I have tried here to put the emphasis on those basic properties that are common to all semiconductors and that distinguish them from other solids. It is interesting as well as surprising to see how the many and various semiconducting compounds are all governed by the same simple chemical and structural rules. These rules present a challenge to the theoretician, who has yet to interpret them in a rigorous way. They present a challenge also to the experimentalist because they introduce him to large families of new and unexplored semiconducting materials. And the challenge is all the greater since it is to be expected that, as our knowledge of semiconductors and their properties increases, the chemical and structural rules will be reflected in at present largely unknown but much-sought-for relationships between the chemical composition and structure of semiconductors on the one hand and parameters such as energy gap and charge-carrier mobility on the other.

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Doomsday: Friday, 13 November, A.D. 2026

At this date human population will approach infinity if it grows as it has grown in the last two millenia.

Heinz von Foerster, Patricia M. Mora, Lawrence W. Amiot

Among the many different aspects which may be of interest in the study of biological populations (*1*) is the one in which attempts are made to estimate the past and the future of such a population in terms of the number of its elements, if the behavior of this population is observable over a reasonable period of time.

All such attempts make use of two fundamental facts concerning an individual element of a closed biological population—namely, (i) that each element comes into existence by a sexual or asexual process performed by another element of this population ("birth"), and (ii) that after a finite time each element will cease to be a distinguishable member of this population and has to be excluded from the population count ("death").

Under conditions which come close to being paradise—that is, no environmental hazards, unlimited food supply, and no detrimental interaction between elements—the fate of a biological population as a whole is completely determined at all times by reference to the two fundamental properties of an individual element: its fertility and its mortality. Assume, for simplicity, a fictitious population in which all elements behave identically (equivivant population, *2*) displaying a fertility of γ_0 offspring per element per unit time and having a mortality $\theta_0 = 1/t_m$, derived from the life span for an individual element of t_m units of time. Clearly, the rate of change of N, the number of elements in the population, is given by

$$\frac{dN}{dt} = \gamma_0 N - \theta_0 N = a_0 N \qquad (1)$$

where $a_0 = \gamma_0 - \theta_0$ may be called the productivity of the individual element. Depending upon whether $a_0 \gtreqless 0$, integration of Eq. 1 gives the well-known exponential growth or decay of such a population with a time constant of $1/a_0$.

In reality, alas, the situation is not that simple, inasmuch as the two parameters describing fertility and mortality may vary from element to element and, moreover, fertility may have different values, depending on the age of a particular element.

To derive these distribution functions from observations of the behavior of a population as a whole involves the use of statistical machinery of considerable sophistication (*3, 4*).

However, so long as the elements live in our hypothetical paradise, it is in principle possible, by straightforward mathematical methods, to extract the desired distribution functions, and the fate of the population as a whole, with all its ups and downs, is again determined by properties exclusively attributable to individual elements. If one foregoes the opportunity to describe the behavior of a population in all its temporal details and is satisfied

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with a general account of its development over long stretches of time, the problem reduces to solving Eq. 1, except that N, γ_0, and θ_0 have to be replaced by appropriate mean values (γ, θ) taken over several generations, over all ages, and over all elements.

The difficulties encountered in establishing the distribution functions for γ and θ from observations of the behavior of the population as a whole should not be confounded with the predicament which arises if one drops the fictitious assumption that the elements are all thriving in a hypothetical paradise. While the former difficulties can be overcome by "merely" developing the appropriate mathematical apparatus to cope with this intricate problem, the difficulties in the latter case are of a different kind, since now the fate of the population is not any longer solely dependent upon the two intrinsic properties of the elements—their fertility and their mortality. Hazards in the environment, competition between elements for limited food supply, the abundance of predators or prey—to name just a few factors—may all act on either mortality or fertility or on both, and in the absence of further insight into these mechanisms, Eq. 1 becomes obsolete and nothing can be said about the long-term development of our population. The usual way out of this predicament is to devise plausible arguments which will link the two intrinsic properties of our elements with some of the characteristics of the environment, in the hope that the linkage is adequately described and also that one has picked those attributes of the environment which are most relevant in studying the population under consideration (*4, 5*).

