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Some Ideas About Growth and Quality in Technology

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ABSTRACT

The assumptions behind the exponential theory for the rate of improvement of the "quality" of technologies are studied. It is shown that the conformity of a measure of quality to the exponential law reveals that the technology is "motivated" and only "ingenuity-limited." It is shown that exponential growth suggests that quality is driven from within and resistant to the influences of such external factors as economics and politics. During the last century and a half, the exponential growth rate of a technology has increased with its inception date. This suggests means for analyzing the evolution of hybrid technologies.

A Preliminary Personal Prejudice

I am less interested in measuring technology than I am in taking pleasure in it. There is quality and beauty in technology, and there is a kind of innocent animal inexorability to it. It evolves at a pace that is quite independent of the people who seem to be responsible for making it happen.

We look at our technological product and it seems wonderful and remarkable—even inspired. Yet humankind has very little power to influence it. The human race is defined by its compulsive tool-making—its *technology*. Anthropologists do not decide whether or not a particular ancestor of ours was human, based on its physiognomy. They make the judgement on the basis of whether or not they can show that it made tools in any serious and methodical way.

Several French anthropologists (Andre Leroi-Gourhan and Maurice Daumier, for example [4]) have convincingly argued that tool making precedes human intellectual evolution—that the expansion of our intellect actually *follows* the development of tools, that the erect walk which freed the hand and the opposed thumb which made serious tool manipulation possible were causes of a great intellectual leap forward, not its results. I

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have seen what the computer has done for—or to—my students and my children. It has altered them. It has permitted them to see things that I could not see when I was a student or a child.

When I look at the growth or the improvement of technology, what I see is not *man-driven,* but rather *man-driving*. This state of affairs is even pointed out in Genesis. We are told that we will be compelled to pursue our technology, and the fruit of our knowledge, whether we want to or not. It seems fairly clear that the real expulsion from Eden has only begun. The change from a symbiosis of man-and-garden to a situation where we must totally control any garden that we occupy is well underway, but it is far from complete.

General Description of the Method

SCOPE

We propose a method for predicting the rate of improvement of the quality of a technology. Of course we cannot predict quality until we form some sort of a definition of it. The very act of defining will preshape the prediction.

We thus form a definition which, when analyzed, yields a simple exponential growth law.[1] Exponential growth laws are not new,[2] but our focus is on the logic underlying such laws; it goes like this:

1. we define quality;
2. a prediction based on this definition says that the quality improves at an exponential rate;
3. the predicted growth law is subject to restrictions that are inherent in the definition;
4. a comparison of the prediction with data is successful, insofar as the data represent qualities that are consistent with the definition;
5. the data that fail to conform therefore sharpen and clarify the definition;
6. we thus achieve a quantifiable and predictable (though not all-encompassing) definition of quality. This improves our understanding of how technical change has taken place.

The motivation for this work is, in fact, not to make predictions, but rather to improve our understanding of the history of technology with the help of quantitative prediction.

DEFINITION AND ASSUMPTIONS

We first consider the rate of improvement of the quality of a technology.

Technologies are only included in these considerations if they are sufficiently complex that they cannot be brought to completion with a few inventions. We are interested in steam power plants and digital computers, but not in ball point pens or mousetraps.

Quality is a term we use to describe those improvements that are motivated, quantifiable, and ingenuity-limited. The quality of a technology will stop improving when it

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[1] This method was originally detailed by Lienhard [5] in 1979.

[2] Starr and Rudman made an interesting formulation of such a law in 1973 [11]. Another proponent of exponential growth laws has been Marchetti. (See, e.g., [6, 7]).

is replaced with a different technology, or when it becomes complete owing to the fact that it has become ingenuity limited.

Thus we are interested in those qualities that people feel strongly driven to improve (energy efficiency, clock accuracy, speed of long-distance transportation, etc.) We are interested in qualities to which we can assign a numerical description (like an efficiency or a speed.) We are interested in a given quality only as long as we can improve it by being sufficiently clever. We abandon interest in it when it becomes limited by a physical constraint such as the second law of thermodynamics, the speed of light, or the Heisenberg uncertainty principle. And we are only interested in a given technology as long as it is the one people pursue to achieve a given function. When a different and improved technology replaces it, people are no longer motivated to improve its quality.

We thus exclude several potential qualities from consideration. For example,

> There are many measures of pure magnitude that people do not appear to be strongly motivated to improve. Building a taller building offers no significant advantage in itself. It simply involves a tradeoff between the cost of construction and the cost of land. Therefore the maximum heights of buildings do not increase exponentially in time. The same is true of many measures of pure size—the length of ships or of single bridge spans.
>
> The thermal efficiencies of steam power plants stopped increasing exponentially when they started bumping against the ceiling set by the second law of thermodynamics. The enormous accuracy of modern time measurement is rapidly reaching the point at which it is limited by quantum uncertainties. The depth to which a man can dive in the ocean without being encased in a vehicle is restricted not by his ingenuity but by the frailty of his body. These are examples of what we mean when we call *complete technologies*.
>
> The accuracy of the mechanical clock improved in a certain way until about 1920 when it was replaced by electrical timekeeping. Electrical timekeeping then improved in a different way, while the technology of mechanical clocks has become frozen in the state that it had reached a half-century ago.

Technical Description of the Method

We presume that technologists, and/or the society of which they are a part, share the same hopes and expectations for any technology. In a working lifetime, during which they function effectively with the technology, they neither demand nor absorb a greater percentage of improvement of any quality of that technology than they have come to associate with that device. This is a strong assumption. It says that the rate of improvement of a quality becomes frozen forever as soon as serious work begins on that technology.

How long is the typical working lifetime L of a technologist? Most technologists become fully defined in their mid-to-late twenties and they normally start to slow down anywhere from their mid-forties to late sixties. The quantity L is probably something like 30 years, give or take a few—rather close to what we sometimes call a "generation."

We specify the improvement during a working lifetime L in terms of an n-folding. That is to say, the quality Q improves by a factor of n during L. A simple doubling ($n = 2$) seems to be a tempting possibility. However, n doubtless varies in some way with the expectations of the society in which the particular technology emerges.

