The Dynamics of Long-Term Growth

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ABSTRACT

The authors have studied the effect of tool-making on man's evolution. They argue that growth is not exponential, but hyperbolic, and that a positive feedback exists linking technological development to population. Exploring the nature of this mechanism in order to improve the predictive capability of global models is the goal of the article.

I. Introduction

Dynamic growth is one of the major phenomena of human development. The increase of human population is often referred to as "explosive" [1]. Similarly, technology and its consequences, such as pollution, are expanding dramatically. The report by Meadows [2] and a number of other publications [3] call attention to the consequences of unlimited growth, but they leave aside a number of points that should be clarified. In particular, the inaccuracy of past population forecasts points to the unreliability of accepted models of growth. It is important to ascertain whether or not the phenomenon of growth follows an exponential law. The present article argues that growth is, in fact, hyperbolic. The data seem to show a positive feedback mechanism, linking technological development and population, to exist. Exploring the nature of this mechanism in order to improve the predictive capability of global models is the goal of this article.

II. Quantifying Growth

It is of the greatest interest to obtain as precise a quantitative view as possible of the acceleration of growth. In our observation, the phenomenon is *underestimated* in terms of its own dynamic properties.

Let us first consider world population as a variable. The growth phenomenon has unique characteristics that make population forecasts inaccurate and lead to a *systematic extrapolation lag.* The authors of a recent report [34] have observed: "Projected future population figures rest on a . . . much firmer basis than any other *set* of figures . . . and still there have been monstrous mistakes in projections." A case in point is the inaccuracy

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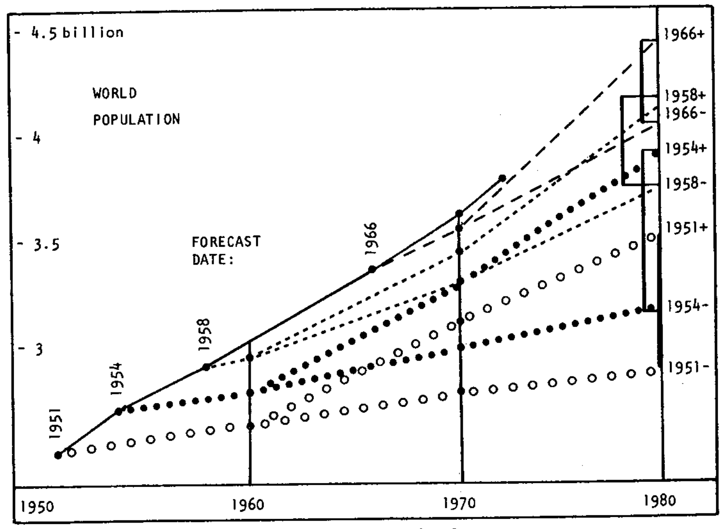

FIG. 1. Forecasting lags.

of predicted population levels computed by the Social Affairs Department of the United Nations. These forecasts use analytical indices and careful computations based on classical methods. They have been published in 1951, 1954, 1958, and 1966 [11]. They have fallen consistently short of the observed values. Figure 1 is a display of the high and low predicted values. It allows one to witness an alarming failure of the forecasting model.

A. GROWTH IS FASTER THAN EXPONENTIAL

Most researchers hold growth to be exponential. This is, in particular, the assumption underlying the work of Meadows [2] who presents a classical analysis of steady exponential growth; this analysis, embedded in a dynamic programming model, anticipates the effects and the consequences of demographic and technological growth. Our conclusion is that a more detailed analysis would show growth to be *faster* than exponential. This can be demonstrated in a number of ways. As early as 1951, Julian Huxley [4] called attention to the fact that the *rate of growth* of world population increases constantly, not

TABLE 1

Year	Population (millions)	Yearly rate of growth (%)
1972	3,782	2.03
1971	3,706	2.02
1970	3,632	1.97
1960	2,982	1.82
1950	2,486	0.91
1930	2,070	0.86
1900	1,600	0.62
1850	1,070	0.52
1800	900	0.44
1750	720	0.31
1700	620	0.27
1650	540	

only in contemporary times, but since prehistoric times. The demographic growth of the species, therefore, does not follow an exponential development curve with a constant rate, but a hyper-exponential law with increasing rate. More recently, this property of the growth curve has been rigorously established by Cailleux in 1951 [5], by Meyer in 1958 [6], and by Von Foerster, Mora, and Amiot in 1960 [7].

Table 1 gives the numerical values for world population and growth rate since 1650 [8]. Simple examination of this table shows that evolution is not a constant rate exponential, but rather a hyper-exponential one with an increasing rate.