Environmental Influences

The usual approach in trying to account for the environmental influences is to make the productivity α in Eq. 1 a monotonic *de*creasing function of the number of elements N. Since, in an environment of given size, N is also a measure of the density of the population, it is easy to see that increased density may in many cases reduce the probability of survival for an individual element—for example, where increased density aggravates mutual competition or improves availability of elements for predators. A typical and popular choice of α is a simple linear dependence of the form

$$\alpha = \alpha_0 - \alpha_1 N \qquad (2)$$

which, inserted in Eq. 1, results after integration in what demographers prefer to call the "logistic growth curve," displaying a "sigmoid" shape, if N is plotted linearly against linear time (*6; 7*, p. 67). The choice of this particular function is usually justified by our general observation that populations do not grow beyond all measures but settle down to a stationary value N_∞, which is given at once for $\alpha = 0$ from Eq. 2 as $N_\infty = \alpha_0/\alpha_1$. Furthermore, reasonable fits of the resulting function have been observed with actual biological populations—for example, fruit flies in milk bottles (*8*), bacterial colonies in petri dishes (7, p. 71), and so on.

Regardless of whether or not the simple expression given in Eq. 2 is still valid if the mechanisms of the interaction between environment and population are analyzed more carefully, there seems to be strong evidence that, for instance, in sexually reproducing species the advantages of having mates more readily available in larger populations is more than counterbalanced by the disadvantages resulting from a stepped-up competitive situation if more and more elements have to struggle for existence in a finite environment. In other words, the general idea that the productivity may decrease with an increase in the number of elements has undoubted merits.

Coalitions

However, what may be true for elements which, because of lack of adequate communication among each other, have to resort to a competitive, (almost) zero-sum multiperson game may be false for 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 historical time, its vigorous urbanization in recent centuries, and its extensive development of the means of mass communication in recent decades.

Since α, the productivity, reflects in a sense the living standard of the population, one is tempted to hypothesize that the productivity of populations comprised of elements capable of mutual communication is a monotonic *in*creasing function of the number of elements. Tentatively, let α be a weak function of N:

$$\alpha = \alpha_0 N^{1/k} \qquad (3)$$

where α_0 and $k \approx 1$ are later to be determined from experiment. Inserting Eq. 3 into Eq. 1, and integrating, yields, with the integration constant determined ($t = t_1 \ldots N = N_1$) at once the desired dependence of $N(t)$:

$$N = N_1 \left(\frac{t_0 - t_1}{t_0 - t}\right)^k \qquad (4)$$

where the characteristic date t_0 replaces a collection of constants:

$$t_0 = t_1 + \frac{k}{\alpha_0} N_1^{-1/k} \qquad (5)$$

For obvious reasons, t_0 shall be called "doomsday," since it is on that date, $t = t_0$, that N goes to infinity and that the clever population annihilates itself.

If "dooms-time" $\tau = t_0 - t$ (that is, the time left until doomsday), Eq. 4 can be rewritten as $N = K/\tau^k$. This form is listed below together with two other relations easily derived from Eqs. 3 and 4.

$$N = K/\tau^k \qquad (6)$$

$$\alpha = k/\tau \qquad (7)$$

$$\Delta t_p = (1 - p^{-1/k}) \cdot \tau \qquad (8)$$

where

$$K = \left(\frac{k}{\alpha_0}\right)^k \qquad (9)$$

In these equations the constant K represents the fundamental constants α_0 and k as seen in Eq. 9; in Eq. 7 the productivity is given as a function of doomstime and increases more and more rapidly as one approaches doomsday; Eq. 8 expresses the time interval Δt_p before a population which has N elements at time τ will have pN elements. If $p = 2$, one speaks about the "doubling time" of the population, and it may be worth while to note that in this population, $\triangle t_p$, the "p-folding time" is a linear function of dooms-time, in strong contrast to exponentially growing populations, where these intervals are fixed for all times: $\triangle t_p = (1/\alpha_0) \ln p$, $1/\alpha_0$ being the time constant of the growth process.

