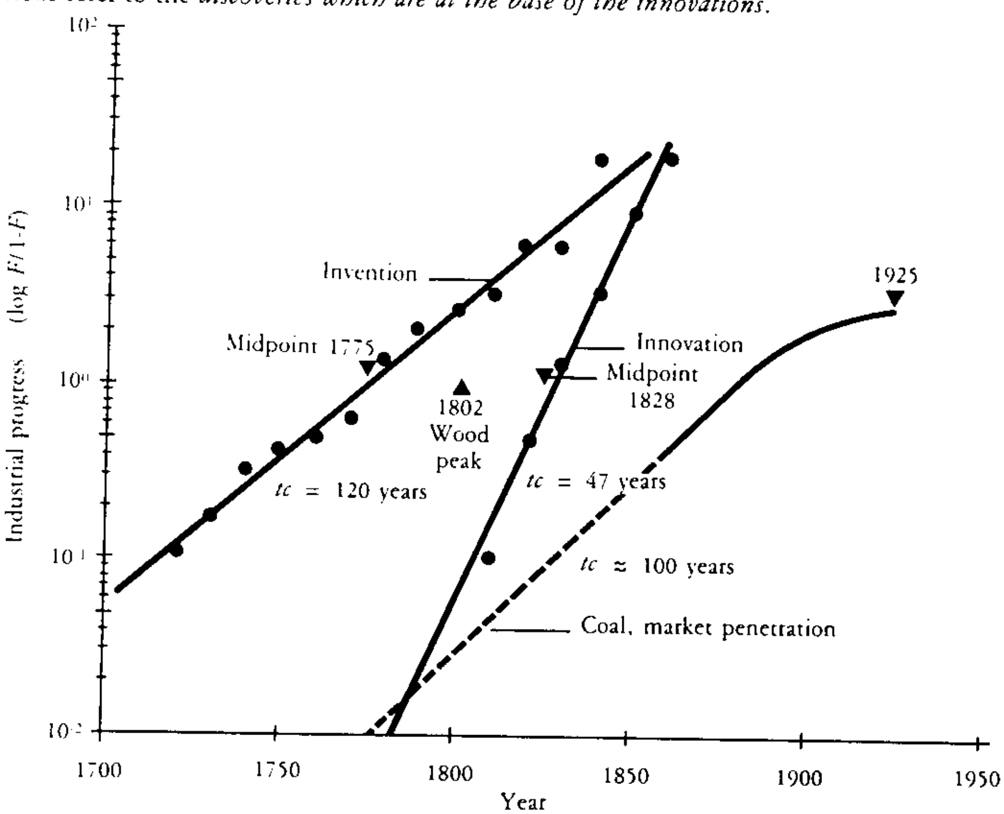

Figure 7. The 1802 cycle of innovations and corresponding inventions. Midpoint year for each wave indicates when 50% of innovations or inventions were in existence. The cycle center of 1802 is halfway between the midpoints of the two waves (1775 and 1828). F is the fraction of the total set implemented up to time t, with tc as time constant. Each set (innovations and inventions) is based on a sample taken from 21 items (Tables [illegible] et-penetration curve for coal to 1925 is superposed for further considera-

TABLE 1
THE 1802 CYCLE

	Invention	Innovation
Electricity production	1708	1800
Blast furnace with coke	1713	1796
Photography	1727	1838
Crucible steel	1740	1811
Lead-chamber process	1740	1819
Insulated conductor	1744	1820
Portland cement	1756	1824
Locomotive	1769	1824
Pharmaceutical production	1771	1827
Pulled wire	1773	1820
Rolled rails	1773	1835
Potassium chlorate	1777	1831
Puddling furnace	1783	1824
Quinine production	1790	1820
Telegraph	1793	1833
Arc lamp	1810	1844
Pedal bicycle	1818	1839
High-voltage generator	1820	1849
Electric-impulse stimulator	1831	1846
Vulcanized rubber	1832	1852
Deep-sea cable	1847	1866

SOURCE: Data from Mensch, *Das technologische Patt*, chap. 4.

In Table 1 the two sets of inventions and innovations are matched, in the sense that inventions which did not develop into innovations are not listed.

As my phenomenological analysis will be made in relative terms, the completeness of the sets is not important, provided the selection of the cases is reasonably random. On the other hand, I could not influence with my prejudices the choice of the data; that was made by Mensch, who had other ideas in mind.