B. GROWTH OF POPULATION IS HYPERBOLIC

A simple graph will make this fact more visible and more significant. Figure 2(a) shows population growth on an arithmetic scale. Figure 2(b) shows the same data with a logarithmic scale: One can observe that the curve is not linear, as we would expect for an exponential function. Figure 2(c) shows the phenomenon on a double logarithmic scale with a time origin at t_0 = 2026. On this scale, the curve becomes a straight line, yielding the linear equation:

$$\log P = 11.310 - \log(2026 - t),$$

and the following expression for world population as a function of time:

$$P = \frac{2 \times 10^{11}}{2026 - t}.$$

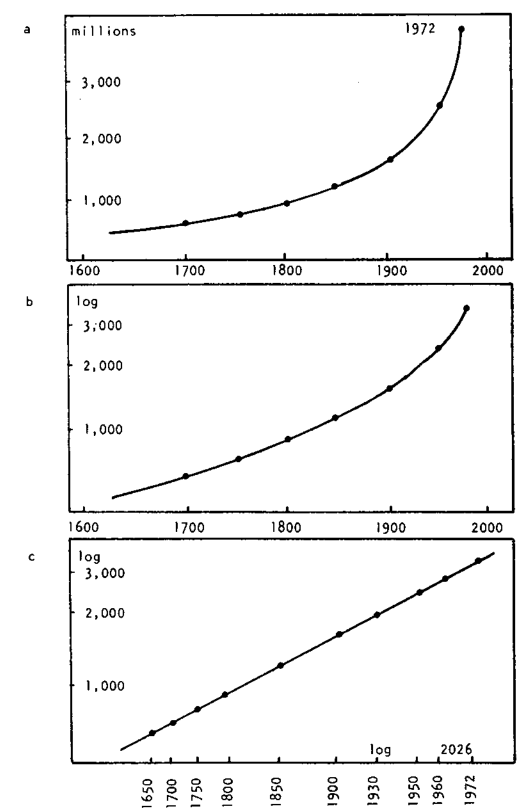

FIG. 2. Population growth from 1650 to 1972.

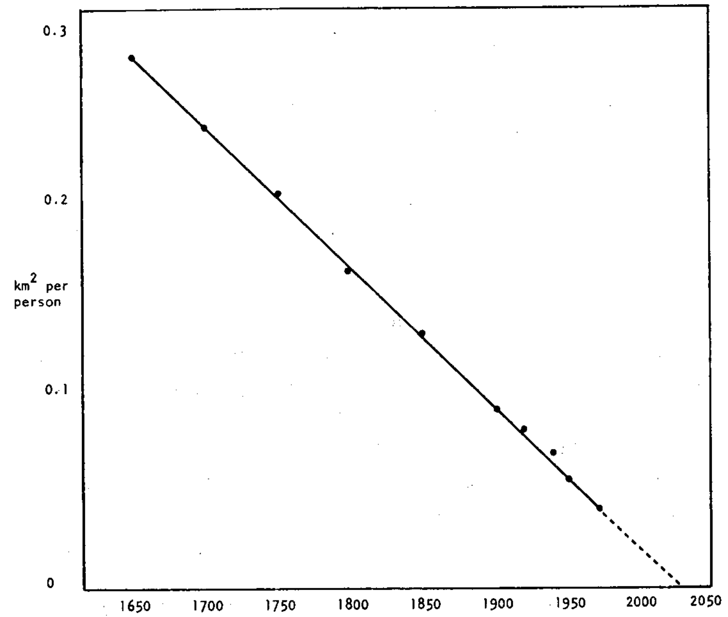

FIG. 3. Available area per inhabitant.

This equation shows demographic growth to follow a *hyperbolic,* rather than exponential law, at least in the time interval under consideration.

The asymptotic date of 2026 was obtained by empirical fit of the numerical values. It is noteworthy that Von Foerster (*op. cit.*) proposed a similar date (2026.87 ± 5.5) on the basis of his own sources. Another determination in this range is that of Kaplan in *The Theory of Development of Civilizations* [32], who finds an asymptote within the decade of 2020–2030. Furthermore, this empirical estimate receives a direct confirmation from a study of available area per inhabitant, taking as the inhabitable land the surface of the earth above sea level (150 million km^2). This available area has decreased from 0.28 km^2 in 1650 to 0.04 km^2 in 1970. The graph in Fig. 3 shows that the available area becomes equal to zero about 2026.

It is of interest to determine whether the hyperbolic shape of growth curves also applies for demographic data of a more remote past. H. von Foerster went back to the beginning of the Christian era [7] and again found a double logarithmic law with the same coordinates. Andre Cailleux [5, 9] has derived data for demographic growth as far back as the paleolithic era. His figures are given in Table 2, together with the historical figures and the corresponding rates for each time interval.

The graph representing this set of data points duplicates a double logarithmic linear function (Fig. 4) with some variations in the more remot past. Hence, a quasi-hyperbolic growth model appears to provide a suitable approximation of the demographic growth for the human species.

It must be remembered that this overall curve represents the integration of a number of elementary contributions coming from particular historical and geographic circumstances. (The population of Western Europe, for instance, actually *decreased* between the Roman Empire and the seventeenth century; it increased in the later period and now tends toward zero population growth [8]). World population as a whole, however, must be regarded as the envelope of these local curves. As such it continues to exhibit a hyperbolic increase pattern.