Human Population

In order to check whether or not the hypothesis expressed in Eq. 3 has any merit at all, we took the human world population as a test case, since it was felt that the most reliable long-range data on the development of a population comprised of communicating elements may be found in the history of men. The use of estimates of the world population rather than of populations of certain geographical regions eliminates to a certain extent the influence of local fluctuations and migration. A bibliographical search produced 24 estimates (see *9–11*) of the world population, ranging over approximately 100 generations from the time of Christ ($t = 0$) almost to the present ($t = 1958$). These estimates were carefully checked with respect to their independence, and those which were suspected of being merely cross references in the literature were eliminated from the statistics in order to avoid improper weighting.

The method of least squares was employed in order to extract from the data the three values t_0, K, and k; the following values were obtained:

$$t_0 = \text{A.D. } 2026.87 \pm 5.50 \text{ years} \qquad (10a)$$

$$K = (1.79 \pm 0.14) \times 10^{11} \qquad (10b)$$

$$k = 0.990 \pm 0.009 \qquad (10c)$$

The root mean square deviation for all points considered is approximately 7 percent.

With these values Eqs. 6, 7, and 8 become, with $p = 2$:

$$N = 1.79 \times 10^{11}/\tau^{0.99} \qquad (11)$$

$$\alpha = 0.99/\tau \text{ per annum} \qquad (12)$$

$$\triangle t^2 = 0.445 \cdot \tau \text{ years} \qquad (13)$$

And finally, through Eq. 9, with Eqs. 10*b* and 10*c*, we obtain for α_0, $\alpha_0 = 5.5 \times 10^{-12}$

Figure 1 is a graphical representation of the accepted data together with the theoretical function (Eq. 6) for which values of Eq. 10 have been employed. By using logarithmic axes for the number N of elements, as well as for dooms-time τ, advantage has been taken of the fact that, if (and only if) an appropriate value for t_0 has been established, experimental results should appear on a straight line with negative slope k in a double logarithmic plot.

For convenience, the abscissa is marked on the lower margin in historical time t and reads from right to left, while on the upper margin, from left to right, dooms-time τ is indicated. Similarly, on the left margin of the abscissa the number N of elements is recorded, while the right-hand margin gives the global population density n in elements per square mile; this value is simply obtained by dividing the number of elements by the area A of all the lands of the earth: $A = 5.27 \times 10^7$ square miles. For comparison, some density estimates for 1958 are indicated.

From inspection of Fig. 1 and consideration of the small root mean square deviation of 7 percent, it may be seen that, even without making such generalizations as led to Eq. 6, Eq. 11 seems to serve as an adequate empirical formula for representing most of our recorded data on human population growth, covering a time interval of about two millenia. In the light of the interesting singularity supposed to occur at $t = t_0 \approx$ A.D. 2027, the question arises as to the reliability of an extrapolation beyond a time $t^* < t_0$.

It requires only simple calculations to show that if Charlemagne had had Eq. 6, with the evidence he could have had with respect to the world's population, he could have predicted doomsday accurately within 300 years. Elizabeth I of England could have predicted the critical date within 110 years, and Napoleon within 30 years. Today, however, we are in a much better position, since we are required to extrapolate our evidence only 4 percent beyond our last point of observation: we can predict doomsday within approximately 10 years.

Although it is always fascinating to imagine one's future fate, the possibility of deriving some fun by extrapolating our function into the past should not be overlooked. We find that 1 million years ago the world population was about 200,000 individuals, and 12 million years ago, not more than perhaps 15,000 of Hurzeler's Abominable Coal Men (*12*) populated Tuscany. If we wish to extrapolate much further into the past we must be prepared to find inconsistencies, since the assumption of the communicability of elements will to some extent lose its meaning. Thus, if one desires to calculate the date of the emergence of a hypothetical "Adam"—that is, $N = 1$ —one finds it about 200 billion years ago. Even astronomers in their wildest speculations have not yet come up with an age of the universe which would approximate this figure [current estimates $\approx$ 24 billion years (*13*)].

