The Scientific Revolution in Demography

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ABSTRACT: Since 1960 a debate has taken place between demographers and natural scientists over projections of world population into the future and the methods appropriate for making projections. Underlying this debate is a disagreement over the factors which influence human population growth. To the usual factors of fertility and mortality the natural scientists emphasize the human population's ability to communicate and thereby to enlarge available resources. Also at issue are different philosophies concerning the manipulation of data. The debate between demographers and natural scientists bears many of the features of a scientific revolution as described by Thomas Kuhn. The new theory also meets the criterion of scientific growth contained in the correspondence principle. The theories used by demographers and natural scientists have political implications, since the demographers assume stability whereas the natural scientists observe instability.

A STRUGGLE BETWEEN TWO THEORIES

A scientific revolution is currently taking place in the field of demography. The opening shot in the revolution was fired in 1960 when *Science* published the article, "Doomsday: Friday, 13 November, A.D. 2026," by Heinz Von Foerster, Patricia Mora and Lawrence Amiot (1960). Since these three co-authors were at the time located in the Department of Electrical Engineering at the University of Illinois, the event was somewhat more like a scientific invasion than a scientific revolution. The new point of view came from outside the field of demography rather than from inside.

Nevertheless, the debate between demographers and natural scientists

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about world population growth bears a resemblance to Thomas S. Kuhn's well-known analysis of the structure of scientific revolutions (Kuhn, 1970). Kuhn described the way that scientific theories usually change. Most scientific work occurs during periods of what Kuhn called "normal science," when scientists are guided by a widely accepted set of concepts, models, examples, and techniques. Most scientific work takes the form of puzzle solving—existing theories suggest logical or experimental difficulties which scientists try to solve. During a period of normal science, anomalies accumulate. Eventually a new theory is proposed which claims to resolve the anomalies. The field then enters a revolutionary period in which the adherents of the old and new theories compete for dominance and for followers. Those who adhere to the old position rarely change their minds. The issue is resolved by the members of the younger generation, who must choose which theory best facilitates puzzle formulation.

THE ORIGIN OF THE NEW THEORY

The new theory did not emerge from an effort to resolve anomalies in the field of demography. Rather, it emerged from reflections about populations whose elements can form coalitions. Under a grant from the National Institutes of Health to the Biological Computer Laboratory at the University of Illinois for a study on the kinetics of cellular proliferation, Heinz von Foerster and his collaborators developed some conceptual tools for dealing with populations of dividing and differentiating cells, and the mathematics for age-specific cohorts in a complex cellular environment (Von Foerster, 1959; Von Foerster, 1961; Trucco, 1965; Witten, 1983).

In these studies an intriguing side issue emerged, namely, how to perceive a population whose elements not only act upon their environment which in turn, affects the elements, but whose elements also interact with each other through coalitions, cooperation, communication, etc.

Whereas Malthus, Lotka, Verhúlst, and others saw in interactions of elements essentially only mutually inhibitory functions (e.g., competition for limited resources), Von Foerster *et al.* developed expressions that would allow in addition for the formation of mutually supporting activities through cooperative clusters "playing" a non-zero sum game with their environment.

The general form of these expressions

$$N = K / (t_0 - t)^k$$

(where N is the number of elements, t is time, and K, k, t_0 are characteristic constants) showed two unexpected features. One is the hyperbolic nature of the growth of these kinds of populations with an indication of instability at time $t = t_0$ when N grows beyond all bounds. The other is the temporal behavior of these populations' "doubling times," a notion borrowed from studies of dividing cells and, with the doomsday article, introduced into demography. For such populations, doubling time decreases linearly with time:

$$\text{doubling time} = (t_0 - t) * (\ln 2) / k.$$

Since humans, communicating and cooperating through language, would be a perfect case for testing these ideas, Von Foerster *et al.* collected all the data they could on human population.