In Figure 7 the cumulative number F of inventions and innovations is reported, normalized over the total set in the cycle. The ordinates are the usual ones, to make the logistic behavior optically evident. The waves are characterized through their midpoints (1775 and 1828), the dates when 50 percent of the inventions or innovations have appeared. Time constants are measured in years elapsed between two decades in the ordinate.* This is a meaningful way to measure slopes. A portion of one of the curves of Figure 5 (market penetration of coal) is superposed to Figure 7, following a suggestion by Graham and Senge that innovation waves and primary-energy waves may be interconnected.[8]

8. Graham and Senge, *Long-Wave Hypothesis*.

Since the number of elements in a set is quite limited, the fitting logistics should be chopped below $F = 5$ percent and above $F = 95$ percent (or thereabouts). In the graphs, however, they are often prolonged to $F = 1$ percent in order to show some interesting interlacing with the energy cycles. The center point, 1802, between the wave midpoints, 1775 and 1828, is also of significance in this connection. I will use the term 1802 to characterize the cycle.

A historical study of invention and innovation enables us to predict phenomena of a social and economic character.

Mensch made the interesting observation that the two sets, inventions and innovations, are basically similar, that is, ordered. In other

**Time constants are measured in the number of years taken for a given quantity to increase from 10% to 90% of its maximum level.*

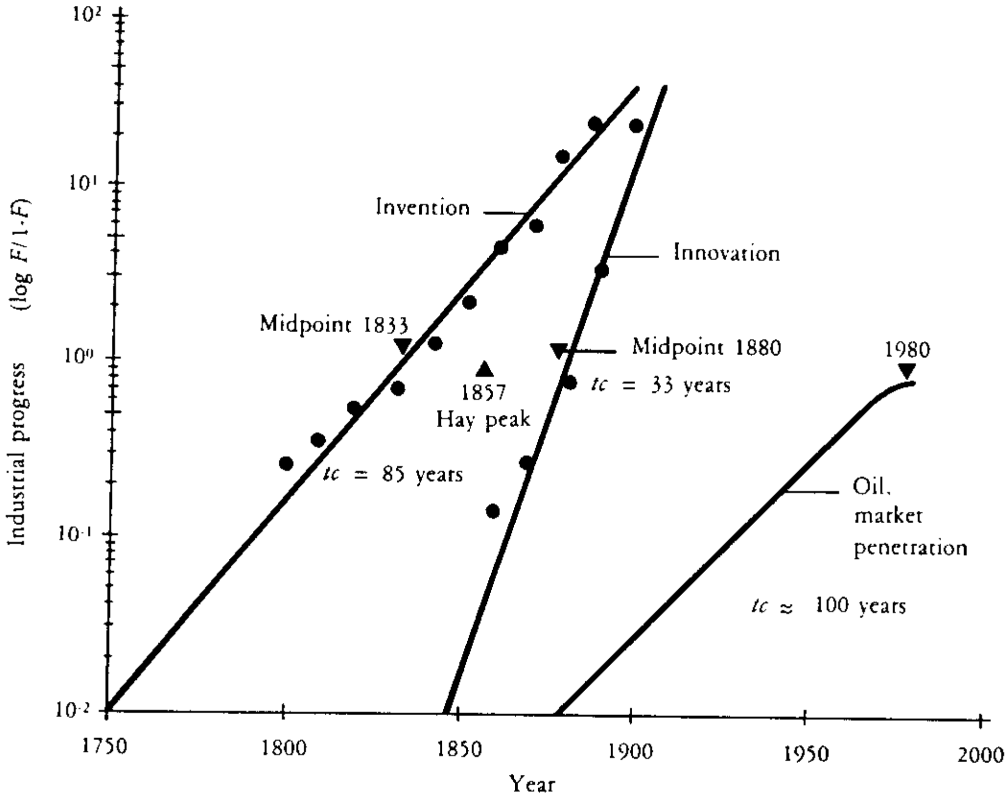

Fig. 8. The 1857 cycle of innovations and corresponding inventions. The cycle center of 1857 is halfway between the midpoints of the two waves. F is the fraction of the total set implemented up to time t, with tc as time constant. Each set is based on a sample of items taken from Table 3. Market-penetration curve for oil to 1980 is added for comparison (cf. Fg. 5).

