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Science: Endless Horizons or Golden Age?

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At the end of each year, and even more customarily at the close of every decade, we are wont to look back and summarize our gains and our losses, and to look forward in the hope of forecasting as well as possible what the next year, the next decade, or even the next century may hold for us. For the scientist it seems particularly appropriate, since the future of science itself—its rate of advance in various directions and the roadblocks or morasses ahead—will likely be mirrored in the rates of technological change and consequently in the attainment of human well-being or the advent of catastrophe. One need not be a prophet to attempt an analysis and critique of scientists' views about the future of science, and these may themselves sharpen our vision of the problematical years that lie ahead.

Scientists themselves often seem little concerned about the matter. They are concerned about the quantitative measurement of all sorts of phenomena except that of the growth, stasis, or decline of their own collective activity. Young scientists, in particular, seem to find it sufficient to harbor a personal liking for scientific exploration and discovery, without much worry about the magnitude of the edifice they are constructing, the depth of the mine they are excavating, or the extent of the continent they are invading. With advancing years one commences to wonder about the relative position of one's own work in a broader, more extended perspective. Thus one is led to try to evaluate present scientific knowledge not only in comparison with the past but also the future of man's understanding of nature. Then the question must be faced: Are there finite limits to scientific understanding, or are there endless horizons?

I have chosen two phrases for my title to represent the extremes in the spectrum of belief in the future of science—the one, the view of limitlessly expanding knowledge and of infinite bounds; the other the view that scientific knowledge, like our universe, must be finite, and that the most significant laws of nature will soon have been discovered. The Golden Age is thus the age of perfected knowledge, of consummated applications, and of social stasis. The first of these phrases is the title of a book written in 1946 by Vannevar Bush about the future of science (*1*). The phrase "Golden Age" is also from the title of a book, *The Coming of the Golden Age*, written by Gunther Stent and published in 1969 (*2*). They thus epitomize the views of two eminent scientists, one a physical scientist and engineer and the other a geneticist and molecular biologist. Each of them was writing at the close of a period of unparalleled development in his respective area of science. In 1946, Vannevar Bush could contemplate from the vantage point of his recent work as director of the wartime Office of Scientific Research and Development what Karl T. Compton called "the greatest mobilization of scientific power in the history of the world." Not only could Vannevar Bush think with just pride of the advanced weaponry which had been created but, even more important, of the harnessing of scientific talent in new ways through operations research and systems analysis. His own inventions, the network analyzer and the differential analyzer, were harbingers of the Age of Computers. He foresaw the problems involved in converting atomic energy from a military secret jealously guarded by a few nations to a worldwide basis of power production open to all nations but subject to the hazards of power politics. He recognized the difficulty in promoting scientific advance in the atmosphere of secrecy, in the face of demands for "classified" information. He was foremost among those who planned and advocated national support of basic scientific research, which he felt had lagged during World War II, and he was one of the fathers of the National Science Foundation. It may thus have been quite natural for him to see ahead of us the "endless horizons" of scientific knowledge, the greatest challenge to moderns for whom the West has been reached, the world's continents settled and the oceans crisscrossed, for whom in fact the excitement of the geographical frontier has vanished.

Like Bush, Gunther Stent was writing at the end of the greatest advances ever made in his own scientific field. Genetics, as a science, did not even exist before the opening of the 20th century. Molecular genetics, which Stent identifies as the third and fourth phases of the science, its so-called "Dogmatic" and "Academic" periods, began only in 1953 or thereabouts, and yet in the ensuing years it has added a greater knowledge of the chemical basis of heredity and its mechanisms than in all the years before, and seems, according to Stent, to be well into a final period of diminishing returns.

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More and more scientists, publishing more and more papers, fill in missing details and extrapolate knowledge in quite predictable directions. The great conceptions, the fundamental mechanisms, and the basic laws are now known. For all time to come, these have been discovered, here and now, in our own lifetime. They can never be discovered again unless man loses his scientific heritage; and even so, they cannot be discovered again for the first time. They can only be reexhumed, refined, or modified. Like Newton's laws of motion, like the Copernican solar system, like the origin of species, or like relativity and quantum mechanics, they are now the known, not the unknown—and by just so much is the extent of unknown Nature diminished.