They chose to study world population in order to eliminate the effects of local fluctuations and migration. If the human population had been growing at a constant rate of growth, then, when plotted on linear-logarithmic paper, the data would fall on a straight line (Von Foerster, 1966). Instead, the data curve upward, indicating that the rate of growth is increasing (see Figure 1). By drawing lines tangent to the curve and determining the slopes of these lines, it is possible to estimate the rates of growth at different points in time. From the observed rates of growth and the identity

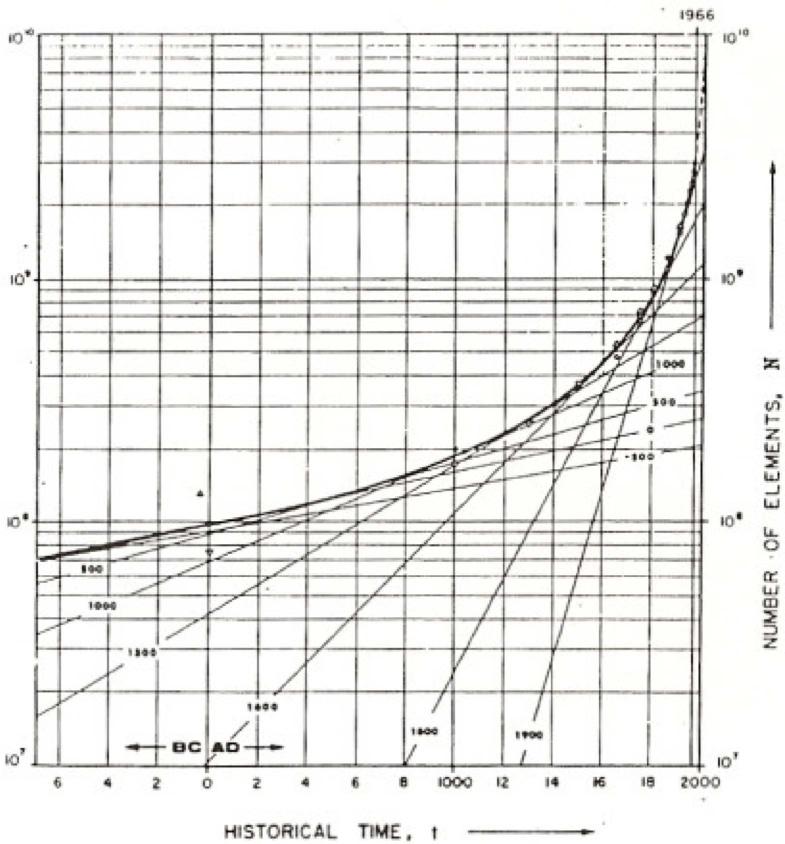
$$\frac{70}{\text{percent rate of growth}} = \text{doubling time}^{\dagger}$$

one can calculate the corresponding doubling times. The doubling times can be graphed as a function of time. Figure 2 indicates that the time required for the human population to double declined from about 390 years in 1500 to about 50 years in 1950. The most interesting point is the date at which the line connecting doubling times goes to zero, or the rate of growth becomes infinite. Von Foerster called this date "doomsday" and, as seen from Figure 2, it occurs about the year 2027.

The fact that the doubling time decreases linearly indicates that the actual population dynamics are appropriately represented by the proposed formalism. A determination of the three constants by the method of least squares produced $k = .990 \pm .01$, $K = 179 \pm 14$ billions, and the year of "doomsday" $t_0 = 2026.9 \pm 5$ years. With these numbers Von Foerster

†70 is an approximation to $100 * \ln 2 = 69.315$.