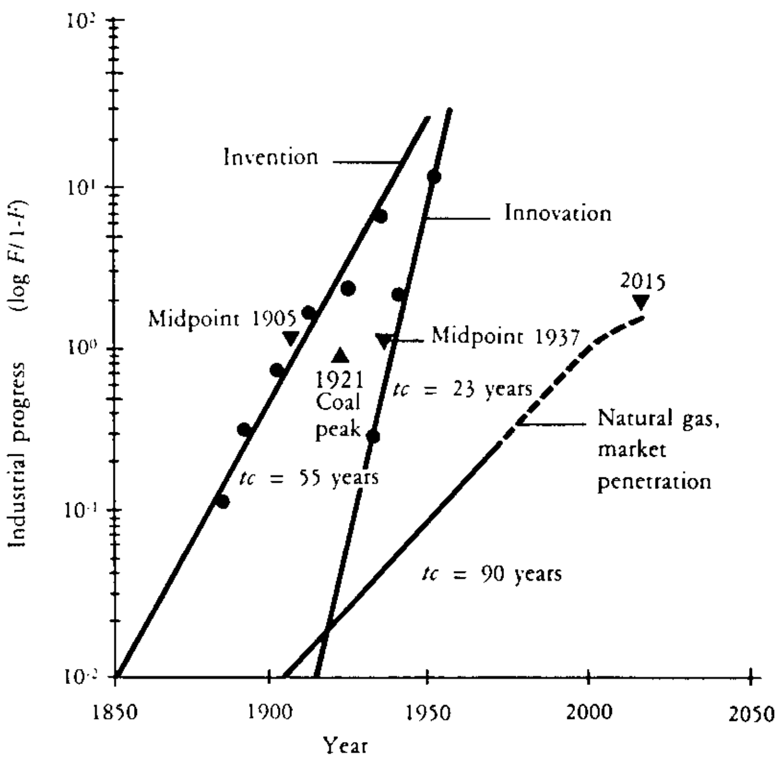

Figure 9. The 1921 cycle of innovations and corresponding inventions. The date represents the cycle center. F is the fraction of the total set implemented up to time t, with tc as time constant. Each set is based on a sample of items taken from Table 4. Market-penetration curve for natural gas to 2015 is added for comparison (projected after 1970; cf. Fig. 5).

TABLE 2
INVENTION AND INNOVATION FOR THE STEAM LOCOMOTIVE

	Invention	Intermediate steps	Innovation
Watt patents low-pressure steam machine	1769		
Cugnot develops steam-gun vehicle		1770	
Read develops steam-powered road vehicle		1790	
Watt's patent on steam engine expires		1800	
Trevithick begins work on steam locomotives		1801	
Evans constructs road steam locomotive		1804	
Blenkinsop patents first toothed-gear locomotive		1811	
Hadley develops locomotive to ride on rails		1813	
Stephenson begins building locomotives		1814	
Stephenson builds first locomotive plant			1824
Consequence, 1825: Stephenson opens Stockton and Darlington Railway line in England			

SOURCE: Data from Mensch, *Das technologische Patt,* chap. 4.

words, inventions go into innovations following the rule of first come, first served. Consequently one can predict the date of the innovation if the invention can be located. As a general rule the distance in time between the two keeps decreasing along the way, to start long again in the next wave, as we shall see. The current idea of a long-term reduction of delay from invention to innovation is certainly false, although more subtle accelerations actually occur.

The 1857 cycle is reported in Figure 8 (data in Table 3). Topologically

TABLE 3
THE 1857 CYCLE

	Invention	Innovation
Electrodynamic measurement	1745	1846
Plaster cast	1750	1852
Baking powder	1764	1856
High-grade steel	1771	1856
Analine dyes	1771	1860
Lead battery	1780	1859
Gas heating	1780	1875
Cylinder-armatured motor	1785	1872
Electrolysis	1789	1887
Sodium carbonate	1791	1861
Incandescent light bulb	1800	1879
Arc lamp	1802	1873
Safety matches	1805	1866
Cooking fat	1811	1882
Mass production of sulfuric acid	1819	1875
Double-armature dynamo	1820	1867
Cable construction	1820	1882
Iodoform	1822	1880
Water turbine	1824	1880
Aluminum	1827	1887
Phenazone (synthetic pain killer)	1828	1883
Chloroform	1831	1884
Transformer	1831	1885
Commutator	1833	1869
Synthetic alkaloid (quinoline)	1834	1880
Preservatives	1839	1873
Chemical fertilizer	1840	1885
Electric locomotive	1841	1879
Resistance welding	1841	1886
Steam turbine	1842	1884
Dynamite	1844	1867
Synthetic alkaloid (cocaine)	1844	1885
Meter (measuring apparatus)	1844	1888
Arc welding	1849	1898
Aspirin	1853	1898
Telephone	1854	1881
Thomas steel	1855	1878
Rayon	1857	1890
Electric heating	1859	1882
Gasoline motor	1860	1886
Induction smelting	1860	1891
Oxyacetylene welding	1862	1892
Veronal (barbiturate)	1863	1882
Refrigeration	1873	1895
Antitoxin	1877	1894
Electric railroad	1879	1895
Indigo synthesis	1880	1897
Long-distance telephoning	1893	1910
High-tension insulation	1897	1910

SOURCE: Data from Mensch, *Das technologische Patt*, chap. 4.

the cycle is identical with the previous one. All the time constants are different, however, showing 85 years for inventions and 33 years for innovations, instead of 120 and 47 years, as in the 1802 cycle; this indicates a certain level of acceleration.

