Did the genes for these toxins evolve by chance from other prokaryotic genes, specifying proteins that were of value to bacteria or their viruses, which then with slight modification lost their previous function and specified toxins instead? This seems to us very unlikely. The alternative, which by default remains the more attractive, is that many of the toxins produced by pathogenic bacteria are the products of descendents of eukaryotic genes that were randomly incorporated into phage genomes during chance association with certain eukaryotic cells.

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# Parameters of Technological Growth


Chauncey Starr and Richard Rudman


In recent studies of the limits to population growth in a finite world, the assumptions concerning the future availability of new technologies are crucial. The predictive scenarios developed by Meadows *et al.* (*1*) and Forrester (*2*) assumed only a few discrete contributions of technology to ease the world stresses produced by growth. Meadows states, "The basic behavior mode of the world system is exponential growth of population and capital, followed by collapse . . . . When we introduce technological developments that successfully lift some restraint to growth or avoid some collapse, the system simply grows to another limit, temporarily surpasses it, and falls back." On the other hand, Boyd (*3*) has shown (Fig. 1) that a "technological optimist" approach of a continuous flow of technological change completely alters the conclusions from Forrester's world model simulation, and avoids the overshoot, collapse, and human tragedy implications of Meadows *et al.* (*1*) and Forrester (*2*).

It is, of course, an obvious outcome of elementary mathematics that an exponential will overtake any fixed quantity or some fixed multiple of it. In


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*The Limits to Growth* analysis, future technology was assumed to double resources and land yield and to reduce pollution by a factor of 4, but other key parameters grew exponentially. Thus the results, which indicated that these technological improvements only changed the time scale for future system collapse, were to be expected. Unfortunately, *The Limits to Growth* generalized these narrow findings as follows. "As we have shown in the model runs presented here, this behavior mode occurs if we assume no change in the present system or if we assume any number of technological changes in the system." This is clearly contradicted by Boyd's study of the effect of a continuous technological growth in the same model.

It is therefore valuable to examine in greater detail the historical genesis of some of our major technological capabilities—in order to use their general characteristics as a basis for estimating the future production of technological options which may be available to meet the pragmatic needs of the world. Whether such options are actually used will be, of course, a sociological matter involving all manner of human values, trade-offs, and perceived costs, and will depend on the