FIGURE 1. Linear-logarithmic representation of estimates of the human population N by various authors and interpolated (solid curve) over the last 25 centuries. Straight lines tangent to the curve at various instances in historical time represent exponential growth as apparent only in the vicinity of these instances. (Von Foerster, 1966)

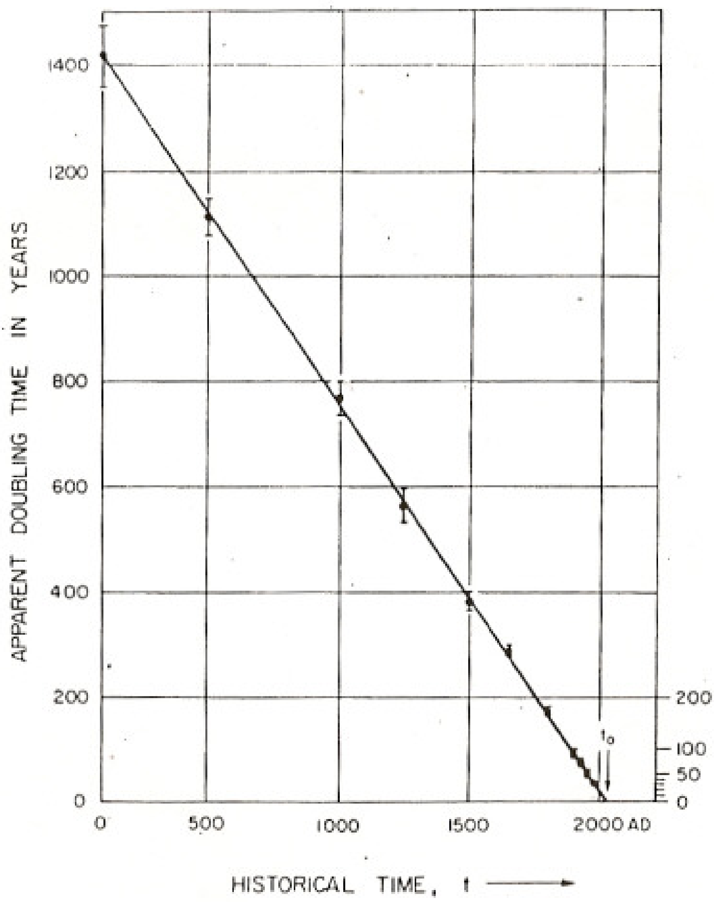


and his team could present the following numerical relationship between the world population and historical time, t, (here rounded off):

$$N \text{ in billions} = 180 / (2027 - t).$$

The previous assumption had been that the rate of population growth would decrease as population density increased due to factors such as competition for resources. However, the doomsday equation is based on

FIGURE 2. Apparent doubling time in years of the human population as a function of historical time. The values were calculated from the data given in Figure 1. (Von Foerster, 1966)



the assumption that the rate of growth increases as population increases. A communicating population can form a coalition and engage in a game with its environment. "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'" (Von Foerster *et al.*, 1960, p. 1292).

Richard Fowler, also a physicist, independently came to the same conclusion. ". . . for many years, perhaps as many as a million, the growth rate has been enhanced by the social support of the surrounding populace, and has never followed simple exponential behavior" (Fowler, 1982, p. 84).

THE CORRESPONDENCE PRINCIPLE

Philosophers of science maintain that a theoretical advance should meet the condition set forth in the correspondence principle. The correspondence principle states that any new theory must reduce to the old theory to which it corresponds for those cases in which the old theory is known to hold. Hence, a new theory should incorporate an additional dimension which previously had not been considered or had been assumed to be zero (Krajewski, 1977).

In the case of the scientific revolution in demography the dimension which has been added by the natural scientists is the amount of communication and coalition formation among the elements of the population. The old theory in demography assumed that the human population was affected only by the same factors which affect non-communicating populations.

CRITICISM AND REPLY

Kuhn notes that during a scientific revolution the debate between the two camps is usually quite emotional. This has certainly been the case with the revolution in demography. Soon after the Doomsday article appeared, Robertson, Bond, and Cronkite (1961, p. 936) expressed concern that it "may be taken too seriously." and claimed that it is "obvious that such a theory has no relation to reality and is of no value whatever in predicting future populations." Shinbrot (1961, p. 940) wrote that the article "would be too ridiculous to comment on if it were not such an outstanding example of the inadmissible use of mathematics to prop up a manifestly absurd conclusion."