Like Roderick Seidenberg, with whose book *Posthistoric Man* (*3*) Gunther Stent is apparently unacquainted, Stent expects that the cessation of scientific advances will ultimately lead to an end to technological and social progress. Both Seidenberg and Stent acknowledge their debt to Henry Adams in charting the dynamics of progress and predicting its ultimate cessation. Where Seidenberg pictures the final state of society as posthistoric, in the sense that, having achieved ultimate knowledge and its applications to man's life in numerous ways, society will crystallize into a changeless pattern, Stent, foreseeing the virtual end of an exponential increase in human power in a very few centuries, and the consequent end of the arts and sciences, predicts a Golden Age, when man will live in a way "not very different from a re-creation of Polynesia on a global scale." It is worth quoting his description of this final state of society (*2*, pp. 137–138):

> The will to power will not have vanished entirely, but the distribution of its intensity among individuals will have been drastically altered. At one end of this distribution will be a minority of the people whose work will keep intact the technology that sustains the multitude at a high standard of living. In the middle of the distribution will be found a type, largely unemployed, for whom the distinction between the real and the illusory will still be meaningful and whose prototype is the beatnik. He will retain an interest in the world and seek satisfaction from sensual pleasures. At the other end of the spectrum will be a type largely unemployable, for whom the boundary of the real and the imagined will have been largely dissolved, at least to the extent compatible with his physical survival. His prototype is the hippie. His interest in the world will be rather small, and he will derive his satisfaction mainly from drugs or, once this has become technologically practicable, from direct electrical inputs into his nervous system. This spectral distribution, it will be noted, bears some considerable resemblance to the Alphas, Betas, and Gammas in Aldous Huxley's *Brave New World*. However, unlike Huxley, I do not envisage this distribution to be the result of any purposive or planned breeding program, but merely a natural population heterogeneity engendered mainly by differences in childhood history. Furthermore, in contrast to the low-grade producer roles assigned to Betas and Gammas, beatniks and hippies will play no socioeconomic role other than being consumers.
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> As far as culture is concerned, the Golden Age will be a period of general stasis, not unlike that envisaged by Meyer [*4*] for the arts. Progress will have greatly decelerated, even though activities formally analogous to the arts and sciences will continue. It is obvious that Faustian Man of the Iron Age [we of today imbued with the idea of progress] would view with considerable distaste this prospect of his affluent successors, devoting their abundance of leisure time to sensual pleasures, or what is even more repugnant to him, deriving private synthetic happiness from hallucinatory drugs. But Faustian Man had better face up to the fact that it is precisely *this* Golden Age which is the natural fruit of all his frantic efforts, and that it does no good now to wish it otherwise. Millennia of doing arts and sciences will finally transform the tragi-comedy of life into a happening.

Here, then, are diametrically opposed views of the future of man which grow out of the contemplation by the scientist of the achievements of science itself. What are the basic assumptions on which these views are founded? It seems to me that the implicit assumption of greatest importance relates to the finiteness, or alternatively the infinitude, of possible knowledge. No one really questions, I believe, that even now we may be like little boys on the shores of a vast ocean, tossing pebbles into the waves. What remains to be learned may indeed dwarf imagination. Nevertheless, the universe itself is closed and finite, or at least bounded to our knowledge by the radius of the light-years since its beginning, about 10 billion years ago; and our telescopes have now plumbed space almost to those limits of the observable. Their growing knowledge of the universe has led scientists to believe more and more firmly that the laws of nature have universal applicability. Matter is composed of the same particles and elements everywhere. Radiant energy moves with the same speeds and has the same characteristics everywhere. Local differences are explicable in terms of local conditions and past history.

The uniformity of nature and the general applicability of natural laws set limits to knowledge. If there are just 100, or 105, or 110 ways in which atoms may form, then when one has identified the full range of properties of these, singly and in combination, chemical knowledge will be complete. There is a finite number of species of plants and of animals—even of insects—upon the earth. We are as yet far from knowing all about the genetics, structure and physiology, or behavior of even a single one of them. Nevertheless, a total knowledge of all life forms is only about 2×10^6 times the potential knowledge about any one of them. Moreover, the universality of the genetic code, the common character of proteins in different species, the generality of cellular structure and cellular reproduction, the basic similarity of energy metabolism in all species and of photosynthesis in green plants and bacteria, and the universal evolution of living forms through mutation and natural selection all lead inescapably to a conclusion that, although diversity may be great, the laws of life, based on similarities, are finite in number and comprehensible to us in the main even now. We are like the explorers of a great continent who have penetrated to its margins in most points of the compass and have mapped the major mountain chains and rivers. There are still innumerable details to fill in, but the endless horizons no longer exist.