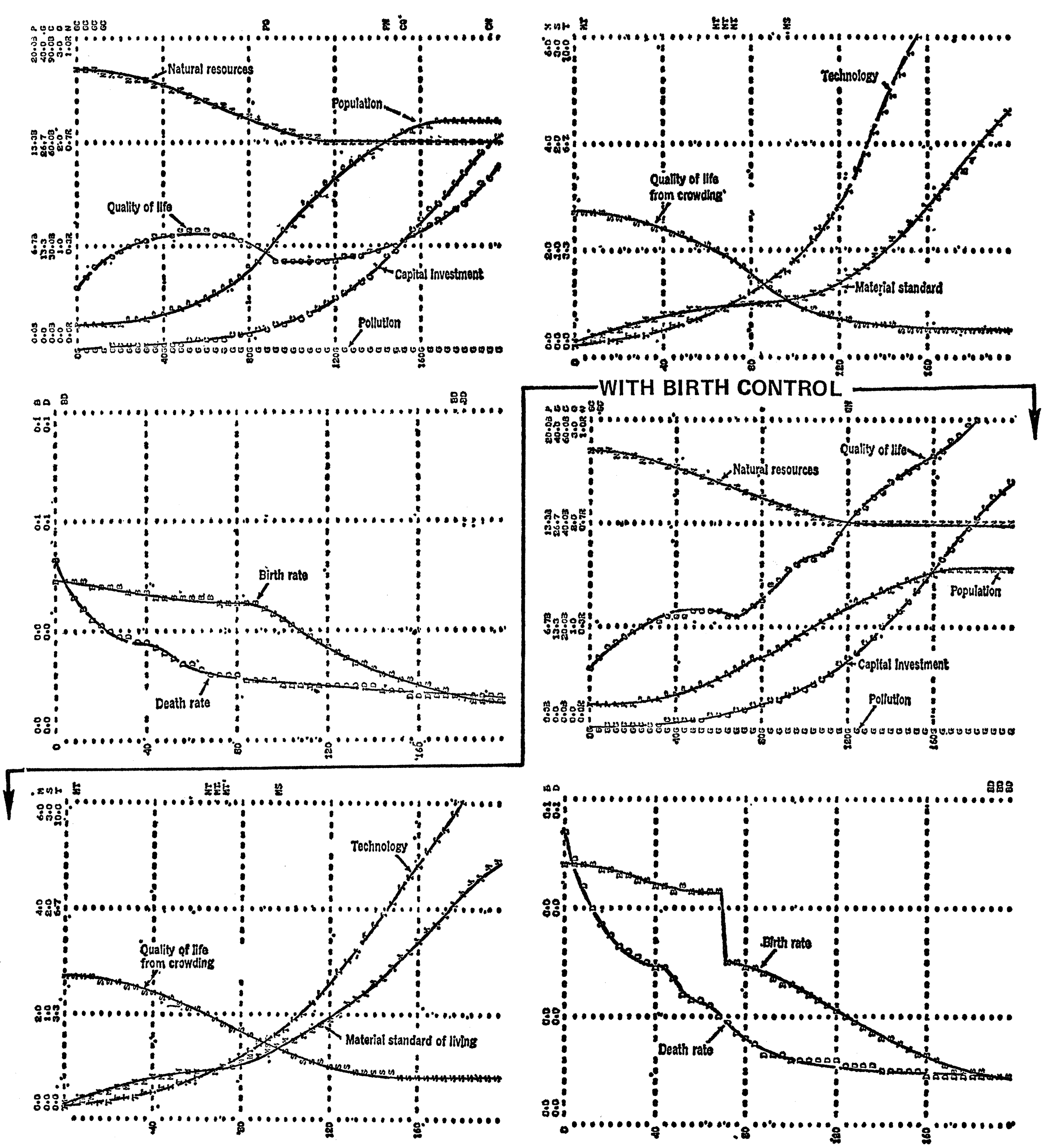



Fig. 1. Results of the world dynamics simulation altered to include the assumptions of the technological optimist. The simulation starts at 1900 and runs through 2100. [From (*3*)]

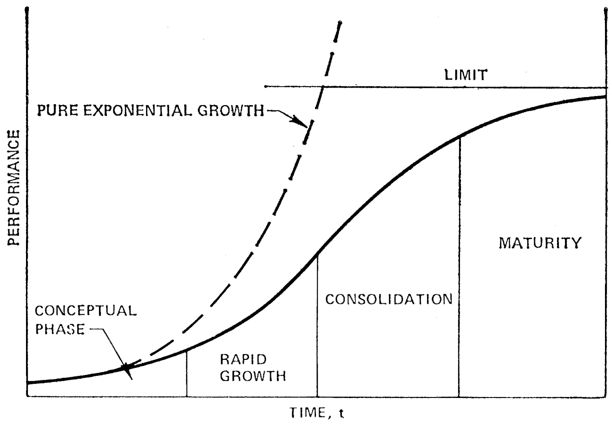



Fig. 2. General form of the sigmoid curve. Performance = limit/(1 − $be^{-at}$).

existence of social institutions structured to advantageously exploit such new technologies. While it is obviously not possible to predict the content and time scale of specific technical achievements which may be important in future social change, it may be feasible to scope the general characteristics of growth of that societal resource encompassed by the common term "technology."

Of most value to a society seeking solutions to a myriad of problems is not only the performance of existing operational technical systems, but, more importantly, the number of technical options available at any time to meet new needs and new constraints in a desirable manner. We will assume in this analysis that a choice among new options results in technical change that is a function of both the technology in use at the time and the amount of societal resources previously made available to develop such new options.

The strength of technology within a society can be measured by the relative role that technology plays in the establishment and attainment of societal objectives. A strong technological base is characterized both by the abundance and the quality of the technological resources and by the society's ability to mobilize and efficiently use these resources to meet changing needs. For the purposes of this discussion, we assume that the strength of a society's technology can be inferred from technological resources and societal expectations from technology. Technological resources refer to (i) knowledge relating to natural phenomena and their end-use applications, for example, science, industrial arts, and know-how; (ii) physical and industrial resources and institutions—for example, laboratories, testing and development facilities, supporting manufacturers, universities, libraries, and computing centers; and (iii) manpower, which consists of scientists, engineers, managers, and planners.