Von Foerster, Mora and Amiot (1961, March, p. 943) replied by reminding their readers that in the scientific community "support of a hypothesis is gained through compatibility with experimental observation rather than by arguments about what should be the case or what should not be the case."

Recognizing the difficulty that the demographers were having in interpreting equations of the form

$$\lim_{X \to Xo} Y = \text{infinity}$$

Von Foerster *et al.* noted that such "singularities" occur quite commonly in nature:

> For instance, let X and Y represent, respectively, velocity and pressure at Mach 1; or voltage and current at breakdown voltage in gaseous conduction; or wavelength and index of refraction in optical absorption bands; or temperature and magnetic susceptibility at Curie point in the theory of ferromagnetism; and so on. Physical theory behind these expressions is termed neither absurd nor ridiculous, nor is it customary to deny that such theories have predictive value because of these singularities. On the contrary, since the generally accepted interpretation of expressions such as these, in which a parameter increases rapidly beyond all bounds, is that the system as a whole becomes highly unstable in the vicinity of the critical value Xo of the corresponding parameter, these singularities serve as welcome warning signals that some breakdown of the system's structure is to be expected (Von Foerster *et al.*, 1961, March, p. 943).

Coale, apparently not persuaded, continued the debate with another extensive critique. He stated, the

> . . . whole argument will not stand critical scrutiny . . . It is not true that population growth rates are positively associated with density, nor even that population growth rates are positively associated with man's control over nature . . . Von Foerster and his co-authors neglect the causes of accelerated population growth in the world. Growth has accelerated wholly because of a reduction in mortality, because of a lower world death rate (Coale, 1961, p. 1931).

Coale concluded, "These questions are among the most serious facing the world today, and to give wide currency to such clearly nonsensical ideas as an infinite birth rate and Doomsday in A.D. 2027 contributes nothing to their solution."

Von Foerster, Mora and Amiot (1961, June) in their reply further explained that in the vicinity of a singularity a system may undergo drastic changes—for example, evaporation, rupture, or disintegration. They suggested consulting a physicist if conceptual confusion persisted. On the relationship between technology and population growth they wrote,

> . . . if we apply "Coale's law" of the inverse relationship of population density with growth rate and technological know-how—as suggested in his letter—to the development of the human population as a whole over the last couple of millennia, we arrive at the peculiar conclusion that either Stone Age man was a technological wizard who carefully removed his technological achievements so as not to upset his inferior progeny, or that—if he was at the level at which most of us believe he was—our population dwindled from a once astronomical size to the mere three billions of today (Von Foerster *et al.*, 1961, June, p. 1932).

They concluded,

> The tragic error . . . is to insist that mankind has to be treated—like fruit flies—as a set of independent elements whose only properties are their fertility and their mortality schedules which are established *ad hoc* by looking into census figures. Very little indeed can be expected from such an approach, which not only fails to describe the past of the human population beyond a dozen generations but also is invalid for projecting population trends over such short an interval as only one generation. Therefore, it does not come as a surprise that recognition of an obvious trait in man—namely, his capacity to form coalitions, the ability of two men *jointly* to do things which the two independently are never able to achieve—immediately leads to expressions which adequately describe human population growth over several hundred generations, from the prehistoric past up to today. As we pointed out, the process which governed the growth rate for a couple of thousand of years and which is still acting today, exhibits a most dangerous intrinsic instability, which is now—so to say—around the corner (Von Foerster *et al.*, 1961, June, p. 1935).

Dorn (1962, p. 285) cited the Von Foerster article as probably setting "a record, for the entire class of forecasts prepared by the use of mathematical functions, for the short length of time required to demonstrate its unreliability." He pointed to the projections made by the United Nations as being "the most authoritative."