The simple idea of a constant *n*-folding rate can be expressed mathematically as

$$\frac{Q}{Q_o} = n^{(t-t_o)/L} \equiv e^{(t-t_o)\ln(n/L)}, \tag{1}$$

where Q_o is the quality at the time t_o where motivated improvement of Q begins. It is useful to rewrite Eq. (1) in the form

$$\frac{Q}{Q_o} = e^{(t-t_o)/T}, \tag{2}$$

where T is the time-constant of exponential growth:

$$T \equiv \frac{L}{\ln(n)}. \tag{3}$$

We note that, if n is 2, a working lifetime of 30 years yields $T = 43.3$ years. This time constant provides a kind of reference value that we should keep in mind.

Others who have worked with exponential laws have found it necessary to emend them in various ways. However, what we claim is that they can be applied correctly in their pure form, and significance can be attached to T, if we strictly require that Q is motivated, ingenuity limited, incomplete, and unreplaced.

Case Studies Involving the Method

FOUR ORIGINAL CASE HISTORIES

Many people have assembled data showing how various attributes of technology have changed with time. Some of these attributes—but by no means all of them—fit our definition of quality.

We begin with four such data sets of our own making. The sources and assembly of these data are documented in [5], and the data are plotted on semi-logarithmic coordinates in Figures 1–4. Figure 1 shows the thermal efficiency of steam power plants beginning with Smeaton's 1769 analysis of an earlier Newcomen engine.

The initial thermal efficiency Q_o would be 0.63 at a date t_o sometime between 1718 and 1769. Of course, a least-squares-fit curve through the data will never pass exactly through the initial point here, or in any of our other examples. We must therefore set a slightly arbitrary initial point of $Q_o = 0.57$ percent at $t_o = 1742$. From that point it increases with a slope, $1/T = 1/33$ yielding $n = 2.5$.

The efficiency then rapidly levels off after it reaches about 20 percent in 1850. The reason is that a 20 percent efficiency is high enough to start squeezing the limit set by the second law of thermodynamics. From this point on, efficiency can no longer be doubled by mere inventiveness. It can only be increased a percent or so at a time as advances come about in other technologies—for example, as major metallurgical, welding, or heat exchanger improvements are made. Thus the highly motivated and ingenuity-limited improvement of thermal efficiency was completed by 1850.

The second data set includes the accuracy of mechanical clocks beginning with Usher's [12] estimate of the accuracy of the first foliot-and-verge clocks toward the end of the 14th century. The five-hundred-year history of the improvement of the accuracy

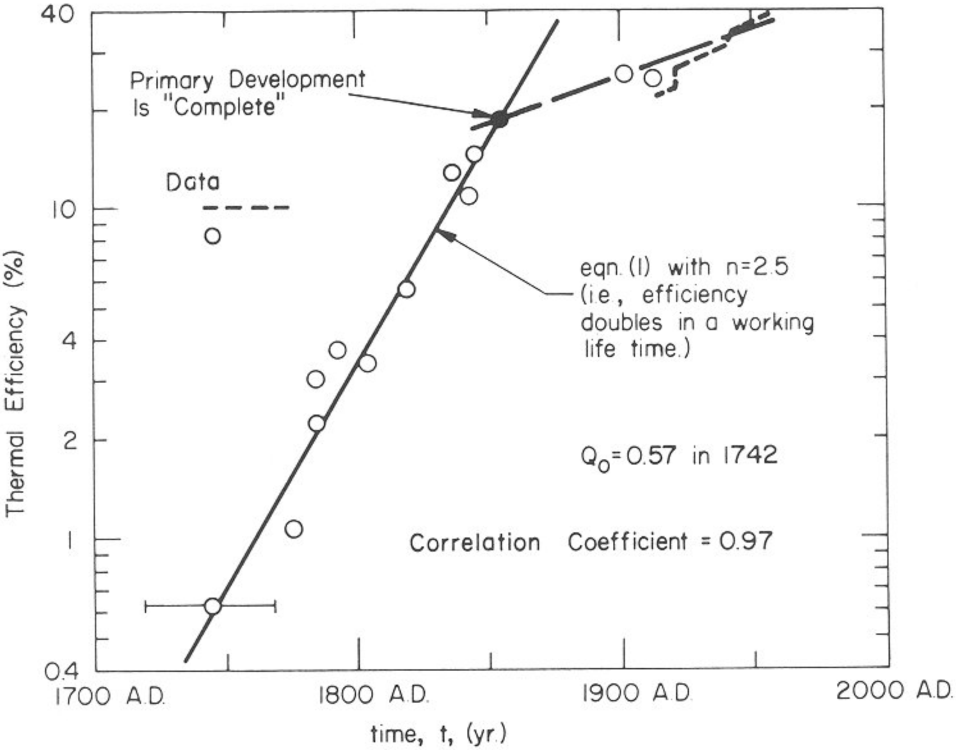

Fig. 1. Increase of thermal efficiency with time for hydrocarbon-fueled stationary steam power plants.

of clocks, given in Figure 2, yields $n = 1.96$ or $T = 43.3$ years. Thus our notion that technologists are somehow "tuned" to doubling ($n = 2$) the quality of technologies during their working lifetimes looks rather reasonable from these first two examples.

The third data set illustrates several of the important restrictions built into the definition. Figure 3 shows the speed with which humans have been transported by machines. The first point in the lower-left corner represents Murdoch's steam car. This was doubtless an isolated novelty in 1784, as were earlier Belgian experiments. When Trevithick developed a 17 mph steam locomotive in 1804, however, people took it seriously and began working in earnest on the automobile and the railroad train. Thus our starting point for the technology of land transport is (again, slightly arbitrarily) $Q_o = 21$ mph in $t_o = 1808$. The n-folding for land transport is 1.86 which is still close enough to 2 to sustain our interest in the idea of a simple doubling law.

There is a second curve in Figure 3 representing the speed of human transport through the air. After a few random attempts to create a controllable propeller-driven balloon, starting in the middle 18th century, the idea caught people's fancy and serious dirigible building began, followed by the airplane just a few years later. The curve for air transport rises with an n-folding of 10.1, starting with a speed of 8.5 mph in 1884.