Optimists versus Pessimists?

It is hoped that the preceding exposé will add some fuel to the heated controversy about whether or not the time has come when something has to be done about population growth control. This controversy has divided those elements of the population under consideration who profess to show some interest in human affairs into two strictly opposed camps (*14*): the optimists, who see in the population explosion a welcome expansion of their clientele, be it consumers of baby goods (*15*), voters, or devoted souls (*16*), and, on the other hand, the pessimists, who worry about the rapid depletion of the natural resources and the irreversible poisoning of our biosphere (*14*, *17*). While the optimists adhere to the thesis that no matter how fast the population is growing, food technology and the industrial sciences will easily keep pace with the development and thus will maintain the elements of the human population—at least for some generations to come—in a perfect state of economic and individual health, the pessimists prefer to paint the future of mankind in not quite the same rosy colors by pointing to the increasing growth rate of the population while assuming that industrial and scientific development will proceed at a much slower pace. Hence, the pessimists anticipate that further rapid increase in the population density will be accompanied by a deterioration in human dignity, and they see the ultimate fate of the human race as a mere vegetation of the individual on the edge of existence, *if* no measures are introduced to keep the world population under control (*18*).

When we refer to our population growth curve as given in Eq. 11 and in Fig. 1 and remember the premise under which it was derived, it is obvious that the optimist's viewpoint is