Von Foerster and his colleagues (1962) examined the population projections made by the U.N. at different points in time and noted that estimates of future world population increased as the date of the estimate progressed. They then compared the U.N. estimates with the results from the doomsday equation (see Table 1). They concluded that the values produced by the equation are

> . . . the asymptotes, at the moment of truth, to the "most authoritative projections"; we might mention in passing that the "most authoritative" projectors changed their minds in the last decade by roughly a factor of 2, while the "most unreliable" values (from the equation) are almost independent of the time of their derivation (Von Foerster *et al.*, 1962, p. 173).

Von Foerster, Mora, and Amiot then explained their view of how their method differs from the one used by demographers.

> The question remains as to what causes the "analytical" (demographic) method to be so poor in making even short-range projections. The answer is suggested by Dorn, who stresses the point that this method of dealing with a growth process takes into consideration instantaneous first derivatives only—fertility, mortality, and migration. However, it is well known in prediction theory that consideration of higher derivatives will diminish the variance in the expectation values. For instance, we could not catch a ball in flight if we were unable to compute at least its trajectory's second derivative, which happens, in this case, to be a constant. On the other hand, computation of higher and

TABLE 1

Low, Medium, and High World Population Projections (in Billions) for A.D. 2000, Made by the U.N. in Four Different Years and Derived from the Doomsday Equation (Von Foerster, *et al.*, 1962)

Projection	Estimate in 1950	Estimate in 1957	Estimate in 1958	Estimate in 1959	Doomsday Equation
Low			4.88		6.44
Medium	3.20	5.00	5.70	6.20	6.91
High			6.90	7.00	7.40

> higher derivatives requires more and more data regarding the process under consideration, which can, by the blind ones whose vision of the future is blocked, be obtained only by studying the past! This simple procedure is, alas, unacceptable to the "analyticist," to whom the past is, for unexplainable reasons, tabu (Von Foerster *et al.*, 1962, p. 173).

In addition to the sharply worded debate over the article by Von Foerster, Mora and Amiot, other natural scientists who have expressed similar views have faced condescension and have encountered difficulty in publishing their articles (Lambert and Fowler, 1988).

THE TEST OF TIME

By the end of 1962 the positions in the scientific debate were well defined. Public awareness of world population growth was rekindled with the publication of Paul Ehrlich's book *The Population Bomb* (1968). In the early 1970s issues related to population and the environment were widely discussed.

Serrin (1975) took a look at the doomsday equation after fifteen years. For 1975 the equation gives a value of 3.65 billion people while the Population Reference Bureau in mid 1975 estimated a world population of 3.97 billion. Although the equation underestimated the actual value, Serrin noted, "other predictions of the 1975 world population, made at essentially the same time as von Foerster et al.'s, ranged from 3 billion to 3.5 billion and thus were considerably less accurate."

In the late 1970s demographers began to report that population growth rates were dropping and that world population was coming under control (Tsui & Bogue, 1978). By the early 1980s some journalists had become convinced that world population growth was no longer an important issue (Wattenberg, 1981). Whereas the late 1960s and early 1970s were a period of concern, the early 1980s became an "era of good feeling" about our progress on world population growth.

In the late 1980s Umpleby (1987) pointed out that the world population trend was still ahead of the doomsday projection. Deevey (1987) in reply critiqued the use of humor and irony in the doomsday articles and gave a vote of no confidence to the wit of government officials. As articles in the popular press expressed the return of public interest in world population, some demographers (e.g. Haub, 1987) attempted to offer an explanation for population figures higher than those forecasted.

POST HOC POPULATION GROWTH

In the mid 1980s while studying data on population estimates, this author made a startling discovery. Estimates of human population continue to rise after the fact. Whereas Von Foerster *et al.* had shown in 1962 that demographic estimates for world population rise as the date in question approaches (see Table 1), an examination of population estimates made between 1951 and 1984 indicates that human population continues to increase after the date in question has passed. For example, as indicated in Table 2 the estimate for the 1970 world population made in 1982 is larger than the estimate made in 1973, and the estimate for 1970 made in 1984 is larger than the estimate made in 1982. Usually in the scientific community, once a particular date has passed, variables associated with that date do not change. Apparently, estimates of human population as compiled by demographers are regarded somewhat like the subject matter of historians—they are subject to reassessment after the fact.