Societal expectations and objectives determine the allocation of resources among all of the technological and nontechnological activities within our society. The expectation associated with each technology dependent activity is a function of (i) the relative importance of the activity to the society, and (ii) a payoff factor that defines the perceived marginal utility of the particular allocation.

Apart from the existing difficulties of finding such unique parameters and a measure of this combination, it is sufficient for this study that we assume that such a measure exists.

The "strength of technology" as a measurable concept suffers from the same vagueness as most aggregate terms such as quality of life, environment, pollution, health, happiness, and others used to describe the human condition in our society. Each such term must eventually be defined as the sum of many specific measured components, appropriately weighted either empirically or judgmentally. Although the resultant indicator will have a high degree of uncertainty, it will nevertheless be a useful measure of those elements on which there is a general consensus. Because large-scale societal models, like those we are discussing here, tend to require such aggregate classifications, it is meaningful to use such a concept as "strength of technology," provided that the limitations of its content are recognized.

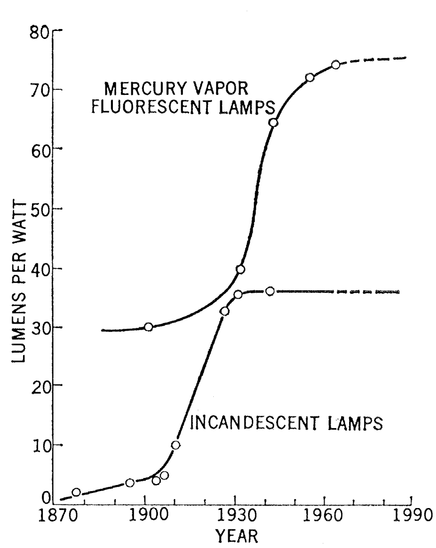



Fig. 3. Illumination growth curves illustrating the sigmoid behavior of two successive technical approaches. [From (*4*); courtesy of Institute of Electrical and Electronics Engineers]

It is generally recognized that the technical systems operating at any time are usually based on technology that came out of the R & D pipeline some one or more decades previously. This lag in diffusing new developments and replacing old systems creates a general societal expectation and desire for change. The recognition that new technological options might better meet perceived needs provides the basic motivation for allocation of societal resources to spur the process of technical development and innovation. The fine structure of this societal assessment of the value of investment in technology must, of course, distinguish between basic and applied science, the various fields of engineering and manufacturing, the incentives for innovation, the constraints and challenges of social values and goals, and—most importantly—the perception of pending as well as existing needs. However, even without such a detailed exploration, it is illuminating to consider a simplified analysis of the relation between the growth of technology and societal perceptions.

## Technology Growth Analysis

As was discussed above, we assume that the discretionary resources of society at any real time, $t = r$, is the proportional product of a past technology at $t = p$ where $r$ is real time and $p$ is past time. Thus, if $T$ is the strength of technology, then societal resources (at $t = r$) $= \alpha T_p$ where $\alpha$ is a proportionality constant. Societal expectations from investments in technology are assumed to determine the fraction of the available discretionary resources that will be allocated to technological development. These expectations are defined by two parameters. The first, the technological "payoff factor," is expressed as the relative difference between the technology ($T_p$) in common use and the perceived potential level of technological capability ($T_r$) based on current resource strength as previously defined. The second parameter is the relative priority which society assigns to attaining the performance objective associated with the perceived potential of the most updated level of technology. Expressing this mathematically, societal expectations from technology are equal to $\beta(T_r - T_p)/T_p$ where $\beta$ is the relative priority factor and $(T_r - T_p)/T_p$ is the technological payoff factor. The amount of discretionary resources allocated can now be defined as the product of the total resources available and the societal expectations; that is, resource allocation to technology is equal to

$$(\alpha T_p)\ (\beta \frac{T_r - T_p}{T_p})$$

If, then, the rate of change of technology is proportional to the societal investment,

$$\frac{dT_r}{dt} = \alpha\beta(T_r - T_p) = \alpha\beta(1 - \frac{T_p}{T_r})T_r$$
$$= \alpha\beta(1 - \gamma)T_r$$

where $\gamma = T_p/T_r$. It is evident that this is a growth relationship—and assuming $\alpha$, $\beta$, $\gamma$, are constants—is of the simple mathematical form

$$T_r = T_0 e^{\phi t}$$

where $\phi = \alpha\beta(1 - \gamma)$ and thus technology exhibits an exponential growth.