The 1921 cycle is shown in Figure 9 (cf. Table 4), with nothing special

TABLE 4
THE 1921 CYCLE

	Invention	Innovation
Gyrocompass	1827	1909
Fluorescent lighting	1852	1934
Synthetic light polarizer	1857	1932
Plexiglas	1877	1935
Titanium	1885	1937
Synthetic detergents	1886	1928
Radio	1887	1922
Radar	1887	1934
Ball-point pen	1888	1938
Insulin	1889	1922
Zipper	1891	1923
Continuous hot-strip rolling	1892	1923
Diesel locomotive	1895	1934
Magnetic tape recording	1898	1937
Tungsten carbide	1900	1926
Watertight cellophane	1900	1926
Power steering	1900	1930
Rockets	1903	1935
Helicopter	1904	1936
Hydraulic clutch	1904	1937
Automatic drive	1904	1939
Silicones	1904	1946
Neoprene (synthetic rubber)	1906	1932
Wrinkle-free fabrics	1906	1932
Television	1907	1936
Kodachrome	1910	1935
No-knock gasoline	1912	1935
Catalytic cracking of petroleum	1915	1935
Cotton picker (Campbell)	1920	1942
Streptomycin	1921	1944
Penicillin	1922	1941
Cotton picker (Rust)	1924	1941
Nylon, Perlon	1927	1938
Continuous steel casting	1927	1948
Jet engine	1928	1941
Sulzer loom	1928	1945
Polyethylene	1933	1953
Xerography	1934	1950
Cinerama	1937	1953
Transistor	1940	1950
Terylene polyester fiber	1941	1955

SOURCE: Data from Mensch, *Das technologische Patt,* chap. 4.

to report, except again the excellent fit of the data to the logistic interpolation and a further shortening of the time constants—to 55 years for inventions and only 23 years for innovations. The time span between the midpoints too is reduced to 32 years, strangely reminiscent of the 33 years of the innovation time constant of the 1857 wave. Incidentally, the span between centers of the 1857 cycle is 47 years, which perfectly coincides with the time constant of 47 years of the 1802 innovation wave.

The data: Testing the hypothesis

Regularities can certainly be coincidences, however improbable. But

TABLE 5
THE LEARNING PROCESS: A COMPARATIVE ANALYSIS OF FOUR INVENTION AND INNOVATION CYCLES

	1802 cycle	1857 cycle	1921 cycle	1980[a] cycle
Innovation midpoints	1828	1880	1937	(1993)
Invention midpoints	1775	1833	1905	(1969-70)
Cycle centers	1802	1857	1921	(1980)
Δt between invention and innovation midpoints [b]	53	47	32	(23)
Innovation time constant [b]	47	33	23	(16)
Invention time constant [b]	120	85	55	(38)
Δt between innovation midpoints	52	57	(56)	
Δt between invention midpoints[b]	58	72	(65)	
Δt between cycle centers [b]	55	64	(59)	
Saturation of market penetration for primary energies	~1800 (wood, U.S.)	~1860 (hay, U.S.)	~1921 (coal, world)	(~1980) (oil, world)

NOTE: Data are summarized from Figures 7-11. Connecting lines highlight comparisons.
[a] Some data projected. Figures incorporating projected data are set in parentheses.
[b] Data given in years.

regularities raise the suspicion of a clockwork sitting behind the face; and they stimulate curiosity. So in Table 5 I put together data connected to the various cycles, corresponding to Figures 7-11, to see if more suspicious regularities would appear.

They do, in fact. One regularity is that the distance between waves is about 55 years, measured at the midpoints of innovations. This has been observed by Mensch and Senge and can be correlated to the Kondratiev cycle*—as a driving force of the cycle by Mensch, and as an effect of the cycle by Senge.

Then, the time constants of the innovation waves become shorter, and they have the constant geometric ratio of 1.414, or $\sqrt{2}$. In the century or so covering the first three dashes, the speed has increased by a factor of two.