Four of the important attributes of the quality, as we have defined it, are revealed by this plot of the speed of human transport:

We suddenly see the rate of improvement of speed n-folding five times as rapidly

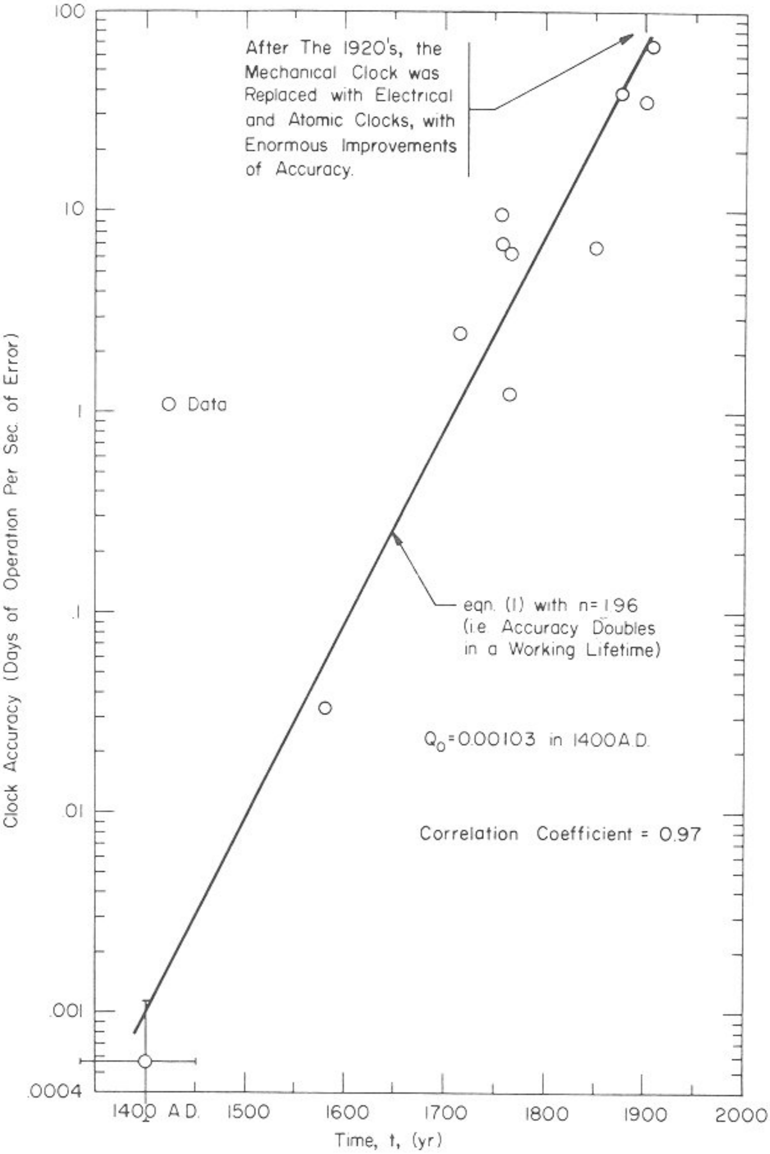

Fig. 2. Increase of accuracy of mechanical clocks with time.

for flight as it did for ground transport. It seems that $n \simeq 2$ cannot be taken as a general result.

Is flight a replacement technology for ground transport as a means for achieving high speeds? Probably not. We sense that the problems of starting, stopping, and loading and unloading will ultimately limit air travel. We still have hopes that much higher speeds may be reached by rail or other guided ground travel systems. The improvement of ground transport thus continues after the invention of the dirigible and the airplane—even after flying machines have greatly outpaced it. (This, by the way, has been borne out by recent ground speed records that were made after this curve was drawn.)

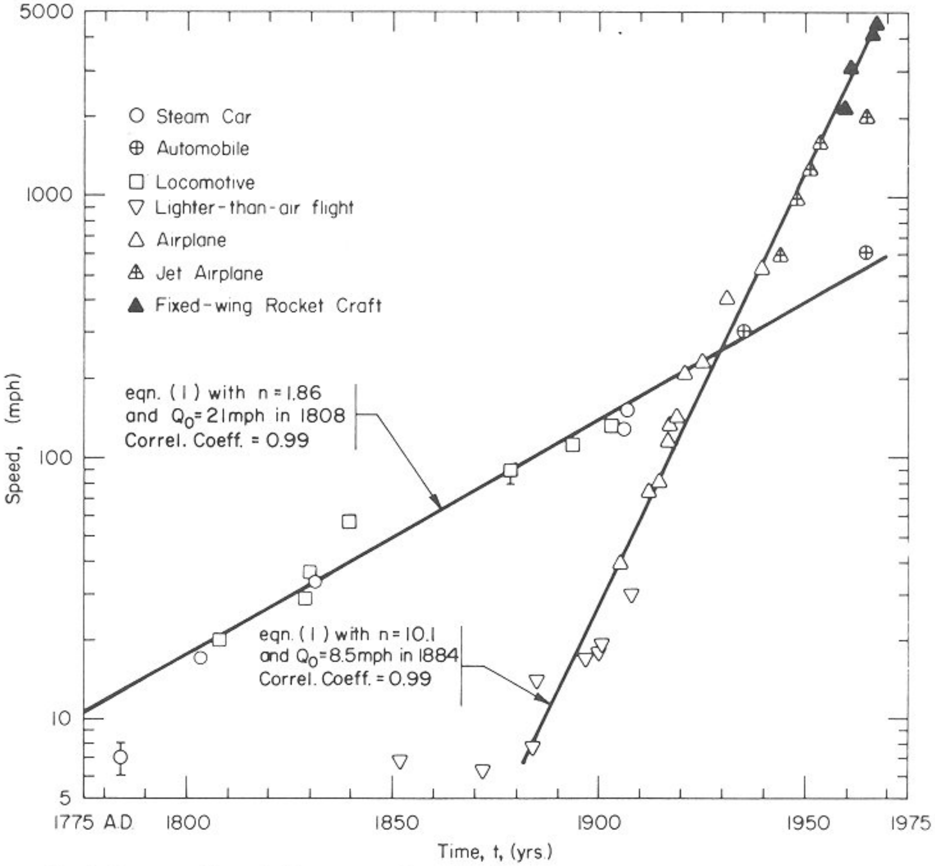

Fig. 3. Increase of speed of transportation with time.

> The speed of flight ceases to be a motivated variable as it approaches orbital speeds. At that point, any velocity becomes possible and the technological problem shifts to that of starting, stopping, and steering.
> The rate of improvement of the speed of ground transport continues to rise with the same *n*-folding after flight as it did before. The rate of improvement of ground speeds is not influenced by the much higher rate of improvement of air speeds.

We return to some of these features subsequently.