If $\phi$ is indeed a constant, then $\gamma$ can be expressed as

$$\gamma = T_p/T_r = \epsilon^{-\phi(r-p)}$$

where $(r - p)$ is the delay time for technology applied to societal needs.

In the convenient nomenclature of doubling time, $D$, we have $\phi D = 0.693$. Conventional wisdom suggests that the technological component of economic growth has a doubling time of 20 to 30 years. For 30 years, $\phi = 0.023$; that is, a 2.3 percent annual compounded growth. If the delay time for practical innovation is roughly 10 years, then $\gamma = 0.79$; and thus 21 percent of potentially available technology is not yet in use. These appear to be reasonable numbers for illustrative purposes, although the use of a single equation for all of technology is an obvious oversimplification.

One area that has not been considered is how the growth of technology will be affected by the interaction between the various scientific and engineering disciplines resulting from the exchange of knowledge and availability of technological devices. These synergistic interactions should provide additional positive feedbacks that will increase the efficiency with which new investments in technology could produce new technical options. It is difficult to separate such interactions from the overall concept of technological strength, and may be more properly a part of the fine structure of the measure used.

In order to apply this analytic procedure, one would have to study individual areas of technology ($T_i$) in order to determine the technological payoff factor, $(T_{r,i} - T_{p,i})/T_{p,i}$, and the relative priority, $\beta_i$, associated with each technological field. Having quantified these parameters, the overall behavior of technology could in principle be estimated by summing over these individual fields. For this presentation, such a theoretical composite is assumed to exist. Societal value systems and cultural expectations, integrated by the political decision-making process, determine the relative priorities of all human activities; and, in turn, determine the detailed allocations for individual activities such as technological fields.

Finally, a qualitative insight into how the priority and payoff factors affect technological growth can be gained by looking at two recent examples. First consider the growth of the U.S. space program during the 1960's. Here the perceived large technological payoff factor was represented by the difference between the Soviet sputnik technology and our own space efforts. The relative priority of the U.S. space program was established at a high arbitrary level because of its political implications. These two factors produced a large societal expectation which, in turn, caused a sizable allocation of resources, and a consequent spectacular growth of the U.S. space program. In contrast, the second example is the application of technology of housing programs, where, although the societal priority factor has always been high, the technological payoff has always been low. As a result, our national endeavors in improving housing through technological development have been modest and have made only modest contributions. Clearly, not every social need can be met by an influx of technology alone.

## Empirical Evidence for Validity of the Growth Concept

The growth of the technological sector of our society depends on many interrelated parameters. Defining one parameter, or a group of parameters, as an absolute measure of technological progress lies beyond the scope of this

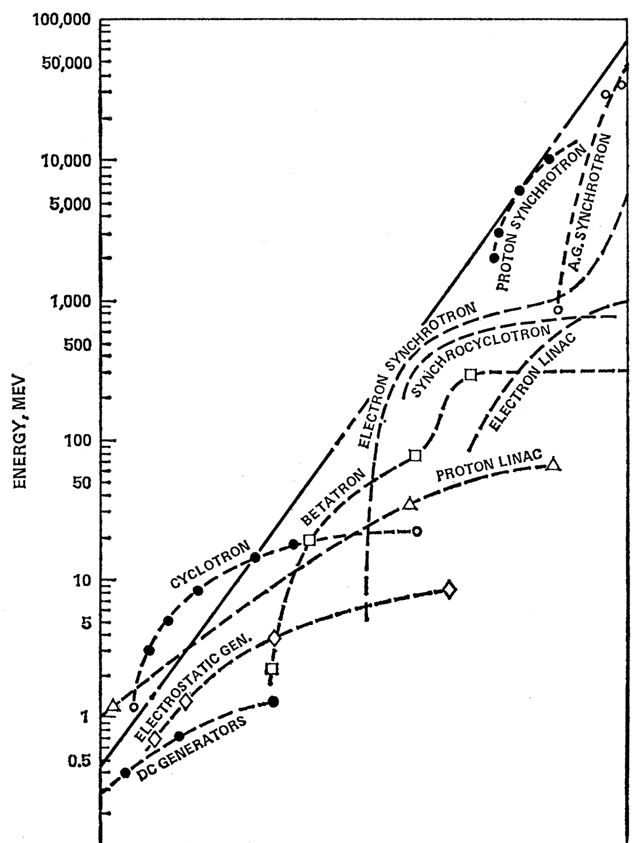
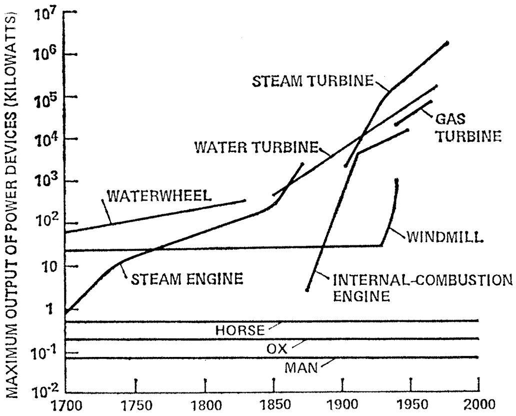