It seems to me that Vannevar Bush would not really disagree with the foregoing analysis. When one examines his book, *Endless Horizons* (*1*), for the expected discussion of the challenge of scientific advancement to mankind and for some consideration of the actual meaning of the title, one seeks in vain. A great deal of attention is given to specific technological advances and to the possible further developments of the future, but the nearest to a discussion of the theme implied by the title is in two brief sections of the essay "As We May Think." These are headed, respectively, "Endless Trails" and "Horizons Unlimited." Yet the endless trails turn out to be only searches through the coded items stored in a vast mechanical memory, or "memex"; while the unlimited horizons unfold only in the form of specific predictions of various ways in which science may in the future develop the production, storage, and retrieval of information, or discover new extensions of our human senses. Whether the horizons are really endless is an idea not only unanswered, it is not even examined. On the other hand, in his final essay, "The Builders," Vannevar Bush likens science to the quarrying of material for an edifice and the process of its construction. ". . . The material is exceedingly varied, . . . the whole effort is highly unorganized [and] . . . the edifice itself has a remarkable property, for its form is predestined by the laws of logic and the nature of human reasoning. It is almost as though it had once existed. . . . Parts of the edifice are being used while construction proceeds. . . . The workers sometimes proceed in erratic ways. . . . On the other hand there are those men of rare vision who can grasp well in advance just the block that is needed for rapid advance on a section of the edifice to be possible, who can tell by some subtle sense where it will be found, and who have an uncanny skill in cleaning away dross and bringing it surely into the light. These are the master workmen."

Are these not the images of one who believes in the finite extensibility of science? Is an edifice with a predestined form infinite in extent? It cannot be affirmed that Bush's metaphors and similes unquestionably imply the finiteness of nature and of scientific understanding, but is that not the most reasonable implication? If so, was the bold title, *Endless Horizons*, not itself a metaphor never intended to be taken literally, but supposed merely to imply that from our present viewpoint so much yet remains before us to be discovered that the horizons seem virtually endless?

If one grants that the universe itself is finite and that its laws too are universal and finite in number—or even if the universe be infinite but its nature and its laws universal—then with each new phenomenon discovered and explored, with each new law confirmed, there is an approach to the finite limits of scientific knowledge. In that case, it is less important to note the absolute bounds of knowledge at the present time than to examine the rate at which, in the past century and a half, our scientific knowledge has been expanding.

By whatever parameters one may choose to select, the accumulation of knowledge has been accelerating exponentially during this period, with a doubling time of 12 to 15 years. As I have described in a fuller study of this phenomenon in a recent book, *The Timely and the Timeless* (*5*), the number of scientific periodicals, the number of scientists publishing or working, and the number of scientific papers have been doubling almost every 10 years. It is of course dangerous to equate the growth of scientific knowledge with growth in the number of scientists or their publication of papers. Yet I suppose, although I cannot demonstrate it satisfactorily, that there must be some relatively stable mathematical ratio between the total number of scientific contributions published in a given period and the number among them of highly important, significant "breakthroughs." Derek J. de Solla Price, writing in *Science Since Babylon* (*6*), suggests that the "stature" of science, which I take to be equivalent to the frontier or attainment of science, doubles at a much slower rate than the increase of scientific information in the gross. He estimates that it has doubled, in the modern period, about every 30 years, the rate being maybe slower because of the cumulative nature of science, which like a pyramid or pile of stones must increase in volume as the cube of any increase in height. Such matters have not been studied carefully, but I suspect that the advances in technology which are basic to progress are more directly related to the rate of this advance of the frontier rather than to the actual total increase of scientific information, as if an 8 percent per annum technological advance would correspond to a 2 percent per annum rate of advance of the scientific frontier, that is, to a doubling time of 35 years for the latter. If our technological level as well as our total scientific information are now 256 times what they were at the beginning of the 20th century, our scientific "stature" is now but four times as great as then.