Furthermore, the introduction of new primary-energy sources seems to be somehow in tune with the innovation waves, crossing them at about the 10^{-2} level; and the saturation point for coal in 1923 coincides with the midpoint of the 1921 cycle. I tried then to look for a saturation point corresponding to the 1857 cycle. With some difficulty in collecting data, I found one around 1860, for presteam mechanical power, that is, draw animals, whose primary source of energy is hay. It sounds a little queer today, but at that time in the United States, 80 percent

*A Kondratiev cycle is a recurring economic cycle of fifty years' duration. Its characteristics are thought to be constant. The existence of such cycles is still argued.

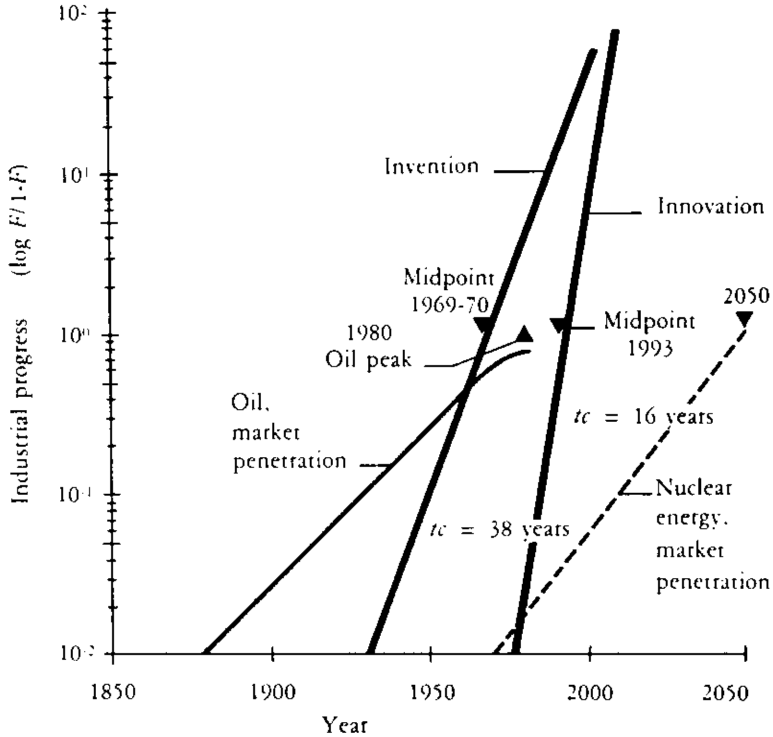

Figure 10. The 1980 cycle of innovations and corresponding inventions. The date represents the cycle center. F is the fraction of the total set implemented up to time t, with tc as time constant. Market-penetration curves for oil and nuclear energy (projected to 2050) are superposed for comparison (cf. Fig. 5).

of all mechanical power (including sailing ships) was located in draw animals. The year 1802 should be at the peak, or at least a sharp bend, for wood fuel, but I have not been able to prove it.

Using all these bits and pieces, that is, the regularities of the 1802, 1857, and 1921 cycles, I tried to reconstruct the characteristics of the next cycle. (It is certainly better than reading tea leaves.) The fact that various parts interlock with a smooth click may be the expression of good mechanics.

The exercise is summarized in the parenthetical data of Table 5 and is presented graphically in Figure 10. The 56-year cycle gives 1993 as a midpoint for the innovation wave. The time constant of 16 years comes from that of the previous cycle, 23 years, divided by 1.414. The distance between midpoints is equal to the time constant of the previous cycle, or 23 years, bringing the midpoint of inventions to 1969-70. The time constant of inventions is derived from the previous one, 55 years, divided by 1.414, which gives 38 years. *The center point of the cycle is 1980, which neatly corresponds to the maximum of oil penetration,* as shown in Figure 5. Also the crossing of 1 percent of the nuclear-energy line with the innovation line matches previous coincidences.

Although the 1980 cycle has already begun, the effective starting point will be 1984, a date that Orwell made famous in a not-very-different context—perhaps prophetically. The crucial years appear to be 1984-2000, when 84 percent of the basic innovations will have appeared. The 1984 wave will also end the recession inside which willy-nilly we are muddling; and in a powerful 16-year dash, the world economy should ride the wave again. The effects, however, will be felt only after 1990.