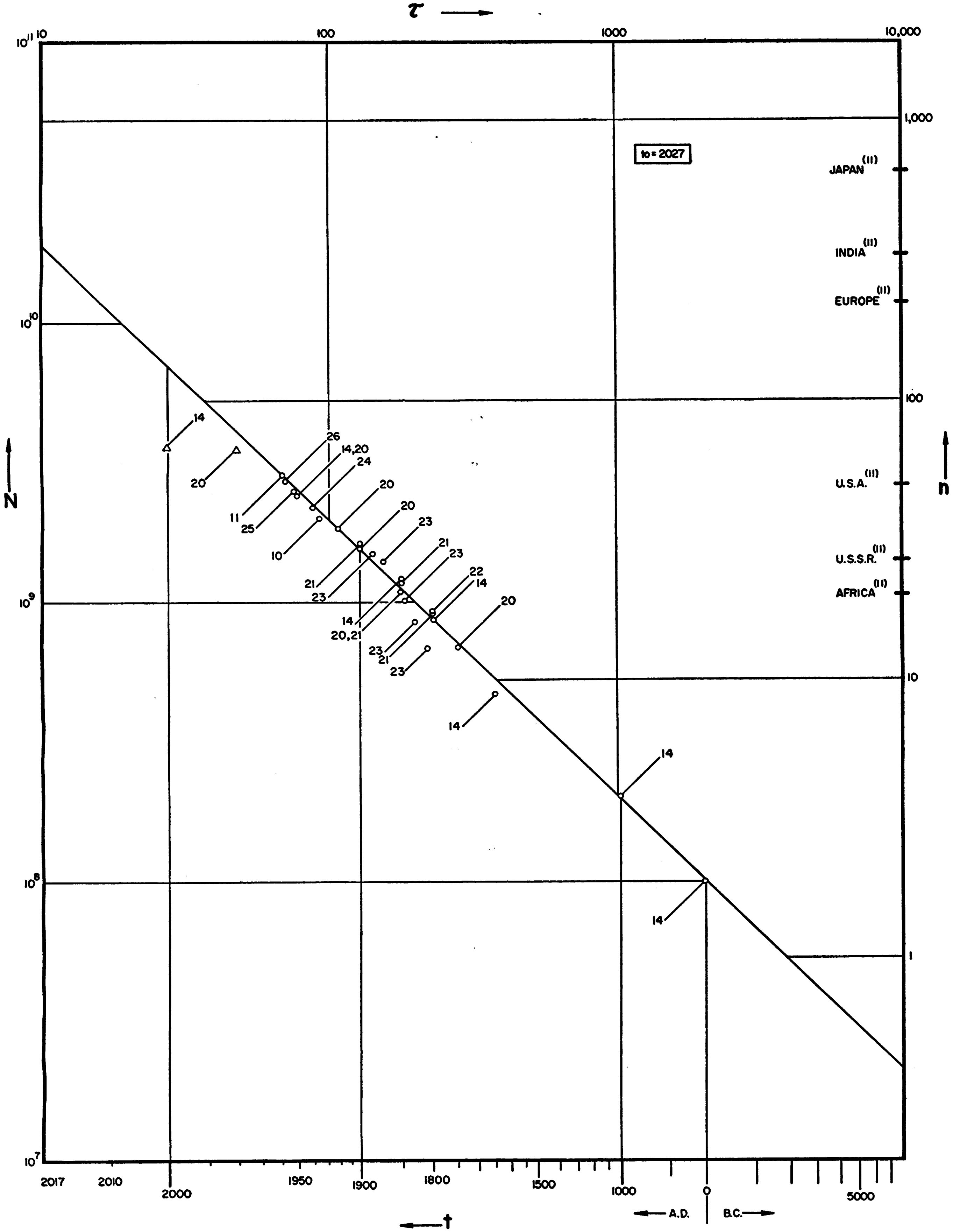

Fig 1. World population N (left scale) and world population density n in elements per square mile (right scale) observed (circles), calculated after Eq. 11 (solid line) and projected by different authors (triangles) as a function of historical time t (bottom scale), and of dooms-time τ (top scale). The numbers associated with each point are references.

correct: man has always been able to develop the appropriate technology to feed himself, or he has always produced the appropriate population to master his technological tasks. This can be conjectured from the relatively small deviations which actual population counts show as compared with calculated values, in spite of the fact that during the last two millennia men underwent several fundamental technological revolutions. Thus, we may conclude with considerable confidence that the principle of "adequate technology," which proved to be correct for over 100 generations, will hold for at least three more. Fortunately, there is no need to strain the theory by undue further extrapolation, because—and here the pessimists erred again—our great-great-grandchildren will not starve to death. They will be squeezed to death.

In view of this uncomfortable picture it is clear that, while the pessimists, one way or another, are "Malthusians by profession," the optimists must be "Malthusians at heart," hoping that at some time, somehow, something will happen that will stop this ever-faster race to self-destruction.

Population Servo

But in a highly communicating society there is no need to invoke good old Malthus again, who may cite this or that environmental factor whose abundance or depletion may curb excess productivity. There is no need to wait until an external mechanism influences human activity. Since today man's environment becomes less and less influenced by "natural forces" and is more and more defined by social forces determined by man, he himself can take control over his fate in this matter, as well as he has done in almost all areas of life where the activity of the individual has influenced his own kind.

There is no doubt that it will be extraordinarily difficult to establish a control mechanism, a "peoplo-stat" so to speak, which would keep the world's population at a desired level. The important point to note here, however, is that it is of secondary importance to find out what this level should be. The primary problem consists of finding means to keep it constant, whatever this level might be. This means that, if a particular N^*, supposed to remain constant, is chosen, obviously dN/dt must vanish, or $a \rightarrow 0$; hence, $\gamma^* = 1/t_m^*$.

Since the tendencies today do not point in the direction of observable efforts to reduce the mean life span, t_m, of human individuals—on the contrary, we see a steady increase in this value—it is clear that our peoplo-stat has to control the fertility γ^*, and has to maintain it at the level $1/t_m$. Today, this means cutting the birth rate to about half its present value or, in other words, cutting the size of an average family to just a little above two children. Tomorrow, of course, it will be more difficult, since—as we have seen—the gap between birth rate and death rate is widening every minute.

Among the suggestions that have been advanced for meeting this problem—legislation, heavy taxation of families that have more than two children, cancellation of tax deductions, and so on—space travel has been proposed recently as an alternative (*19*). It is only unfortunate that no re-entry permit to earth can be given these space-trotters.

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