Figure 4 shows the rate of improvement of the quality of low temperature for the technology of refrigeration. Lowered temperatures are limited at absolute zero, but thermodynamicists know that $1/kT$ (where k is Boltzmann's constant and T the absolute temperature) is probably a more basic and evocative parameter than T itself. Therefore we take the point of view that the technology seeks to maximize the quality of inverse temperature—or temper as it has sometimes been called—with respect to inverse room temperature. Figure 4 accordingly displays:

$$Q = \left(\frac{1}{T} - \frac{1}{T_{\text{room}}}\right)^{\circ}K^{-1} \qquad (4)$$

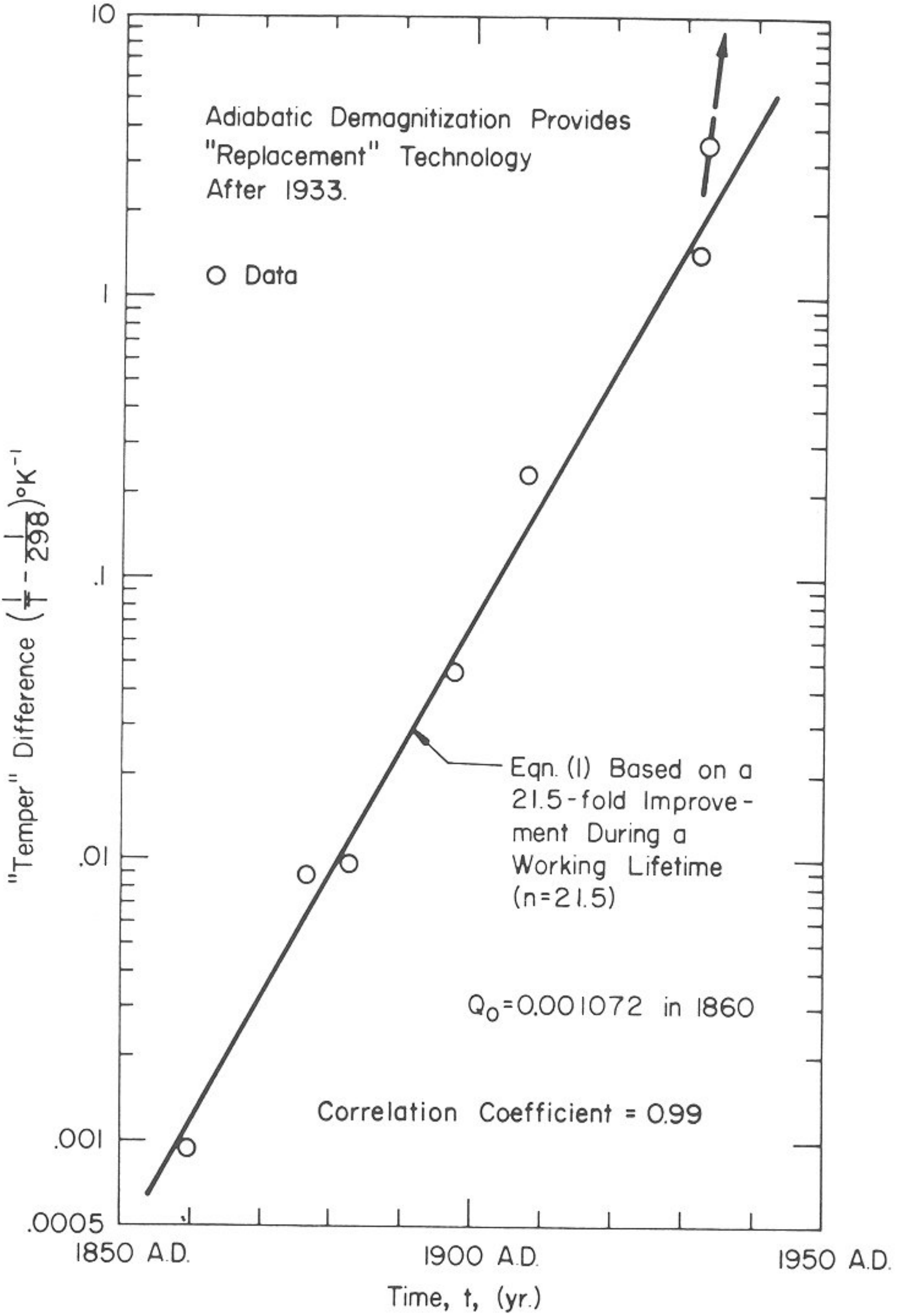

Fig. 4. Improvement in coldness with time.

We trace refrigeration from Carre's 1860 absorption system. The value of $n = 21.5$ is really quite high in this case. The technology of cooling with vapor systems was replaced by the technique of adiabatic demagnetization in 1933. Vapor systems are still in use, but there ceases to be any motivation to use them in the quest for lower temperatures.

SOME BORROWED CASE HISTORIES

Figure 5 presents four additional examples from the Guinness Book of World Records [8]. Two of these—those for the depth of wells and the height reached by people above the earth's surface—give n-folding rates of 2.64 and 2.52, and might seem to support