TABLE 2

Year	Population	Yearly rate of growth (%)
1972	3,782,000,000	2.02
1970	3,632,000,000	0.60
1650	540,000,000	0.07
−2400	30,000,000	0.03
−7000	10,000,000	0.01
−25000	1,300,000	0.001
−70000	700,000	0.0005
−250000	300,000	0.0002
−800000	100,000	

C. GROWTH DOES NOT FOLLOW A LOGISTIC LAW

While it is true that the law of exponential growth does not represent adequately the evolution of world population, we must observe that the *logistic* growth model is not satisfactory either.

Size of population in a limited resource environment follows an S-shaped curve. This logistic law describes growth of bacterial populations in a culture and predators in a given environment. In the first development phase, resources are sufficient and population grows exponentially according to its natural rate. Then resources in food, oxygen, available space, etc., become scarce in relationship to growth. Increased competition, decaying conditions, and decrease of survival probability result. These factors slow down the growth, driving it to a state of equilibrium with environmental resources. This logistic function is called the Pearl-Verhulst law [10] and is expressed by:

$$P = \frac{Po}{1 + e^{-at}}$$

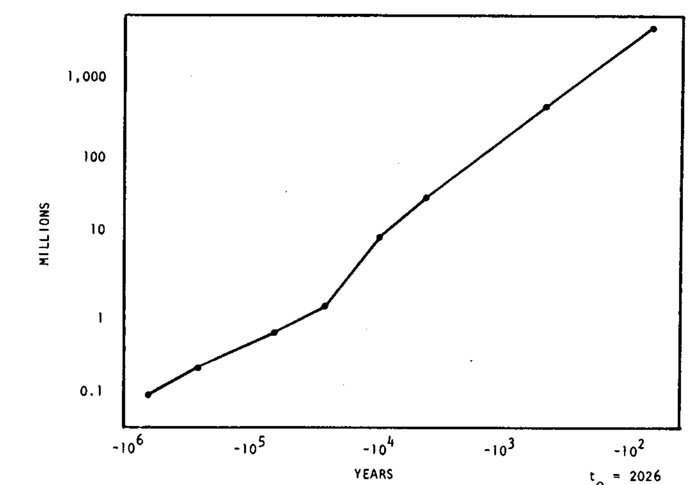

FIG. 4. Population growth in the last million years.

It is tempting to regard the human race as a population in development in the limited environment of the earth resources. However, it turns out that the numerical values of human population worldwide do not obey a logistic law: The figures simply cannot be accommodated by the model. Similarly, rigorous mathematical tests yield negative results.

Far from containing within itself the law of its own limitations, and far from tending "naturally" toward an equilibrium state, human demography exhibits a unique characteristic, that of *self-acceleration.* Human population growth thus has a paradoxical nature: *it follows neither an exponential nor a logistic model.* For comparison we have plotted four curves on Fig. 5: (a) an entire logistic curve; (b) the rising branch of the logistic curve; (c) an exponential; and (d) the actual growth curve.

In spite of this observation, the concept of the logistic law and the expectation of an "imminent" equilibrium state are so ingrained among most researchers that they consistently issue higher and higher "revised" forecasts that *still* fall short of the actual values. In 1930, Pearl himself used his logistic model to forecast a 1950 leveling-off at 2,150 million human beings. In 1945, Notestein [12] announced an *absolute* future ceiling of 3,300 million. This was changed to 4,000 million by Woytinski and Woytinski in 1953 [8].

Current forecasts are well beyond 10,000 million. We are witnessing a forecasting race where, in spite of upward revisions, the predicted figures stay behind the true dynamic nature of the demography.

D. GROWTH OF TECHNOLOGY IS HYPERBOLIC

To the extent that a linking exists between the demographic variable and the technological variable, there must be common evolution dynamics among all of the related quantities. Indeed, this is what we observe. Numerous technological variables, taken from prehistoric times to the present, are self-accelerating; that is, hyperbolic. Let us give two specific examples.

In historical times, the growth curve of the amount of power available to man, from animal energy in antiquity to modern interplanetary rockets, is self-accelerating as shown in Fig. 6 [13].

Where prehistory is concerned, recent research shows similar accelerations in growth dynamics. Thus Leroi-Gourhan [14] has measured the cutting edge length extracted in prehistoric stone industry from one kilogram of raw material. He plots this figure for

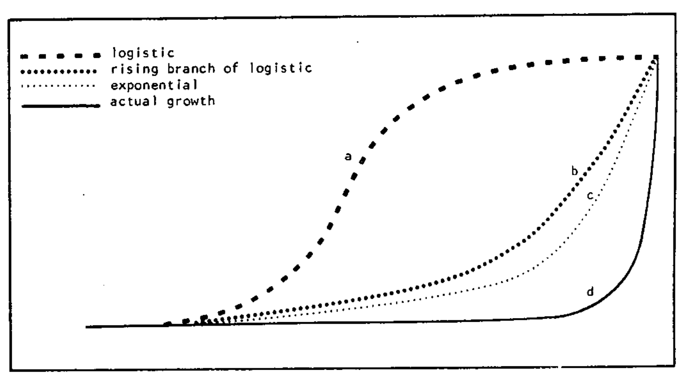

FIG. 5. Alternative models.