This peculiar post hoc rise in population estimates may shed light on an inconsistency in the interpretation of population data. Since the mid 1960s demographers have been saying that world population growth rates are declining. "The growth rate of the world peaked at about 2 percent in

TABLE 2

Estimates of Human Population in Billions, as a Function of Time (United Nations, 1951, 1966, 1982, 1985, 1986, 1989)

Year in Question	1951 Est.	1963 Est.	1973 Est.	1982 Est.	1984 Est.	1988 Est.	Doomsday Equation
1950	2.406*	2.517	2.501	2.504	2.516	2.515	2.432
1955		2.731	2.722	2.746	2.751	2.751	2.599
1960	2.731	2.988*	2.986	3.014	3.019	3.019	2.792
1965		3.281	3.288	3.324	3.334	3.336	3.015
1970		3.592	3.610*	3.683	3.693	3.698	3.277
1975		3.944	3.968	4.076	4.076	4.080	3.650
1980	3.277	4.330	4.374	4.453*	4.450	4.450	3.969
1985		4.746	4.816	4.842	4.837*	4.854	4.438
1990		5.188	5.280	5.248	5.246	5.292	5.033
1995		5.648	5.763	5.679	5.678	5.766	5.814
2000		6.130	6.254	6.127	6.122	6.251	6.884

*The underlined numbers are the estimates made closest to the date in question.

1965 and then began a slow decline . . ." (Murphy, 1981, p. 1) However, demographic estimates of world population have moved ahead of values predicted by the doomsday equation, which is based on an assumption of increasing growth rates (Serrin, 1975; Umpleby, 1987). Hence, there is a discrepancy between population totals and reported growth rates.

If demographers are adjusting upward their estimates of population in previous years, then it would be possible for them to report both a rise in population above that anticipated and a decline in the rate of growth. The logic employed might be as follows: We expected that population in the current year would be P. However, we now estimate it to be P + p. Nevertheless, we *know* that the growth rate is declining and is now only R. Hence, we must have underestimated the population in the prior year. So let us adjust it upward. That way our estimates for all years will be as accurate as possible.

If this is a fair representation of the way that demographers are thinking about their estimates, then the inconsistency of population totals rising faster than the doomsday equation while growth rates are said to be declining can be resolved. Apparently, the statements made by demographers regarding growth rates should be disregarded. The remaining question is which estimate to use for the population in any particular year. A simple solution is to use the estimate made in the year in question.

One implication of this finding is that since the estimates published by demographers change not only before the fact but also afterwards, policy analysts must look elsewhere for a stable reference frame for judging what progress we are making toward reducing population growth. Luckily, an alternative is available in the doomsday equation, which has not changed since 1960.

THE TWO POSITIONS

The views of demographers and natural scientists can now be summarized (see Table 3).

Demographers believe that world population is a function of births and deaths. They focus their attention on estimates of fertility and mortality. The natural scientists claim that human population is also influenced by the human ability to communicate, to form a coalition, and to engage in a game with the environment.

To the demographers population increases when the death rate declines faster than the birth rate. A period of population growth comes to an end either when the birth rate declines to match the death rate (the demo-