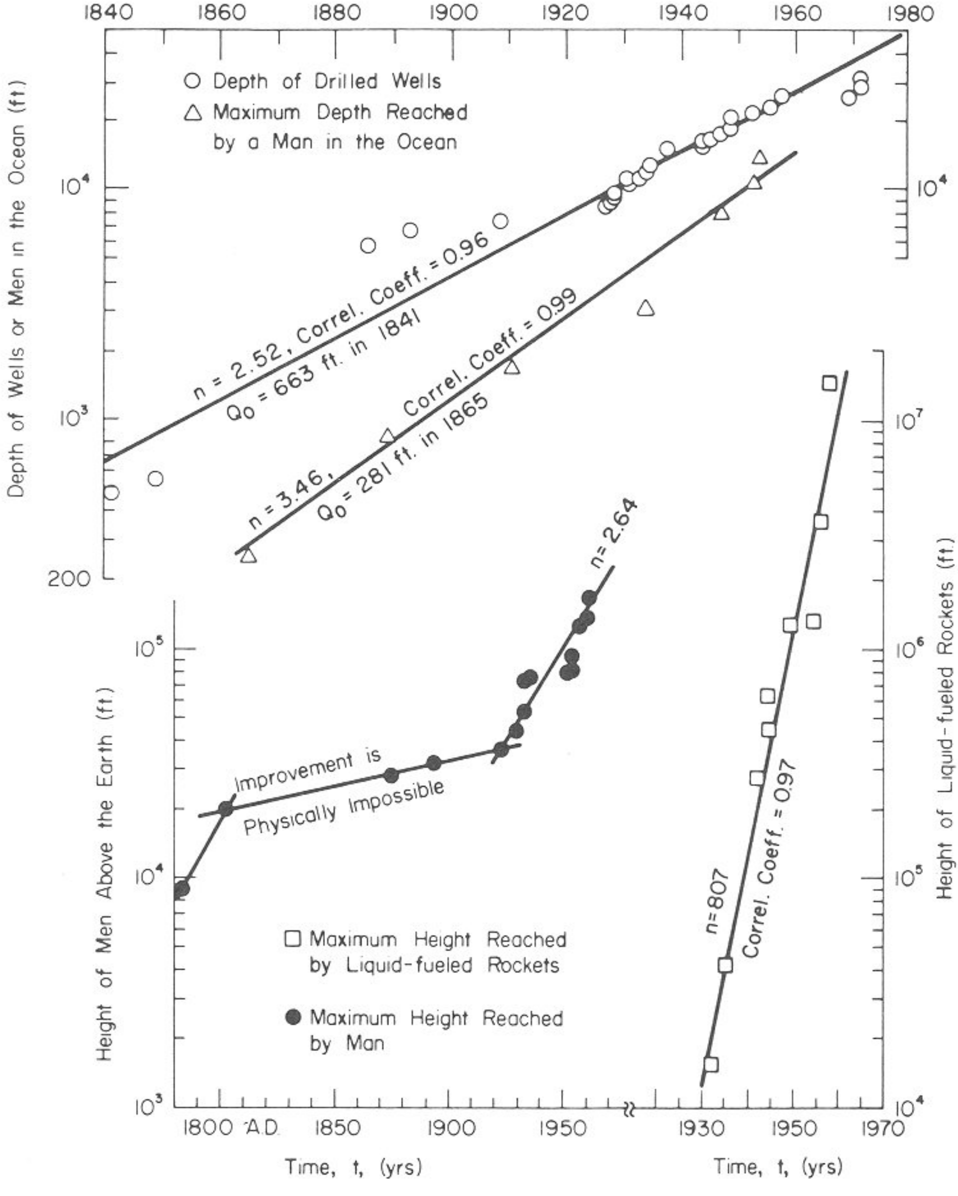

Fig. 5. Four examples from the ***Guinness Book of World Records*****.**

the doubling principle. A third—the depth people have reached in the ocean—yields $n = 3.46$, a bit too high. The fourth example—the height reached by liquid fueled rockets—begins with Goddard's experiments in the late 1920's and increases with $n = 807$. This corresponds with a time constant of only four and a half years.

We see that all of the older case studies give, approximately, a simple doubling during a technological lifetime. It is only recent technologies that yield much more rapid improvement. The example of the height people have reached in the sky is a particularly important illustration: An initial n-folding was set in the late 18th century French experiments and development rapidly became complete as people reached air too thin to breathe. Growth resumed with the development of oxygen systems after World War I, but it resumed *with the old n-folding rate*.

Figure 6 is a similar example provided by members of the Agricultural Engineering Department at the University of Kentucky. Corn yields (in bushels/acre) are given for the United States during the period 1870–1980. Agriculture is the most ancient of all technologies, and this aspect of it was virtually static before the 1930s. The new sciences of plant genetics and biochemistry then provided entirely new tools. The result was a new period of motivated and ingenuity-limited growth. The n-folding constant $n = 2.68$, however, is characteristic of the older technologies.

Utility of the Method

The primary utility of the method is not so much that it provides a predictive tool, although it does that to a limited extent, but rather that it provides a diagnostic tool of some power. This is therefore the appropriate place to present the inferences to which we are led by the cases discussed above, and to indicate some potential uses of the method.

CARDWELL'S FOURTH TURNING POINT

The time constants and n-values from the preceding examples and additional values given by Starr and Rudman [11] are included in Table 1. A recent illustration by Noyes [9] is also included.

Figure 7 shows how T varies with time on semilogarithmic coordinates. The result

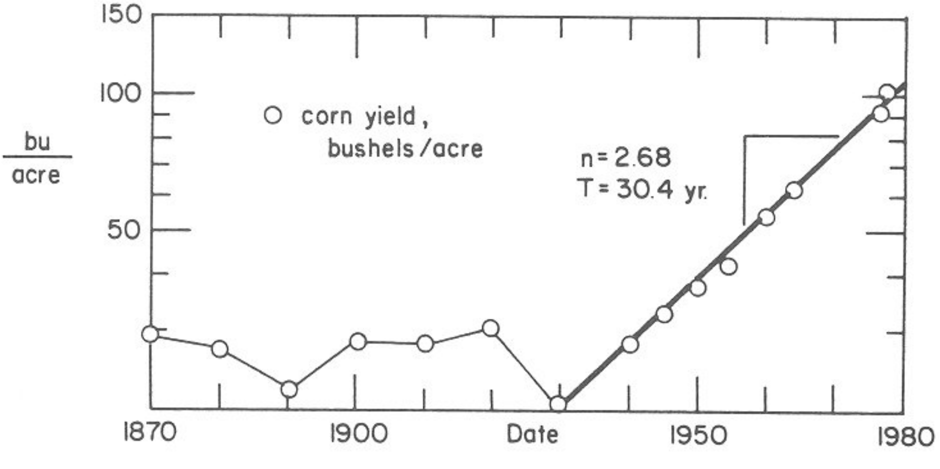

Fig. 6. Increase of corn yields with time in recent years.