Fig. 4. The rate of increase of operating energy in particle accelerators. [From (5); courtesy of McGraw-Hill, New York]



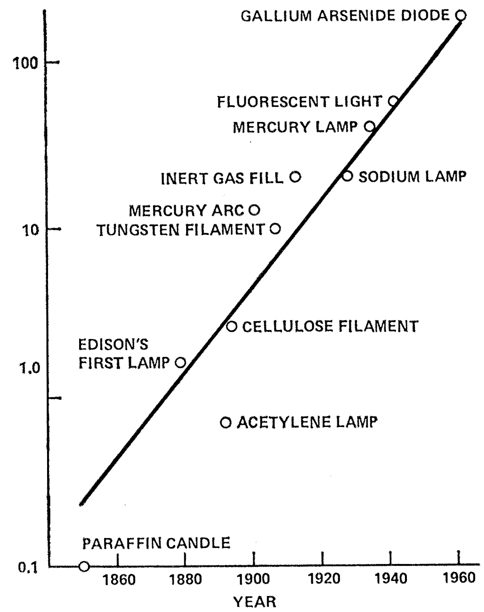




Fig. 5 (left). Power output of basic machines has climbed more than four orders of magnitude since the start of the Industrial Revolution (about 1750). For the steam engine and its successor, the steam turbine, the total improvement has been more than six orders, from less than a kilowatt to more than a million. All are surpassed by the largest liquid-fuel rockets (not shown), which for brief periods can deliver more than 16 million kilowatts. [From (*6*); courtesy of *Scientific American*] Fig. 6 (right). Trend in performance of illuminating devices. [From (*4*); courtesy of Institute of Electrical and Electronics Engineers]

analysis. However, as an initial generalization, it seems reasonable that the strength of general technology at any point in time is related to some combination of the strengths of the individual technical fields. Thus, if a performance growth characteristic can be found to be common in many individual fields, then general technology should presumably have a similar growth pattern.

An historical survey of the performance growth of specific technical options reveals two predominant characteristics. First, when the performance of a given type of device or system is plotted against time it follows a sigmoid curve of the form shown in Fig. 2. This curve exhibits a slow growth during its initial or conceptual phase, a subsequent period of exponential growth, and then a final flattening as the curve asymptotically approaches a limit. The limit may be set by social regulation or constraint, or by physical limitations that constrain the performance level. Examples of socially established limits are the following: the effect on automobile horsepower of automobile insurance rates; the legal speed limit for automobiles, which is set by safety considerations rather than technological feasibility; and finally, the slowdown in the space program during the past several years, which can be attributed to a lack of funding and not to a lack of technological opportunities. Physical limitations include such things as the speed of sound, which defines the limit for the speed of a propeller-driven aircraft; or, the mechanical relays used in the first generation of computers, which set an upper limit on the machines' computational speed, size, and reliability.

The second major characteristic is that the overall growth of a technological field is composed of a series of sigmoid curves. Each curve builds on the performance level of the previous generation device. Each new technological step results in eliminating the previous limit and thereby escalates the technological progress of that particular field. Thus the overall growth of a specific technological field often exhibits an exponential pattern.