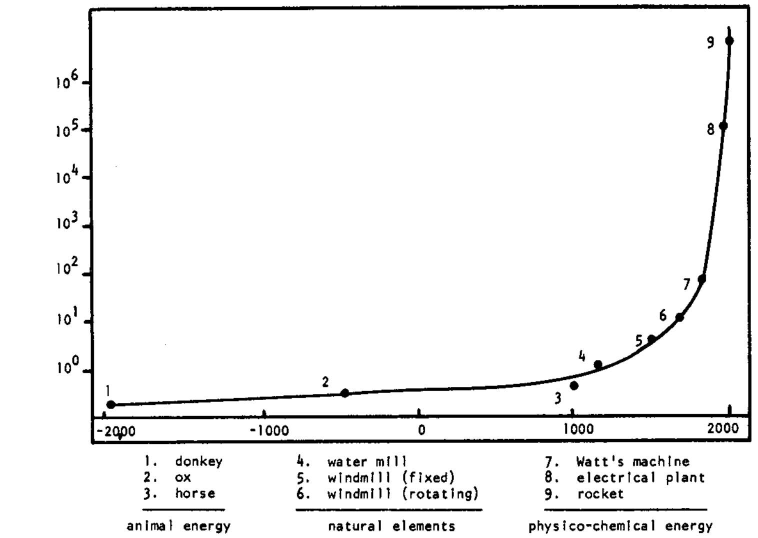

FIG. 6. Amount of power available to man.

successive manufacturing techniques, from the Pebble culture to the Neolithic. The data and the resulting curve again fit a hyperbola, as shown in Fig. 7. This hyperbolic function appears to dominate the whole technological evolution of our species.

It can certainly be pointed out that the variables taken into consideration in these two cases are not homogenous and thus do not yield a clear picture of the unity and of the continuity of the phenomenon throughout technological development. However, every time a homogenous variable is available as a reference, the phenomenon repeats itself in remarkable fashion. Such is the case, in particular, for food production techniques, the evolution of which is plotted in Fig. 8. It will be observed that, on the double logarithmic scale of this graph, the progression of these techniques follows a straight line with good

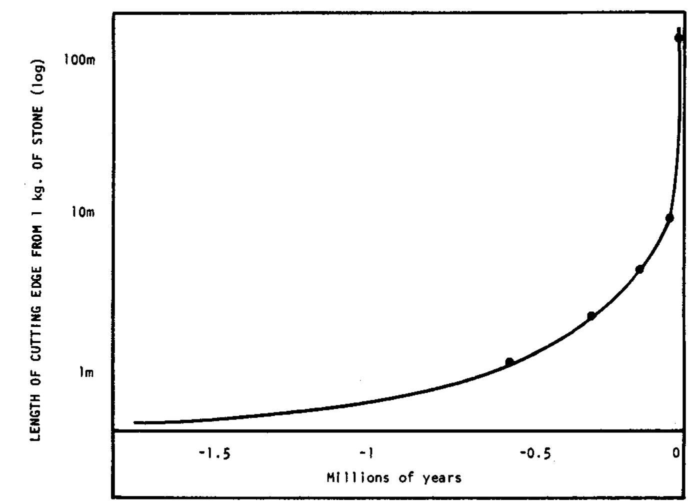

FIG. 7. The progress curve for a prehistoric stone-cutting industry.

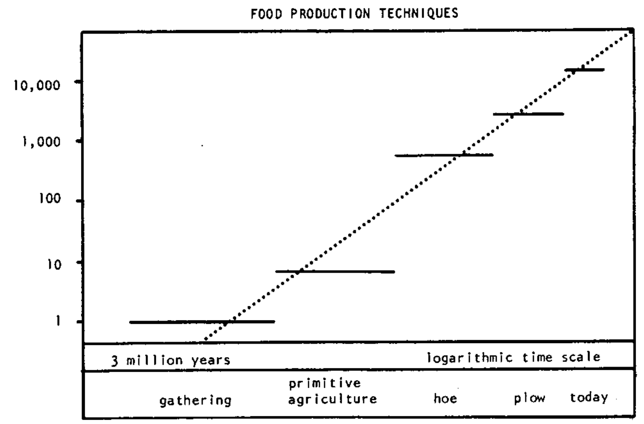

FIG. 8. Number of individuals supported by an area that provided food for one person three million years ago.

approximation. Here again we would infer that growth is hyperbolic, and that the theory is consistent with the dynamics of the observed development.