TABLE 1
Rates of n-Folding of Technological Quality Improvement

Technology	Quality	Inclusive dates	n	$T = 30/\ln n$
Original examples				
Mechanical clock	Accuracy	1400–1920	1.95	44.1
Steam power	Thermal efficiency	1742–1850	2.5	32.7
Land transportation	Speed	1803–1965	1.86	48.3
Air transportation	Speed	1884–1967	10.1	13
Low temperature	Eq. (4)	1860–1936	21.5	9.8
Corn yields	Bushels/acre	?? –1980	2.68	30.4
Examples from the Guinness Book of World Records				
Well drilling	Depth	1841–1962	2.52	32.5
Diving vehicles	Depth	1865–1960	3.46	24.2
Flight	Maximum altitude	1792–1961	2.64	30.9
Liquid rockets	Maximum altitude	1926–1957	807	4.5
Examples from [11], [9], and [3]				
Incandescent bulb	Lumen per Watt	1880–1960	6.4	16.1
Radio	Broadcast frequency	1896–1960	1.85×10^4	3.1
Particle accelerators	Particle energy	1930–1960	10^5	2.6
Computers	Bits/add time	1945–1970	10^{12}	1.1
Printed Circuits[9]	Component per circuit	1959–1976	2×10^9	1.4

is striking. The time constants are very close to a constant average value of 36.6 years until about 1837. Then they plummet exponentially according the following law:

$$\frac{T}{36.6} = \exp\left(-\frac{t - 1837}{35.8}\right). \tag{5}$$

This means that technologies with motivated growth starting today should double in quality in just a little over five months, and that their n-folding in a 30 year period should be 10^{21}—a perfectly astounding number. Indeed, the rate of improvement of new technologies is now so dizzying that we expect that they must surely encounter some natural constraint. We sense this when we see new computer products appearing on the market and becoming obsolete within months or even weeks.

Equation (5) embodies an explanation of the character of the 19th century shift in technological growth. Suddenly technology begins to *breed* more technology. Before the early middle of the century, society—the public and technologists who served the public—demanded and provided improvement at a constant rate. During the last 150 years, however, technology has begun to respond to itself in a new way; it has begun to set its own pace. The faster technologists saw technology improving, the faster they required the rate of improvement of each new technology to increase.

Many historians have talked about this mechanism of change, and other people have

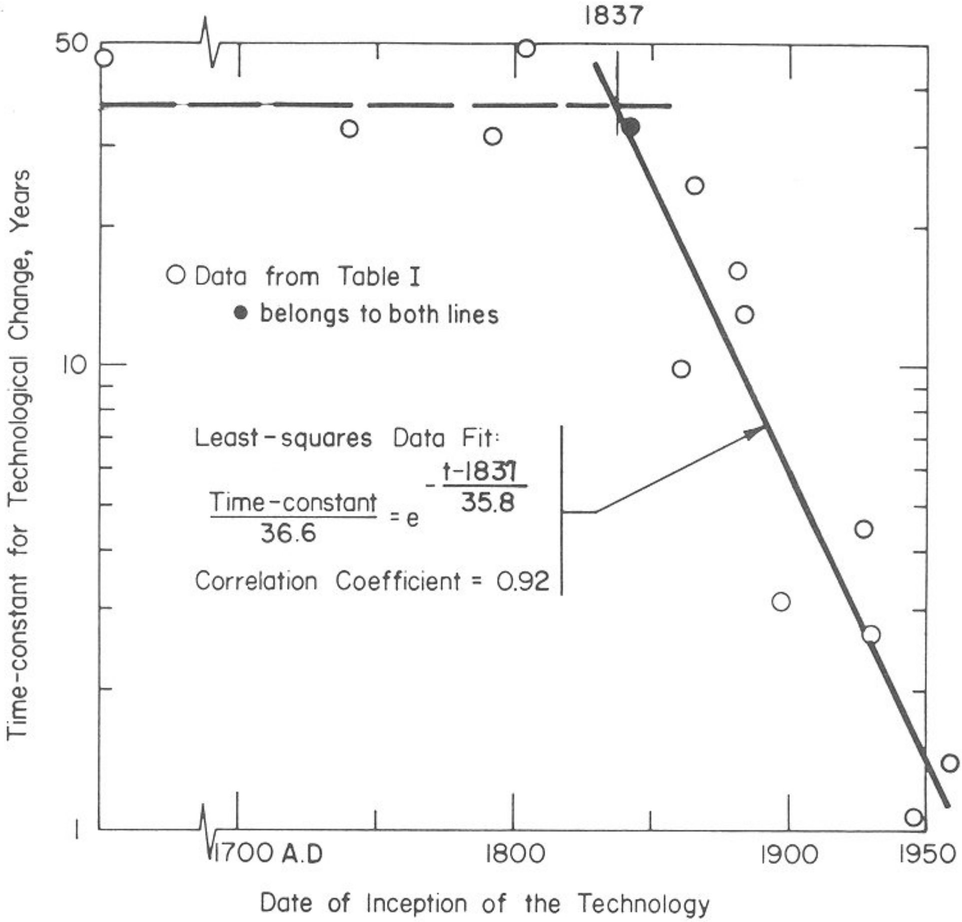

Fig. 7. Historical variation of time Constants for technological change.

noted it quantitatively [3]. Cardwell [1], in particular, discussed the evolution of Western technology in terms of "turning points," the last of which he places in the mid-19th century. This was the turning point between the period of the industrial revolution and the establishment of industrial research laboratories:

> The conspicuous feature of the period was the rapid convergence of science and technology considered as institutions. . . . Whitehead . . . expressed the point very succinctly when he wrote: "The greatest invention of the 19th century was the invention of the method of inventions . . ." The phrase . . . refers . . . to the devising of institutions to ensure technological progress: the research laboratory, . . . the design /development department, the technical sales and services. . . . The main agents of this change have been the increasingly numerous classes of highly trained professional engineers and scientists. . . .

This is precisely the kind of "self-consciousness" and attendant self-excited growth that Figure 7 shows arising in the 19th century. We return to this matter below.

THE CONSTANCY OF *n* AND *T*

The *n*-folding rates and time constants of quality improvement are strikingly independent of outside influence. A 1920s operetta entitled *Robin Hood* includes an "Armorer's Song" in which the armorer at his forge sings:

> Let wars rage still,
> While I work with a will,
> At this peaceful trade of mine.

This bit of doggerel hides a keen insight as to how technology works. Kings and empires, wars and pestilences, come and go; but any given technology moves on inexorably at a pace that seems to be set at its inception, and which remains remarkably resistant to any influence.

The constancy of n and T are surely two of the most interesting results of this exercise. The implication is that there is a powerful inherent conservativism among the practitioners of a given technology. However, the attitudes toward progress *are not shared from one technology to another*. Surely any attempt we make to alter technological growth patterns must come to grips with the way growth rates appear to be immediately frozen at the inception of each technology.

The rate of improvement can be interrupted when absolute constraints arise—when it temporarily becomes complete. This was apparent in Figures 5 and 6. Then, when the constraint is released, the old rate reemerges. A given technology seems almost to have a memory that outlives its practitioners.