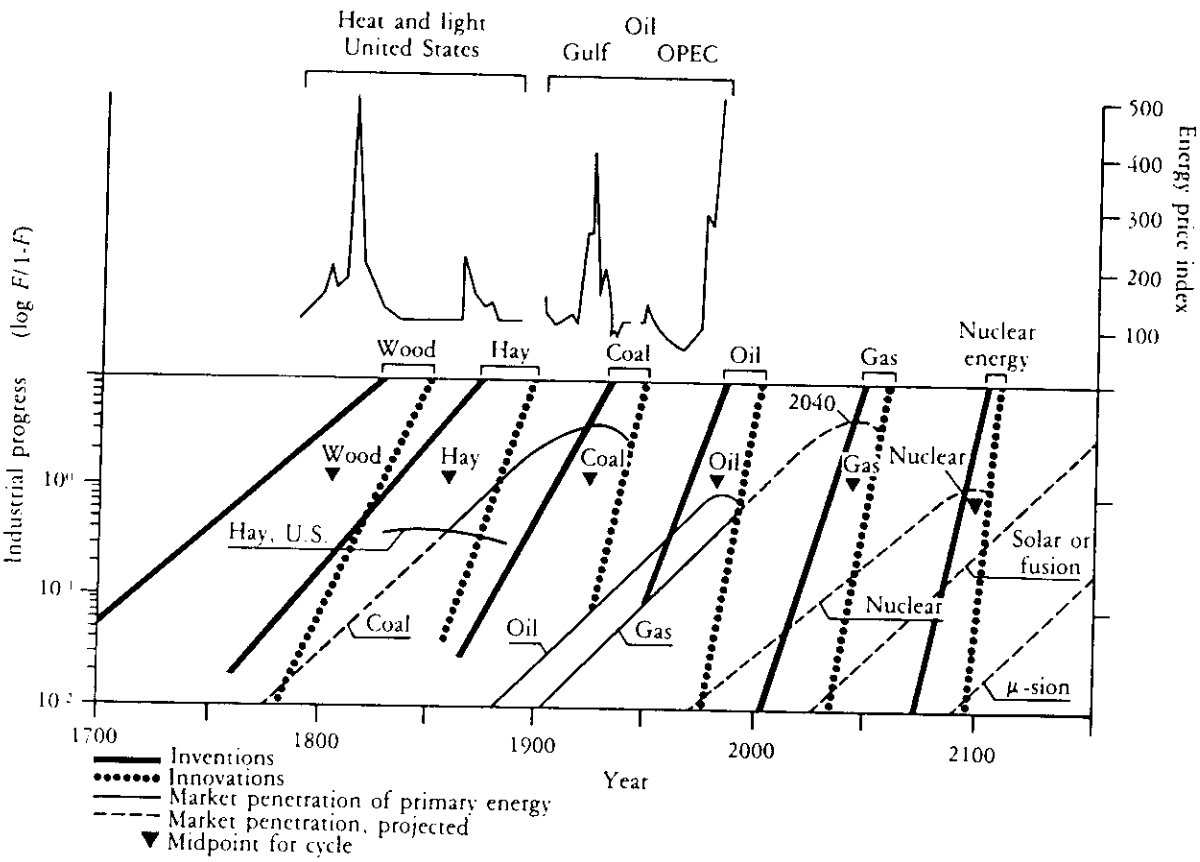

Figure 11. Long-term development of world energy: comparison of invention, innovation, and market penetration of energy sources for six cycles. *Below:* The first three cycles are historical; we live in the fourth cycle; the fifth and sixth cycles are predicted and illustrate the interlocking of the various components. *Above:* There is a close match between energy-price flaring and cycle centers. By analogy, we should expect a rapid fall of the real price of oil in the next few years.
NOTE: Cost index in constant monetary units is 100 for heat and light (base year 1850) and for oil (base year 1940). Cost-index data for heat and light from *Historical Statistics of the United States* (U.S. Department of Commerce, 1975) and for oil from A.F. Beijdorff and J.H. Lukas, *Energy Price: Pervasive Carrier of Information* (London: Shell International Petroleum Co., n.d.).

Application of the hypothesis: Predicting future innovations

As the inventions curve in the 1980 cycle shows, 80 percent of the inventions that will go into the next rush have already been made by 1980. We don't really know yet where they are, and everybody can have his guess. Obvious possibilities are linked to information management and manipulation, including genetic engineering and the resulting sophisticated chemistry—even base chemistry. Less obvious inventions are linked to the management of new energy sources—in this special case, nuclear energy. As electrical systems become saturated with nuclear energy in various countries at the beginning of the nineties, technologies moving from nuclear energy to chemicals and synthetic fuels will have a real chance to enter the industrial web. Also about that time, air traffic will demand performance almost beyond the potential of present technology.[9] A breakthrough is in sight with the use of liquid hydrogen as a fuel, planes redesigned to accommodate this fuel, and hypersonic flight.[10] Hydrogen-fueled cars may also go into the same niche with the

9. C. Marchetti, "The Evolution of Energy Systems and the Aircraft Industry," Proceedings of the Symposium "Hydrogen in Air Transportation," Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt, Stuttgart, Sept. 11-14, 1979.