It would be most interesting if our students of the sociology of science, who are all too few in number, were to demonstrate that this rate is itself declining, as I suspect. It might be taken to indicate not only that the *average* originality of scientists is declining as the number of scientists expands, but also that it is in fact becoming more and more difficult, as scientific knowledge grows, to make a totally new and unexpected discovery or to break through the dogmas of established scientific views. Be that as it may, the amount of extant scientific information, trivial as well as important, is currently increasing at a rate related to the absolute number of scientists, technologists, and laboratory workers in the population. I have pointed out that in the United States this rate, which produces a doubling in somewhat over 10 years, cannot long be maintained, since it is much faster than the rate of population growth for the country and already constitutes about 20 percent of the entire professional labor force. I therefore suggested that the upper limit for the proportion of "scientists and technologists" in the entire professional labor force may perhaps be about 25 percent. Further absolute gains would seem to depend upon the increase in size of the total population, an increase already slackening, or a possible increase of the professional component in the total labor force. Here the limiting factor may well be the requirement for a modicum of intelligence and of advanced education and training on the part of every scientist or technologist.

Science and Progress

Both historian and scientist agree that progress, insofar as it can be defined and measured, must be defined in terms of man's increasing power. This was the theme of Carl Becker, in *Progress and Power*, who humorously summed it up in the following words (*7*, pp. 19–20):

> All that has happened to man in 506,000 years may be symbolized by this fact—at the end of the Time-Scale he can, with ease and expedition, put his ancestors in cages: he has somehow learned the trick of having conveniently at hand and at his disposal powers not provided by his biological inheritance. *From the beginning of the Time-Scale man has increasingly implemented himself with power.* Had he not done so, he would have had no history, nor even the consciousness of not having any: at the end of the Time-Scale he would still be (if not extinct) what he was at the beginning—*Pithecanthropus erectus*, the Erect-Ape-Man. Without power no progress.
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> . . . The significant fact is that the human race, so far from having any aversion from power, has at all times welcomed it as a value to be cherished. Look where we will along the Time-Scale, we see men eagerly seeking power, patiently fashioning and tenaciously grasping the instruments for exerting it, conferring honor upon those who employ it most effectively.

Stent, influenced particularly by Oswald Spengler, adopts the concept of the archetype Faustian Man, whose boundless will to power locks him "in an endless strife with his world to overcome obstacles, conflict, to his mind, being the very essence of existence." Thus, while both Becker and Stent accept the dictum of J. B. Bury that the *idea* of progress is scarcely older than the 17th century and did not really become a prevalent social theory until the beginning of the 19th, they virtually identify *all* history with the occurrence of progress through increasing power.

As long as new instruments of power are multiplied and the command over new sources of power is increased, progress may continue. But scholar and scientists alike are dubious. Says Becker (*7*, p. 98):

> But it is conceivable, even probable, that the possibility of discovering and applying new sources and implements of power will in the course of time gradually diminish, or even be altogether exhausted. In that event the outward conditions of life will change less and less rapidly, will in time become sufficiently stable perhaps to be comprehended, sufficiently stable therefore for a relatively complete adjustment of ideas and habits to the relatively unchanging body of matter-of-fact knowledge of man and the outer world in which he lives. In such a stabilized and scientifically adjusted society the idea of progress would no doubt become irrelevant as progress itself became imperceptible or non-existent.

Roderick Seidenberg pushes his vision of a stable society and a completely adjusted man to the ultimate extreme. When the organization of society has proceeded to its final crystallization "in a period devoid of change, we may truly say that man will enter upon a posthistoric age in which, perhaps, he will remain encased in an endless routine and sequence of events, not unlike that of the ants, the bees, and the termites. . . . Man may likewise find himself entombed in a perpetual round of perfectly adjusted responses. . . . Man will hasten along his predestined way under the illusion of attaining his freedom on even higher levels of existence, while actually sealing his fate by all the devices his dominant intelligence can command." The emotions, he thinks, will have atrophied. Even consciousness, becoming no longer necessary in the absence of tension or unstable equilibrium, will evaporate.

No rate of scientific development equal to that of the past half century can be long maintained. Henry Adams pointed out that the actual doubling times are not so important as the simple existence of an exponential rate of increase, since in any case the acceleration of the process will eventually lead to staggering, and indeed impossible, magnitudes. Do not we all remember the story of the Arabian merchant who contracted with the Sultan to work for one grain of wheat the first day, two the second day, four the third day, and so doubling with each day to the 64th day corresponding to the squares on their chessboard; and how he bankrupted the kingdom. In real increases occurring for a time at exponential rates there is, as Stent emphasizes, a positive feedback. The more offspring are produced, the more adults there will be to contribute to the next generation. The fission of one bacterium into two provides the basis for the next doubling. The recognition of progress in the economic, social, and political condition of man led to the expectation, beginning at about the end of the 18th century, that progress not only was possible but was to be expected, and this expectation led men to push for further progress.