THE DOUBLING PRINCIPLE FOR Q AND THE RATE OF CHANGE OF Q

Equation (5) and Figure 7 reveal that, prior to about 1837, the time constant T of quality improvement was 36.6 years. Subsequently, T increased with its own time constant of 35.8 years. These values are virtually the same and (based on Eq. (3)) they correspond with 25.4 and 24.8 years, respectively, for $n = 2$.

Therefore we might have been overly optimistic in estimating the effective working lifetime of a technologist at 30 years. Perhaps 25 years is a better number. Then we could conclude that:

1. Prior to Cardwell's fourth turning point, technologies improved by doubling their quality every technological lifetime, T;
2. After Cardwell's fourth turning point, technologies improved by doubling their time constant of improvement every technological lifetime.

It therefore appears that what really happened in the early middle of the 19th century was that, as attention was shifted from actual inventions to the method of invention, that the quality of the method was the thing that began to improve exponentially.

POTENTIAL USES OF THE METHOD

The Diagnosis of History. We have already seen how the definition of quality, and the exponential improvement law based on the definition, have permitted us to sharply identify Cardwell's fourth turning point, and to say more clearly what happened in that transition.

By tracing the constancy of n, or its variability, we can learn something about the cross-fertilization—or lack ot it—among technologies. It seems clear, for example, that the problem of speeding human transport awakened a new strain of technological endeavor with the introduction of flight.

It is quite possible that we might gain a clearer idea of the relationship of flight to its supporting technologies if we sought out those with matching time constants.

The Identification of Barriers to Improvement. By studying the growth time constants of various qualities, we can learn which technologies are independent of one another and which ones are linked. We can learn where traditionalism is regulating rates of improvement. It is quite possible that such analyses would suggest new modes of industrial organization to avoid such entrenchment.

The Prediction of the Rate of Improvement of Active Technologies. Actually, people currently do make predictions with the help of exponential growth laws. However, our present scheme of definition and prediction gives us better means of delimiting these growth laws. We can show how this works with the help of an example.

Snigier [10] pointed out in a 1980 editorial that Moore's exponential law was failing. Moore's law said that the memory capacity of electronic devices quadruples every two years. This gave a time constant of growth equal to 1.44 years—appropriate for a technology that began growth in about 1950 according to Eq. (5). This is about the year that motivated work began on the technology of semiconductors.

Snigier objected that the law, or any modification of it, had to fail because such devices were approaching a theoretical limit of information storage density in silicon. In our terminology we would say that the technology was becoming complete. Gordon's paper in this issue coroborates this. His semi-log plot of a "computer index" against time (Figure 5) gives a growth time constant about equal to that predicted by Eq. (5). His curve, however, definitely flattens out during the last decade. Thus the present method predicts Moore's Law and Gordon's computer index growth correctly; it also has the capacity to explain the cessation of exponential growth.

The Development of Multiquality Analyses. The workshop in which this paper was presented made it clear that there is a great need for multifactor analyses of technologies. Fortunately the method can be expanded to include consideration of:

1. measures that represent weighted combinations of several relevant qualities of a given technology;
2. qualities of support technologies that simultaneously serve technologies with different time constants;
3. qualities of technologies that are served simultaneously by other technologies whose time constants differ;
4. the relationship among the several qualities within a given technology.

Other variations are possible. Ayres paper in this issue includes data that illustrate how we might approach consideration 4. Figure 8 displays Ayres' data for the power-to-weight ratio of land transport vehicles between 1804 and 1975. It also includes data from [2] for the power-to-weight ratio of airplanes. (This data set was more complete than, and provided answers to some of the questions left open in, Ayres' table.) Figure 8 shows that both the power-to-weight ratio and the speed yield nearly the same time constants and n-folding rates for the technologies of flight and ground transport. Would this be true for all the qualities of a technology? We think so, but would need more data to so assert.

Alexander's paper in this issue likewise presents data that speak to the question of how the time constant of a technology served by other technologies with different time constants might look. In Figure 9 we plot the inverse of his total-factor-productivity $1/(P/I)$ against time for both the automotive and computer industries. The resulting time constant for the automotive industry is virtually the same as it is for the speed of ground transport, although the time constant for computers is much longer.

Figure 9 strongly suggests that the auto industry is supported by component tech-