10. G.D. Brewer, "Characteristics of Liquid Hydrogen-Fueled Aircraft," Proceedings of the Symposium "Hydrogen in Air Transportation," Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt, Stuttgart, Sept. 11-14, 1979.

synthetic fuels, owing to the expanding use of nuclear energy.

In the field of food and agriculture, many innovations are hovering around in search of a sponsor.[11] Maybe for some of them this is the last chance. The next round is half a century away!

11. C. Marchetti, *On Energy and Agriculture: From Hunting Gathering to Landless Farming*, RR-79-10 (Laxenburg, Austria, December 1979).

The question of how many innovations will pop up in this cycle can also be answered—up to a point. The phenomenological equation says that 10 percent will be on line in 1984. So the only thing we have to do is to go out and count the innovations now. The wave will have 10 times as many. My personal evaluation is that about 100 new industries will be launched before the end of the century.

Because these and other considerations make *our* round appear very plausible, I decided to continue the game in a scenario spirit, building the next waves too. The result of the exercise is reported in the lower part of Figure 11. (Posterity may have fun cross-checking it.)

The findings again make much sense. The next round of primary energies is required around 2025, which is a safer date than the year 2000 for the solar or fusion of Figure 5, a date I chose under the pressure of solar and fusion enthusiasts. Back-of-the-envelope calculations show that a sensible and successful course for fusion will give just about 1 percent of the market in 2025. But then the peak of natural gas is going to move forward to about 2040, which is precisely what the coincidence with the center of the fifth cycle is asking for. On the other hand, the business-as-usual rate of penetration for nuclear energy (100 years *tc*) would be confirmed; its saturation in the year 2090, at about 60 percent of the market, would match the sixth cycle beautifully.

I took poetic license in calling μ-sion the new primary energy associated with the sixth cycle, arguing that scientists tampering with more and more elementary particles will presumably find a way to squeeze energy out of them.

Observations: In energy systems, monetary factors are indicators, not causes, of social-industrial behavior

Coming back to Figure 5, the description of the structure of the energy market is made in physical terms, and the very simple set of logistic equations behind it permits precision forecasting and backcasting over at least 50 years. This means that prices which moved around all the time cannot really be considered voluntaristic causes, as economists tend to think, but superficial indicators, as I find it almost inevitable to think. Assuming prices are effects and the physical structures are causes, I looked for some long-term correlations. The indexed price for energy is shown in Figure 11. The remarkable fact here is that the *prices* for energy flared in coincidence with the center points of the cycles—three times in the past, and now, at the presumed center point of the 1980 cycle. This coincidence helps to support the method of forecasting I used, with the click of another piece falling into place. It also opens the way to the far-reaching speculation that *in real terms the price of energy in general, and of oil in particular, will fall sharply during the next few years.*

At this point a canonical question arises: What are the mechanisms of such regularities, and what determines the length of the period be-