Figures 3 to 5, taken from the sources noted, show how successive generations of technological steps have increased the performance of lighting efficiency, the operating energy of particle accelerators, and the power output of basic machines. In each of these fields the growth of the performance level of a specific generation of devices shows a sigmoidlike behavior, while the overall growth rate of the field is exponential. This overall exponential growth is clearly seen in Fig. 6, where lighting efficiency is plotted, in lumens per watt, for a variety of illuminating

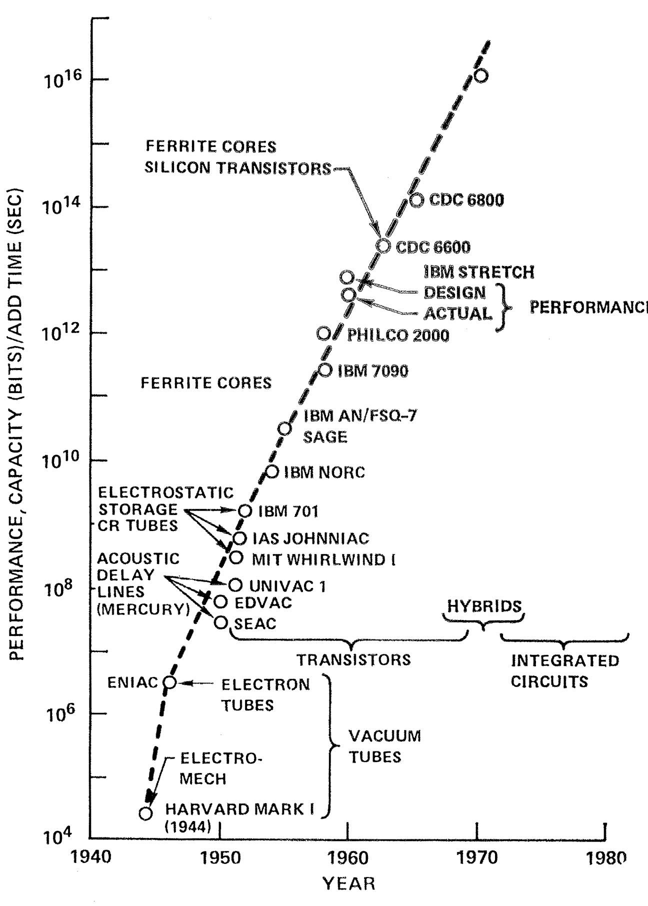



Fig. 7. Computer trends. [From (*7*); courtesy of *Technological Forecasting*]

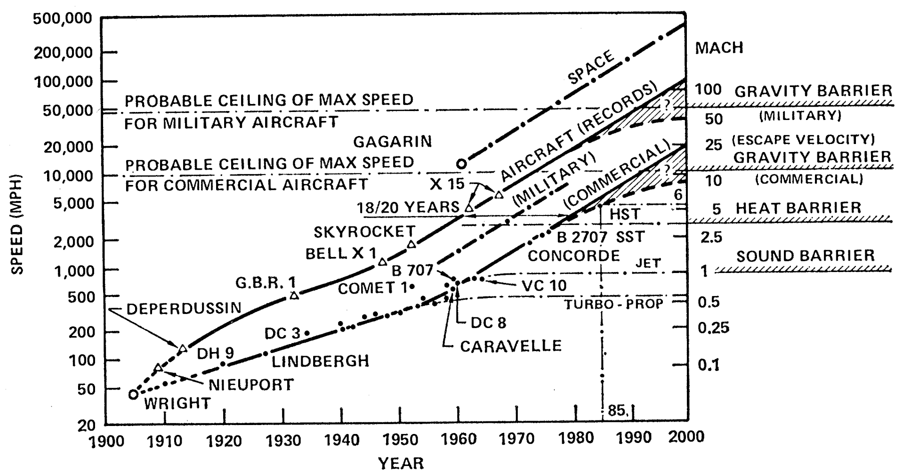



Fig. 8. Aviation trends. [From (*8*); courtesy of *Technological Forecasting*]

devices as a function of the date when the device was introduced. Figure 7 illustrates the performance levels of various generations of computers as a function of time of introduction. Again, as the technical approach shifted from vacuum tubes, to transistors, and then to integrated circuits, we see the computer performance level growing exponentially.