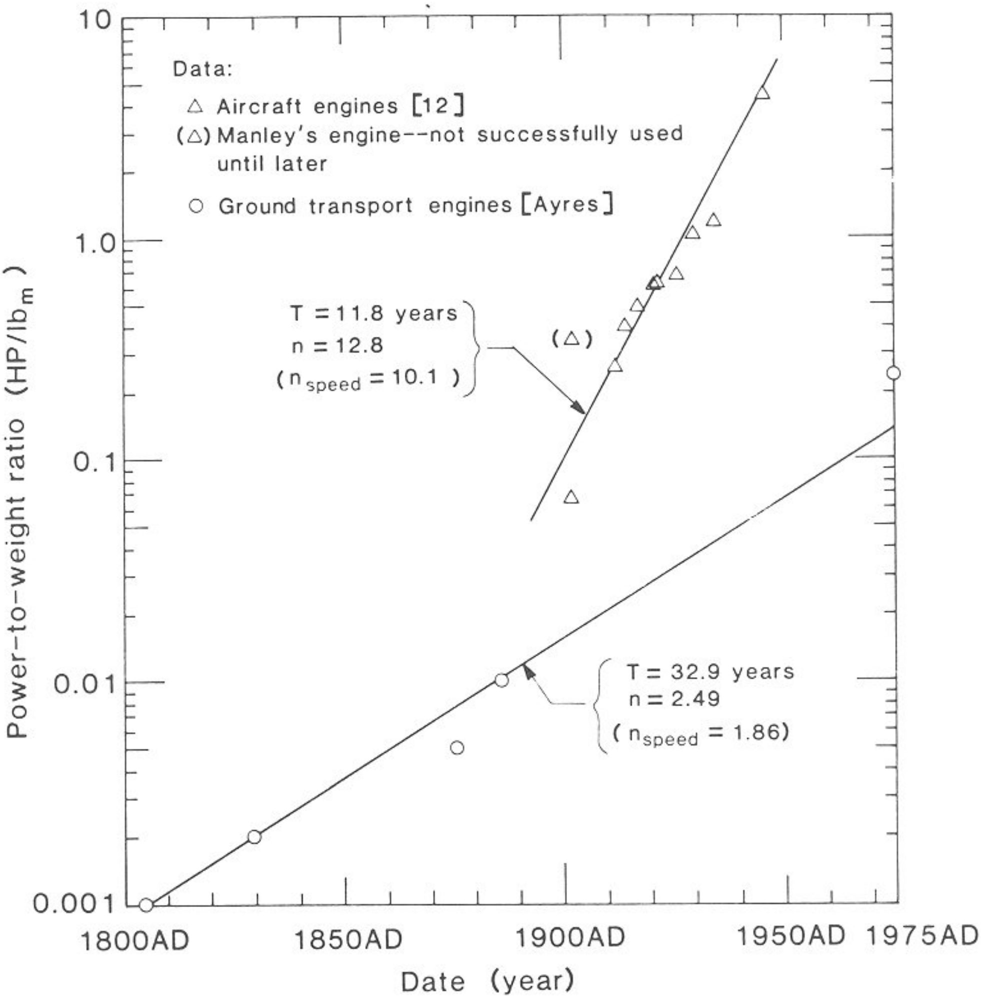

Fig. 8. The improvement of the quality of power-to-weight ratio.

nologies that all grow at an old (hence slow) rate. The computer industry, on the other hand, might well be supported by a variety of both fast and slow technologies, some of which keep it from moving as fast as its technologists would like.

These observations are highly conjectural at this point, but they illustrate how the method might be used to analyze multifactor problems.

Potential Improvements

Many issues remain to be explored. For example, we have noted that there is an element of conservatism in the processes that give rise to the improvement of a given technology, but we have not localized this conservatism. We should find out whether it is controlled by the technologists or by their society.

We have barely suggested a course of future work on understanding the relationship among growth laws for different technologies. Figure 8 suggests that, following the rise of the internal combustion engine in the latter 19th century, the technology somehow

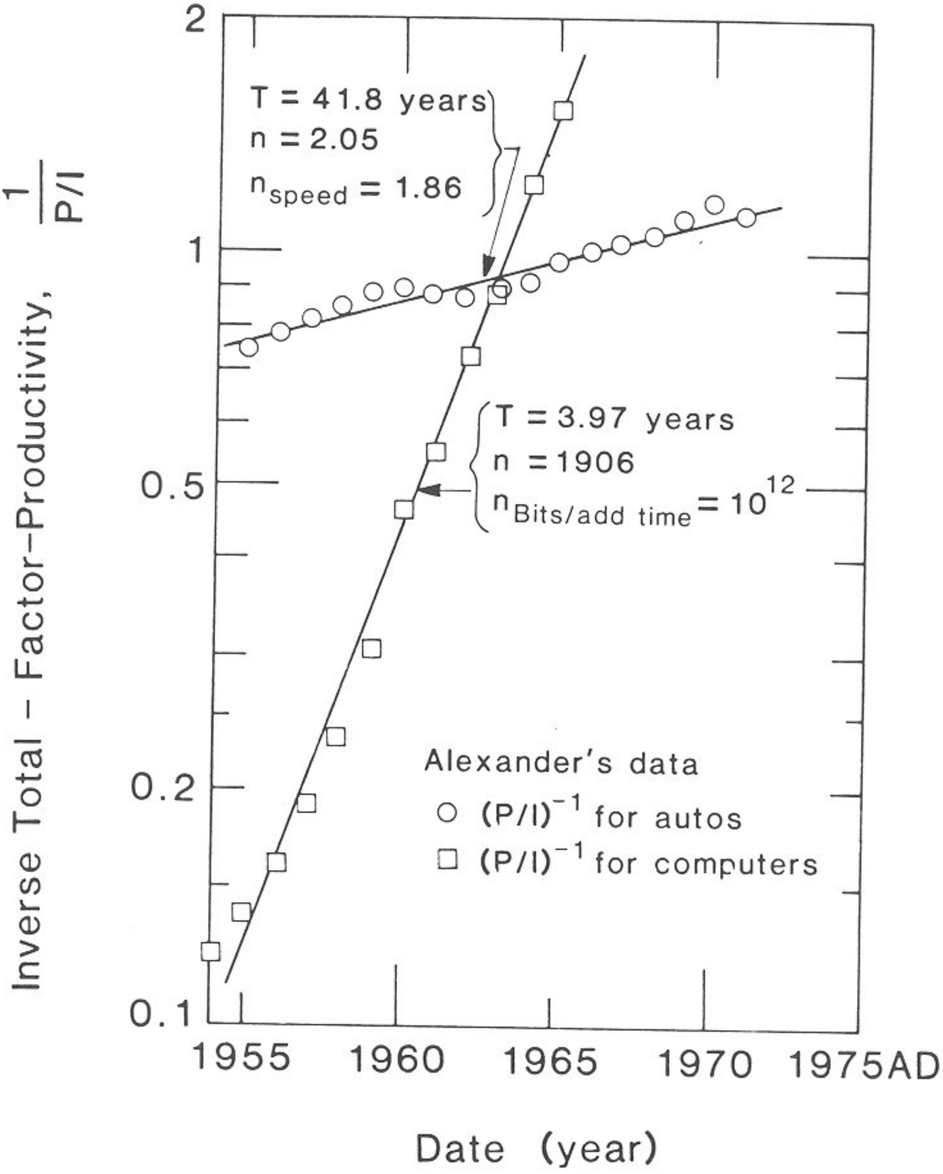

Fig. 9. The growth of inverse total-factor-productivity with time, for automobiles and computers.

divided into two technologies with the advent of flight; but we have no idea what the *mechanism* of such splitting is. Such mechanisms must be understood from historical and sociological viewpoints if the the method is to become truly convincing.

A more fully developed method would be equipped to answer such questions. A next step would be to address specific questions of cross-fertilization and to develop worked-out examples.

There are long-term and short-term problems that should be resolved. The flow of ingenuity is never steady, but we have been able to iron out fluctuations over long growth histories (as we did for thermal efficiency during a growth period of more than a century).

Today we look at time constants that are, perhaps, only a quarter as long as it takes Hewlett-Packard to retool its next product. This means that the normal fluctuations in any growth can look increasingly large when they are superposed on the growth curves for recent technologies.

Additional Comments

I began by saying that technology was part of the animal nature of man. Technology, like any other art, flows from, expresses, and ultimately exalts that nature. Our animal nature will find ways to express itself. It will get around constraints of politics or policy, of feast or famine.

The present definition/method reveals growth patterns that are consistent with this view of technology and humankind. That is what really convinces me that it is correct and will ultimately lend itself to considerable extension.

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