"Evidently," Stent says, "the element of positive feedback embodied by progress is that the rate at which man can gain more power over the outer world is the greater the more power is already at his disposal." Yet, the argument continues, ". . . this very aspect of *positive* feedback of progress responsible for its continuous acceleration embodies in it an element of temporal self-limitation. . . . If one examines one by one the parameters conceivably relevant to estimating the rate of progress, such as world population and energy consumption, per capita income, or speed of travel, one must conclude that none of them is likely ever to exceed some definite bound." The further we have advanced on the accelerating curve, the closer we inevitably come to the time when limiting factors will curb the growth and bring it into some degree of stasis, or equilibrium, or possibly decline.

We may find reason to disagree with various details of these pessimistic visions of man's future, but can we honestly set aside the conclusion that *progress*, in the sense of ever-growing power over the environment, must soon come to an end? We may for a long time to come retain our emotional responses, which to so great an extent depend upon the hormonal balance stabilized in the early phases of mammalian evolution, long before man was man. I do not accept Seidenberg's supposition that in the keen battles between reactions on the basis of intelligence and reactions on the basis of emotion, intelligence will win the upper hand. Seidenberg seems to have mistaken the basis of emotion with instinct. True, in vertebrates such as birds or even mammals, instincts appear often to operate through the machinery of the hormones, but in bees, ants, and termites instincts depend fully as much upon the inborn connections of neurons, in other words, upon the same fundamental mechanisms as intelligence. The distinction to be drawn is between the inborn patterns of the nervous system, which develop irrespective of the external situation, most often in vertebrates before birth, or hatching from the egg, and the malleable patterns which can in some way be modified through experience and learning. Stent certainly does not envisage a decline of emotionality—quite the contrary. His beatniks and hippies, who will comprise the majority of future human populations if he is right, will react to life even more wholly than now on the basis of emotionality.

That is a side issue. Let us keep clearly in mind that the primary basis of agreement of Becker, Seidenberg, and Stent, and perhaps even of Bush, is that progress cannot continue indefinitely. Indeed, so awesome is already the accelerating rate of our scientific and technological advance that simple extrapolation of the exponential curves shows unmistakably that we have at most a generation or two before progress must cease, whether because the world's population becomes insufferably dense, or because we exhaust the possible sources of physical energy or deplete some irreplaceable resource, or because, most likely of all, we pollute our environment to toxic, irremediable limits. Many scientists have in recent decades examined these processes and have tried to flag the runaway express. The present more general outcry, daily growing stronger, against unlimited population growth and heedless pollution of the environment offers a slight ground for hope. The prime difficulty is that so many persons, not only in the highly industrialized countries but even more among the peoples of the underdeveloped countries, now see their hopes for the future bound up with the continuation and extension to all mankind of the progress hitherto limited to a few fortunate lands and people. The momentum of these processes is furthermore such that measures to apply the brakes to population growth or to reclaim and preserve our environment, even if the measures are firm and effective, will take at least one generation—say until the year 2000—to reach full effect.

To say the least, capitalism has not found a way to survive on the basis of a simple replacement economy. The pressure to keep the gross national product growing—in real, not inflationary, terms—comes from all elements of our society, from labor as well as employer and industrialist, from natural scientist as well as economist. (True, a few rumblings of dissent from this point of view have been voiced.) Dependence upon the profit motive, which has in the past stimulated the unparalleled growth of Western Europe and the United States, just as surely presses society into overexploitation.

Socialism, which, as it now operates in other segments of the world, is but a modified governmental capitalism, seems no better able to avoid overexploitation than does pure individualistic capitalism. No socialist country has met the population problem as successfully as highly industrialized, capitalist Japan. The depletion of the world's resources flowing from economic imperialism is as much a characteristic of socialism as of capitalism. The pollution of the environment proceeds with perhaps even fewer checks in a socialist land than in a Western democracy, where the outcry of protesters is freer and the influence upon legislators more direct.