III. The Mechanism of Self-Acceleration

Although it appears as an absurd hypothesis in terms of classical demography, the phenomenon of self-accelerated growth can be systematically analyzed. Logistic evolution applies to a limited resource environment where there is a finite resource *quantum* that, in effect, imposes a ceiling on population growth. Resource limitations act negatively on survival probability; stronger when the population is larger. The result is a gradual decrease in rate until zero population growth is reached.

The human species, on the other hand, is characterized by its *technological strategies.* The effect of these strategies is to draw from the environment a resource quantum that is higher than the one spontaneously "offered" by the environment. Even beyond this, every successive technical step yields a higher resource quantum, a fact which is illustrated by the example of food production: In a primitive economy it takes 5,000 hectares to feed one individual. The same area feeds five in the prehistoric hunting economy, 500 in primitive agriculture, 2,500 when the plow is used, 15,000 in the current technology [9]. Hence, the *useful load* of the soil is increasing for a given area. It is true that for an animal population a given environment imposes a resource ceiling. For man, however, successive technical improvements raise this ceiling. Man is capable of breaking away from the constraints of the limited environment. The ceiling is no longer an absolute concept, but a movable one. Pushing it upward constantly, the human race can sustain a dynamic growth that does not follow a simple logistic model. It is self-accelerating.

A. THE FEEDBACK MODEL

We believe that what is true here for survival techniques is also true for all technological strategies. Whether in aggression techniques, in protection against natural elements, against other animal species, against morbidity, in the social and cultural fields of communication and organization, our techniques have as an effect an increase in survival probability. They contribute to raising the ceiling that is defined by environment conditions. The opposing situations (self-limitation and self-acceleration) can be illustrated in terms of simple feedback models. The logistic curve could be explained in terms of a negative feedback loop between population level and environmental resources. This feedback mechanism decreases survival probability. On the contrary, one could visualize a positive feedback model in which output (level of population and density) acts upon input in such a way as to increase survival probability. This is a better model for human evolution because the rise in population density, health care, welfare, division of labor, etc., may well be a favorable condition for the preservation of the species. An increase in population means more effective synergism and leads to the exploration of more avenues for better technological strategies. Here these better strategies, in turn, increase survival probability, and, with it, the population level. This positive feedback loop forces the system into a state of sustained self-acceleration.

Generally speaking, then, the development of an increasing population can be analyzed as a feedback effect, but one must distinguish among several possible cases.

First we may deal with a constant growth rate process, where, at any moment, growth is the product of the population size and the growth rate (Fig. 9(a)). The result is then an exponential function: a higher population yields a higher growth.

In the logistic case, we have a more complex situation. Again we have a feedback process, but the rise in population comes eventually to have a negative effect on survival probability and, hence, on growth rate, and this quantity tends toward zero (Fig. 9(b)). The system reaches equilibrium.

Let us now assume that the feedback on survival is a positive one. In that case, the system is accelerated in two ways: On one hand, the growth factor acts upon a greater population, and on the other hand, the growth factor itself increases (Fig. 9(c)). This second feedback loop corresponds to the efficiency of technological strategies.

Among these three models, it appears to us that the third one best represents actual demographic development. Furthermore, it accounts for the fact that the demographic

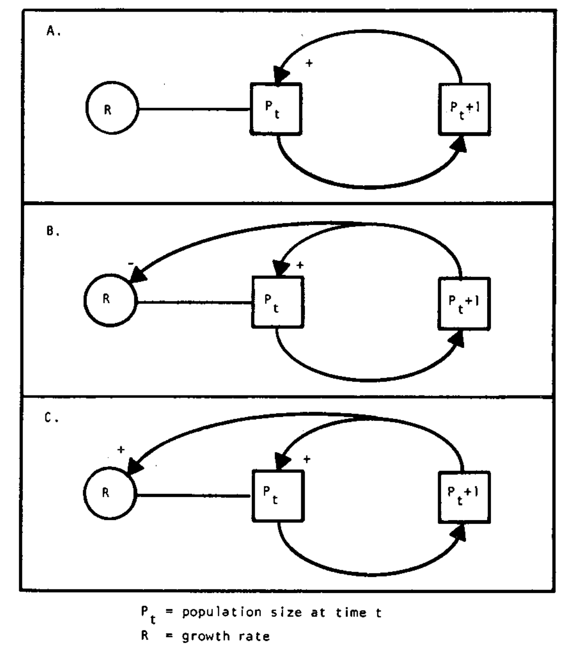

FIG. 9. Three feedback models for population growth.

curve and the technological curve are so similar: They are, in fact, two products of the same process.

B. A TWO-PERSON GAME

Von Foerster has proposed a slightly different model inspired by game-theoretical considerations [7]. In a logistic population, he says:

> Because of lack of adequate communication, . . . [the elements] have to resort to a competitive, almost zero-sum multiperson game.