TABLE 3

A Comparison of the Two Positions

Demographers	Natural Scientists
Changes in world population are a function of fertility and mortality	Fertility and mortality rates are influenced by communication
Population has increased because the death rate has declined faster than the birth rate	The rate of growth has increased because the size of the coalition has increased
Development in particular countries is associated with a declining population growth rate	World population has increased as development has increased
Human beings, like other species are limited by their environment	Human beings are unique in their ability to enlarge their environment
The facts of reproductive biology limit the rate of human population growth	Technology has overcome and will likely continue to overcome limits
An infinite population and infinite growth rates are absurd and impossible	Singularities in the relationships between variables are common in science and warn of instability
Estimates of world population for future dates should be based on estimates of future fertility and mortality rates	Estimates of world population for future dates should be based on rates of change computed from data obtained in the past
Estimates of population in previous years are subject to alteration	Stability in estimates is essential in calculating rates of change

graphic transition) or when the death rate increases to match the birth rate (the demographic trap). Von Foerster and his colleagues noticed that the rate of human population growth has increased as population has increased. If this pattern persists, they suggested that a singularity (a point of instability) would occur about the year 2027.

Demographers believe that development (in particular countries) is associated with a falling population growth rate. The natural scientists observe that world population has increased as development has increased.

Demographers believe that the population of human beings, like the populations of other animals, is limited by the environment. The natural scientists claim that human beings are unique among terrestrial species in their ability to enlarge their environment.

Demographers believe that the rate at which the human population can grow is limited by the facts of reproductive biology. The natural scientists suggest that research on in vitro fertilization is likely to remove reproductive limitations just as other technologies have increased food supplies, life-spans, and habitat.

Demographers estimate world population for future dates by estimating future fertility and mortality rates. The estimated fertility and mortality rates are applied to the previously estimated population and the process continues for dates farther into the future. The natural scientists limit themselves to data already in hand. They look for rates of change revealed by existing data and project these into the future.

Demographers are concerned with the accuracy of their estimates and adjust previous estimates to correct for "undercounting." Rates of change are estimated, based in part on field reports on the success of fertility control programs. They compute totals partly on the basis of estimated rates. Natural scientists compute rates based on recorded totals. Natural scientists believe that if previous data is altered, relational parameters such as rates of change should be recomputed.

THE POLITICAL IMPLICATIONS OF DEMOGRAPHIC THEORIES

The issues being debated by demographers and natural scientists are of more than merely academic interest. The debate traced above reveals a fundamental difference in underlying assumptions. The demographic focus on fertility and mortality rates almost seems to imply that "overpopulation" is not possible. In a sense it is unthinkable. If the population in a particular area becomes too large, mortality rates will rise and fertility rates will fall until balance is restored. Through the lens of their world view, demographers gaze at an essentially stable world. The political implication is that although public policy action may be desirable, it is not really required. Stability will be maintained automatically—if not by one means, then another.

The doomsday equation embodies quite a different world view. Although based on the data collected by demographers, the doomsday equation leads natural scientists to see a highly unstable system. In the midst of the erudite debate on the merits of their work Von Foerster *et al.* never lost sight of what for them was the key issue.

> We hope that in this exchange of arguments about a few side issues the reader has not lost track of the real issue at stake—namely, whether or not the time has come when man must take control over his fate in this matter and attempt to launch perhaps the most ambitious, most difficult and most grandiose enterprise in his entire history: the establishment of a global control mechanism, a population servo, which would keep the world's population at a desired level (Von Foerster *et al.*, 1961, June, p. 1931).

In each of their articles Von Foerster *et al.* stressed the need for urgent human action. In the world view of the natural scientists the human population, unlike the populations of other animals, is not inherently stable. On the contrary, their analysis indicates an essentially unstable system which will avoid catastrophe only through deliberate human action.

Reports based on a diagnosis of instability led to concern about a "population explosion." Reports based on an assumption of stability led to complacency about population growth. Journalists and policy analysts would benefit by understanding the assumptions implicit in the world views of the various authors.

Perhaps the dispute between demographers and natural scientists can be resolved if the two groups work more closely together. Natural scientists have never challenged demographers in collecting population data. Everyone works from the numbers produced by demographers. But natural scientists and demographers have evolved fundamentally different traditions of data analysis. Natural scientists have demonstrated a better grasp of the role of theory in scientific research. So far, the natural scientists have a better record in making forecasts. Cooperation rather than competition between the two groups will no doubt produce superior results.

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