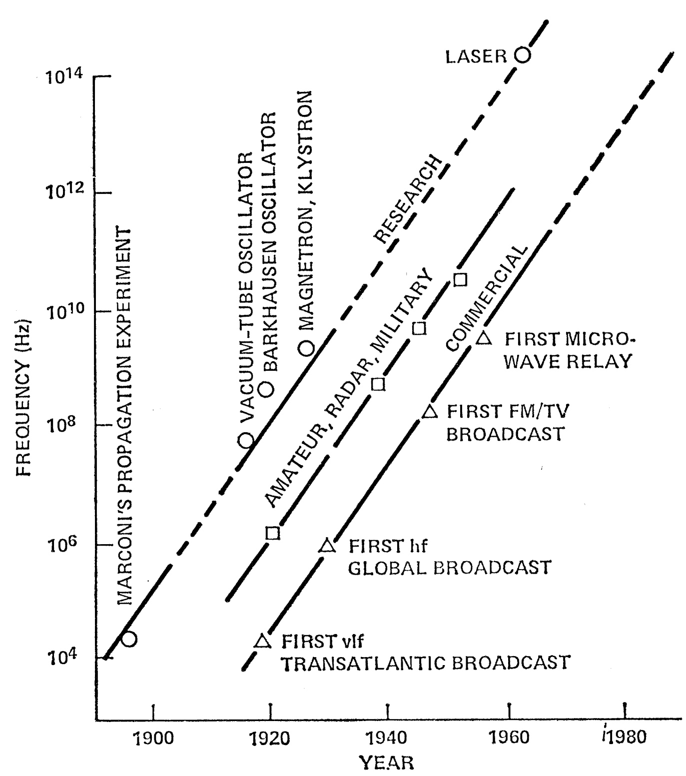
Figures 8 and 9 indicate that another characteristic of technological growth is the relatively constant time lag between the time when the most advanced R & D oriented application of a technological option reaches a certain level of performance and the time when that level of performance is commercially available to the society. For the speed of aircraft this time lag is 18 to 20 years, while for the electromagnetic frequency communication band the lag is in the neighborhood of 25 years.

The technological options just discussed can be thought of as the outputs of the technological development process. As has been demonstrated, these options grow exponentially. Now consider some of the important components of the technological development process such as knowledge, scientific and engineering manpower, and research and development funds. Indicative measures of these parameters are plotted in Figs. 10 to 12. All exhibit an exponential growth. In Fig. 10 the total number of scientific journals is plotted as a function of the journals' founding date. The number of journals is taken as indicative of the production rate of scientific knowledge. In Fig. 11 is plotted the number of scientists and the number of engineers per million of population. Figure 12 shows R & D expenditures as a percentage of U.S. gross national product (GNP).

The exponential rise, shown in Figs. 11 and 12, for the number of scientists and engineers per million population and for research and development funds as a percentage of the GNP, raises an analytic question not addressed in the previous mathematical analysis. It was there assumed that the fraction of societal resources applied to technology was primarily determined by the technological delay time rather than by an increasing importance of technology in the social system, that is, for scientists and engineers per million population

$$\frac{R \& D}{GNP} = \beta(\frac{1}{\gamma} - 1)$$

Thus our elementary mathematical approach produced an exponential growth in technology even with a fixed fractional allocation of available re-



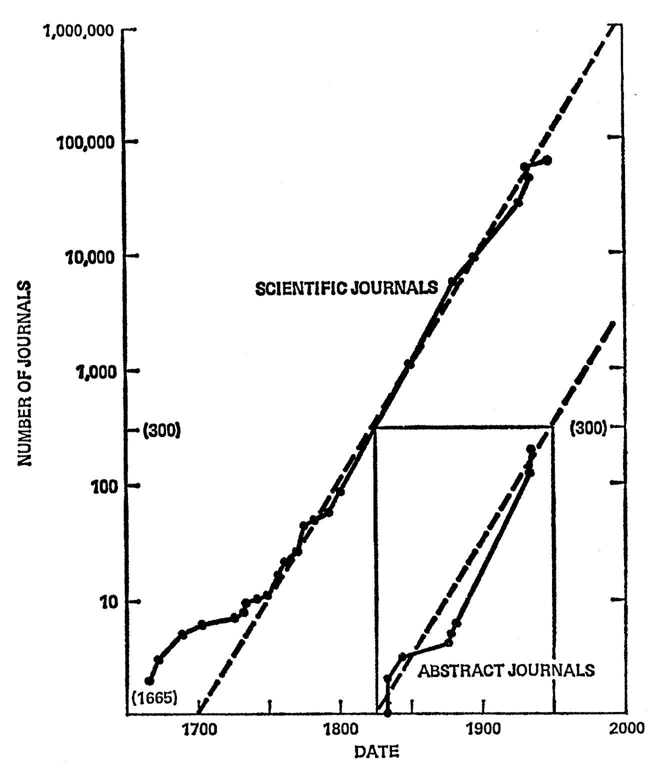
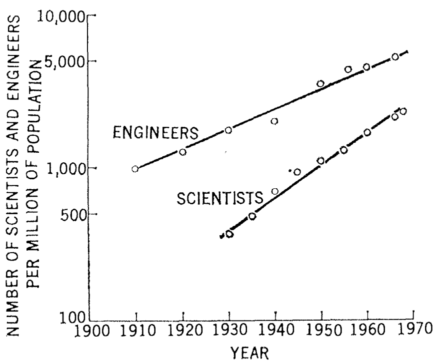