This he contrasts with the state of:

> elements that possess a system of communication which enables them to form coalitions until all elements are so strongly linked that the population as a whole can be considered from a game-theoretical point of view as a single person playing a two-person game with nature as its opponent. In this situation it is not absurd to assume that an increase in elements may produce a more versatile and effective coalition and thus not only may render environmental hazards less effective but also may improve the living conditions beyond those found in a 'natural setting'. The human population may serve as a typical example, as evidenced by its steady social build-up during its historical time, its vigorous urbanization in recent centuries, and its extensive development of the means of mass communication in recent decades.

The two-person game between the human group and nature has as a concrete framework the entire set of technological strategies that are brought to bear through coalition among members of the social group. The abstract idea of a "coalition" covers, in fact, the reality of concrete technical activity, which is both the cause and the effect of the high population level. Thus we find again the positive feedback and the closed loop (population-techniques). It might be more appropriate to think of this loop as a sustained self-accelerating spiral.

C. THE RELAY PHENOMENON

A finer analysis of the self-acceleration process can be made. It exhibits a typical phenomenon of "relaying". Technological variables are progressing according to a series of self-limiting curves that overlap. A clear example is given by a graph of speeds as a

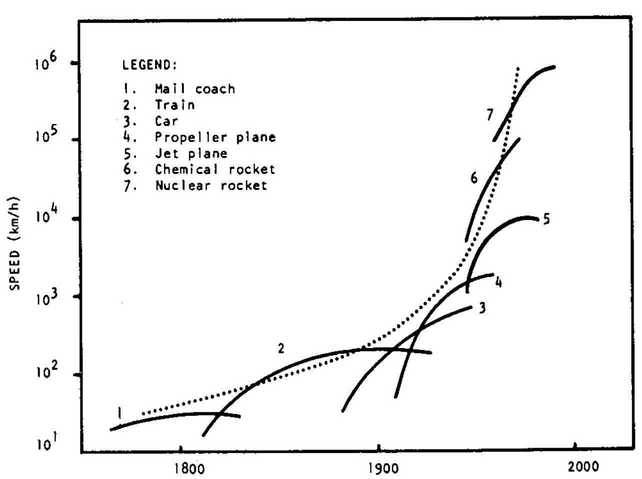

FIG. 10. Speed of vehicles used by man.

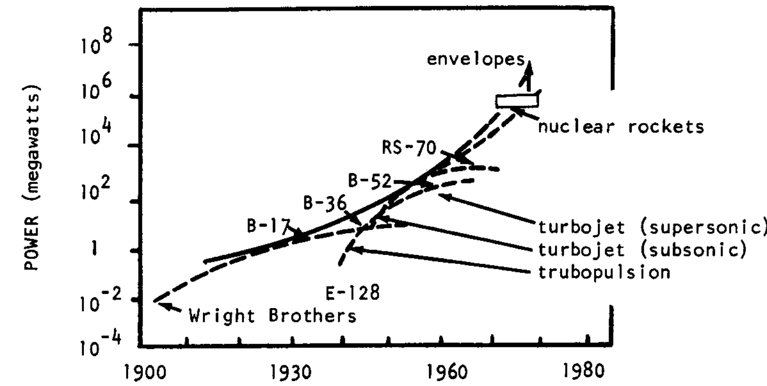

FIG. 11. Power of aircraft and spacecraft.

function of time since 1800 (Fig. 10, [15] and [17]). Every successive type of machine (stagecoach, train, car, propeller aircraft, jet aircraft, rocket) has its own S-shaped evolution and its own ceiling. However, as soon as it reaches its ceiling, another machine, in the sense of another qualitatively different technology, relays the previous one and goes through its ceiling, with the resulting effect of sustaining the acceleration of the quantitative variable. Another example of this relaying phenomenon is found in the progression of the power of aircraft and rockets (Fig. 11, [33]), and in that of the efficiency of external combustion engines (Fig. 12, [33]). Fig. 13 gives a similar graph for typesetting techniques.

It is also possible to show the relay phenomenon for longer-term evolution. Taking once again the figures for available power sources (Fig. 7) and plotting them on a double logarithmic scale, we again observe three distinct phases that correspond to three energy production modes: (a) animal energy, (b) natural elements energy, and (c) physico-chemical energy (Fig. 14).

Long-term evolution is given by the *envelope* of the logistic or quasi-logistic elementary components. We can say that the "perceived order of magnitude" of these variations is the envelope itself; the individual components follow an S-shaped pattern and represent