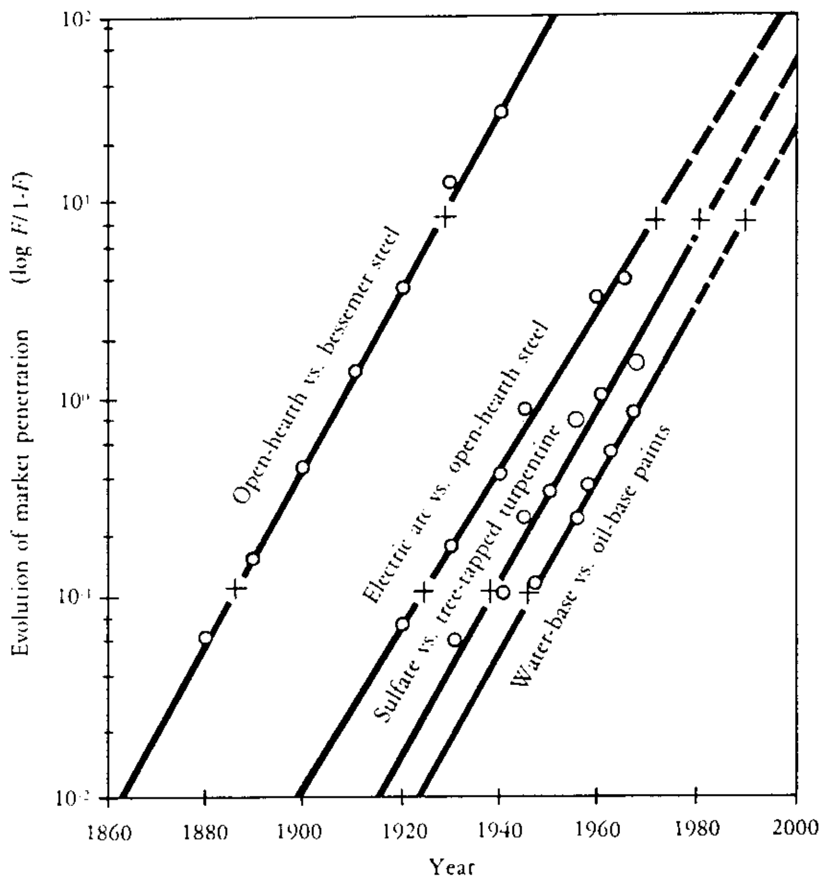

Figure 12. Technological substitution in the production of steel, turpentine, and paint. The figure shows market penetration in three industries in the United States. X marks indicate 10% and 90% market penetration; circles plot statistical data. F is the fraction of the market covered by the expanding market of two competing machines or production technologies. For each industry, tc is in the range of 50 years. The process is one way, and no revival of old technologies has ever appeared. Data from Fisher and Pry, *Simple Substitution Model.*

tween innovation cycles?

To the first part of the question I would say that man and societal feedback loops have been the same for many centuries, contrary to our feeling of fast change; and that the concept of a learning society is the heuristic path to a search for a microscopic description in the spirit of the statistical mechanics that came to buttress macroscopic thermodynamics in the physical sciences. However, it has taken a century for this very intricate branch of science to come to maturity.

The learning process can be the determinant of economic behavior.

To a physicist's eye, present-day econometric models still look much like toddling and stuttering. What I think most dangerous and misleading in them is the blind devotion to monetary concepts. All my analyses of economic systems tend to show that monetary variables are the manifestation of a deeper stratum of phenomena, where the real mechanisms lie. The description of the evolution of the energy market in Figure 5 does not require the concept of money at all and beats any econometric model in precision, simplicity, and capacity to forecast.

The real mechanisms driving an economic system do not appear to be monetary.

As to the second part of the question, I much lean toward the interpretation that the behavior of the final consumer is the central clock of the system. The time constants for market penetration of numerous consumer and also capital products (Fig. 12) tend to cluster around 50 years.[12] The rate of penetration may be closely linked to human behavior

12. J.C. Fisher and R.H. Pry, *A Simple Substitution Model of Technological Change*, Report 70-C-215, Technical Information Series (Schenectady, N.Y.: General Electric Co., 1970). See also *Technological Forecasting and Social Change* 3 (1971): 75-88.

Innovation has an end point—near saturation of the market. At the end point the industry based on the innovation begins a decline. Our understanding of the learning process enables us to predict these developments.

and may be the deep reason for the stability of the length of the cycles. It is a current observation that when a product nears saturation of the market, its industry gets into trouble.[13] At this stage, the industry has probably exhausted its potential for incremental and managerial innovations, thus reducing its capacity to cope with change.

If many industries happen to be born together, they will enter the embalming stage together, and this will liberate capital for new enterprises. Such a Schumpeterian view gives a helpful hint about the self-amplifying mechanism of the waves. The reason why innovation and—more than that—invention fit the straitjacket of precise functional relationships remains a deep mystery, however. Societal mechanisms seem capable of switching genius on and off.

The above considerations are not really intended to explain in scientific terms; they are meant only to wind us up for the next run of analysis.

13. Goel, Maitra, and Montroll, "Volterra Models."

Summary

During the last 300 years, basic inventions and innovations have appeared in cycles of precise configuration and frequency, substantially isomorphic but with a "contraction" of the time scale by roughly a factor of two every century. The introduction to the market of new primary energies, their phaseout from the market, and their prices all appear to be rigidly interlocked with these cycles, adding another dimension to forecasting in the field of energy systems.

This article is a development of several ideas that Dr. Marchetti presented at the Donald S. MacNaughton Symposium, sponsored by Syracuse University in New York, January 14-15, 1981.