Fig. 9 (left). Broadcast frequency trends. Abbreviations: vlf, very low frequency; hf, high frequency. [From (*9*); courtesy of *Science and Technology*] Fig. 10 (right). Total number of scientific journals and abstract journals founded, as a function of date. [From (*10*); courtesy of Yale University Press]



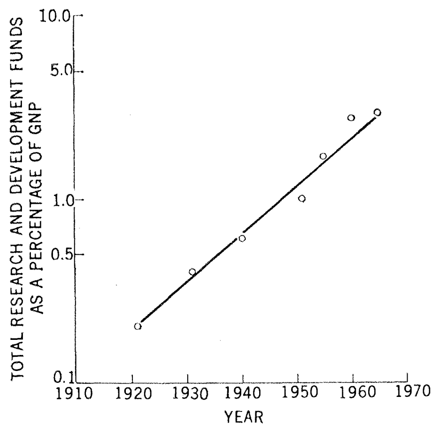




Fig. 11 (left). Growth trend for scientific and engineering personnel in the United States. [Data from (*11*)] Fig. 12 (right). Trend of research and development expenditures as a percentage of gross national product [Data from (*12*); courtesy of Grosset & Dunlap]

sources. Inherent in this approach was the assumption that the new technological options would increase the total resources available and thus result in a continuous growth of technology. The role played by the increasing percentage of the GNP allocated to research and development during the last half-century was not considered in the analysis and would represent an additional forcing device for technological growth. This question should be examined further. However, the key point is that even with a fixed percentage of the GNP directed to new technology, an exponential growth should occur.

## Conclusions

The key parameters to technological growth have been identified as societal resources and societal expectations. Both of these are evident functions of technology, and their combined effects can be expected to continue technology's historical exponential growth. This growth pattern would be substantially altered only if we assume that knowledge is bounded or if society makes a conscious decision to stop the flow of resources into the production of new technological options. Although such conscious selection among individual technical fields is to be expected, it is very unlikely to apply to the totality of technology since, as society grows more complex it continuously creates new needs (priority factor), which in turn provide new opportunities for the application of technological options (payoff factor). The analysis also clearly emphasizes the important role which awareness of new technologies plays in forming societal expectations.

These considerations indicate that the technological component of the world simulation model proposed by Meadows *et al.* (*1*) and Forrester (*2*) is best represented by an exponential growth function. The importance of this has been shown by Boyd (*3*) (Fig. 1), whose "technological optimist" curve has slightly less than exponential growth. Private communication with Boyd indicates that an exponential assumption would reduce the time for equilibrium by several decades. Boyd also indicated that in his modification of the world dynamics model, an exponential technological growth would eventually dominate all other parameters in determining the long-term approach to a steady state. It is evident that the behavior of any world system model is very sensitive to the growth and interaction assumptions for its principal parameters. Thus, model studies should not be easily presumed to represent reality.

The one conclusion that appears to be valid regardless of approach is the evident merit of reducing population growth. The parameter for quality of life shown in Fig. 1, parts 2 and 5, is the product of material levels, overcrowding, food, and pollution. The one factor that a "technological optimist" cannot expect to substantially alter in this model is the effect of overcrowding (Fig. 1, parts 3 and 6). Certainly, the many clear values of reducing population growth and improving the environment do not appear to require the justification of a world system analysis. In like manner, it seems appropriate to encourage the "technological optimist" to provide future options for societal choice, even though there may be present philosophical uncertainties as to their eventual merits. Unlike resources found in nature, technology is a man-made resource whose abundance can be continuously increased, and whose importance in determining the world's future is also increasing.

### References and Notes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