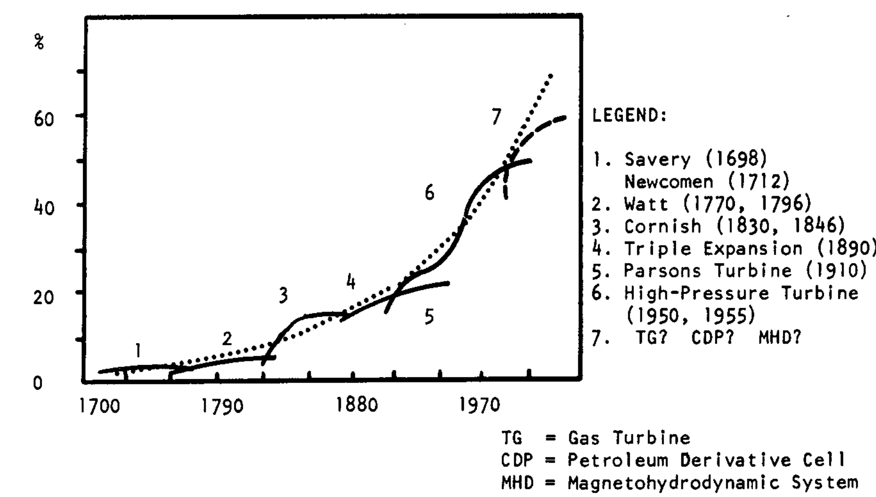

FIG. 12. Efficiency of external combustion engines.

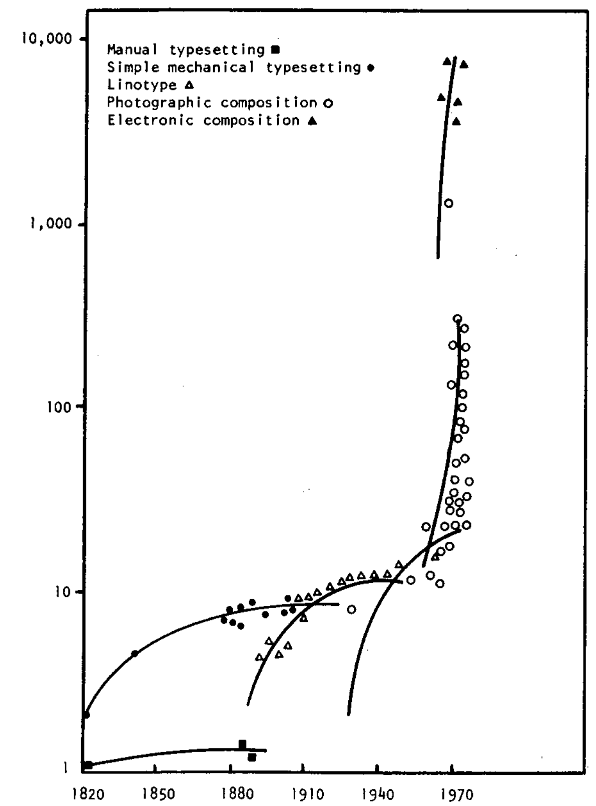

FIG. 13. Number of characters typeset per hour, another illustration of the relay phenomenon. (See the article by N. Carroll Mohn, Application of Trend Concepts in Forecasting Typesetting Technology, *Technol. Forecast. Soc. Change* 3, 255 (1972).

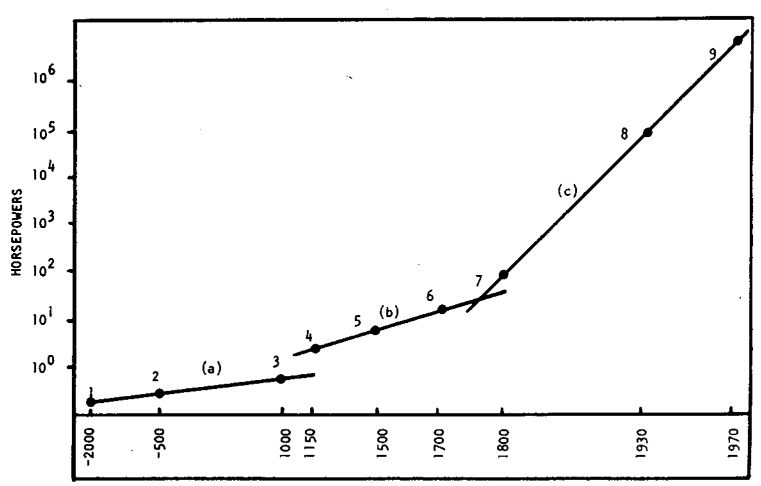

FIG. 14. Power available to man.

only a local phenomenon. As Ayres [15] remarks, "The large systems represented by the envelopes exhibit a more stable evolution than the individual components." This fact is well known to technological forecasters, but it can be generalized as a principle in all long-term variations (Meyer, [16] and [17]).

Finally, we can generalize the relay principle by examining the two extremes of human evolution: *prehistory* and the current period. As far as prehistory goes, if we take the figures showing the development of the stone industry (Fig. 7), and if we plot them on the same graph as the development of skull volume for successive human types using a given stone-cutting technique, we observe that the growth of the technological variable (solid line) is initially slower than that of the biological variable; it begins accelerating precisely when the biological curve (dotted line) flattens out, and the technological variable "relays" the biological variable when the biological variable has reached the ceiling of its dynamic properties (Fig. 15, [14]).

This means that in human evolution, the appearance and development of the technological variable plays a major role in making possible an evolutionary speed that natural genetic development could not sustain. In the current phase, the same phenomenon is manifested in the appearance and self-accelerating development of the informational variable, which is relaying the energetic variable that has characterized the whole of the previous development. *The very fast development of computers and mass media is a*

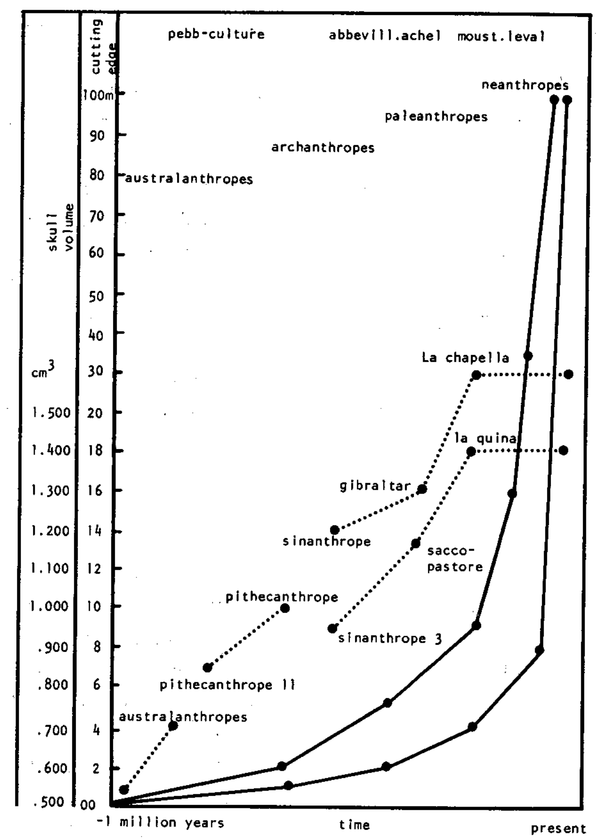

FIG. 15. Technology grows faster than biology.

major relaying phenomenon in the history of man, and its effects will deeply transform the evolutionary dynamics of our species.

Finally, the relay principle applies throughout human development and is consistent with the self-acceleration of development. The succession of technological forms allows a rate of increase higher than that of each previous phase. Everything works as in the case of a driver who shifts into higher and higher gear as he accelerates. It is even through a series of jumps that the enveloping curve sustains its development. The phenomenon is obvious in technological variables, but growth rate acceleration is also observed, as we have seen, for population development.

Discussion

What can we say about the consequences of hyperbolic development? First, while it fits more closely to the observed data points, it does not result from an underlying theoretical model. Hence, it is not as easily understandable as the exponential or logistic models. It is true that the above-mentioned rationalizations (positive feedback, two-person game, relay principle) do justify self-accelerating functions. However, they do not necessarily lead to a hyperbolic function, which remains without a theoretical and epistemological foundation in a simple model, although a more elaborate approach (taking into consideration a communication model of growth, for instance) might explain it.

The most striking phenomenon in these functions is the singular point that they imply in the future. The forecast of infinite growth in a finite time interval is absurd. All we can expect of these developments is that some damping effect will take place very soon. The only question is whether this will be accomplished through "soft regulation" or catastrophe.

In fact, we can only say that if development slows down, this will not be due to such simple constraints as are involved in the classical S-shaped model of growth. From a mathematical viewpoint, we can imagine an infinitely large number of equations that will force a hyperbolic function to change its regime. By hypothesizing various functions of time such that their value would begin compensating hyperbolic development at a definite value of t, one could obtain a collapse, a ceiling, or a cyclical curve as a result.

Investigating all the alternatives seems to be a pointless mathematical game as long as no underlying theory is available. The only information we can draw from the hyperbolic curve is that we should be on the lookout for an imminent change in the rhythm of our development.

Conclusion

The concept of the "acceleration of history" has often been proposed, either explicitly or implicitly. In particular it has been mentioned by Sir John Lubbock [18], Michelet [19], Henri Adams [20], Meyer [16], Halevy [21], Cailleux [5, 9], Fucks [22], Sparks [23], Stine [24], Zeman [25], von Foerster [7], Schlovski [26], Dobrov [27], Perellman [28], Khovanov [29], Kouznetsov [30], and Piel [31]. Some of these researchers have gone beyond a purely qualitative analysis, giving its true significance to the concept of acceleration. Following quantitative analyses made by Cailleux and Von Foerster, as well as our own work, we feel it is possible to reach some objective statements without, however, being able to make precise forecasts; such precision is made impossible by the fact that the hyperbolic development leads to impossible physical consequences. Under these conditions, the only reasonable forecast is that of a drastic change of development rhythm. Furthermore, the date at which the asymptotic state is reached appears to be very close, giving little time for factors of limitation to appear and to have an effect.

It is clear that the rate of growth must eventually decrease. A discussion of the mechanism through which this decrease will take place is beyond the scope of the present study.

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