Man indeed faces hard times unless a new social and economic system, far more responsive to human needs and far more foresighted than in the past, can be invented. What is coming to be called technology assessment is one example of what is needed: a complete systems analysis of all the long-range effects and side effects of each technological alteration, before it is unleashed. Our local, state, and national governments are hopelessly unprepared to exercise such a function. Our legislators and bureaucrats are uninformed and unaware, for the most part, of the crisis facing the world today, and they are perhaps universally incapable of conducting the kind of analysis required. What they could do, if they would, would be to establish in sufficient number and strength the agencies to carry out the studies required; and they could unquestionably, if they would, assess strict penalties upon all, high or low, who waste our resources and needlessly pollute our environment.

In Czechoslovakia, as I have previously informed members of the AAAS, I discovered the existence of an Institute for the Study of the Biological Landscape (*8*). It was a response to an overwhelming technological disaster that occurred when, during the industrialization of Slovakia after World War II, a great mill was constructed in a narrow valley of the Tatra Mountains where an atmospheric inversion layer penned down the fumes, heavy in sulfur dioxide, arising from the combustion of local coal. Every living thing in the valley had been killed, and the workers, so I was told, at times had to wear gas masks and live many miles away, at a great loss of time. In the United States—and in every other country, whether heavily industrial or newly entering the industrial phase—we need a profusion of such agencies for the study not only of the environment and its alteration by technological innovation, but also of the systems for predicting and regulating change. Let me suggest, at the risk of grave misunderstanding, that in future histories of the world the decade of the 1960's may be known not significantly for the miserable Vietnam war but as the time when man, with unbridled lust for power over nature and for a so-called high standard of living measured by the consumption of the products of an industrial civilization, set in motion the final speedy, inexorable rush toward the end of progress.

I am not a hopeless pessimist, however. I have already suggested one way in which mankind might avoid the debacle. These agencies to curb irrational exploitation, widespread in all countries, could mutually reinforce one another. They might form the basis of a most effective United Nations network. In any case, what the United States itself most needs in this juncture is a second Vannevar Bush who could organize and direct a comparable national effort in peacetime as Bush did in time of war. It is consequently disheartening to observe that the technological developments most needed for the kind of systems analysis required, and which Bush foresaw in 1946, are not yet available. His great "memex" system, which would replace private files and public libraries, which would code all extant information on every subject for instant retrieval, and which would provide endless cross trails of reference to stimulate fresh experimentation and analysis, is still unrealized. There seems to be little or no reason why such a system could not be constructed today. The computers, now far exceeding in capacity for storage and rapid retrieval what Vannevar Bush had dreamed of, are here. What is still lacking is the compatibility of different systems and the actual realization of the conception. The machines, in fact, are far superior to the skill of the human programmer who feeds our mechanical memory banks. In consequence, the very accumulation of disorganized scientific information is burying us daily deeper in a profusion of unevaluated, unused knowledge. Scientific information has increased a hundredfold since 1900, but most of it is already forgotten. The next age of scholarship will no doubt promote processors and analysts who need only to delve in the mountains of extant scientific and technological literature for forgotten and uncomprehended items of knowledge.

The Man of the Future

There is one other way in which the crisis provoked by an uncontrolled exponential increase can be surmounted. Every biologist who deals with the population growth of bacteria, mice, or men knows that exponential growth not only must come to a halt when one or another factor of the environment becomes limiting, but also that subsequently a variety of fates may ensue. The population may die out altogether if it cannot adjust rapidly enough. Toxicity may increase, for example, owing to the wastes of the population itself, to such an extent that even in the presence of ample food, all organisms perish. Or fish, in a polluted lake deprived of sufficient oxygen, may die by millions. On the other hand, the population may level off toward a condition of stability, in which proliferation and exploitation of the environment are balanced against the capacity of the environment, especially the food supply, to regenerate. Or, perhaps most interesting of all, after a period of such stabilization the once-limiting factor may become no longer the limiting parameter of the environment. Then the population may set out on a new cycle of exponential growth.

If man learns in time to regulate his

numbers so as not irreparably to pollute his environment, if he learns to utilize ordinary rock in place of rare metals, or to synthesize out of abundant plant materials most of what he needs, it is possible that the limiting factor may become the present supplies and sources of energy. Fossil fuels are exhaustible, perhaps within a century; nuclear energy from fission depends also upon scarce and limited amounts of uranium or artificial transuranium elements. Man's future resources of energy may thus depend upon controlled nuclear fusion. That might indeed initiate a new phase of exponential growth of human *power* (not necessarily of population).

In the new, far more regulated society of man which will inevitably be forced upon us by our exponential rates of increase, the present genetic types of man may not all permit a happy adjustment. The nature and personality of man must change, too, if progress is no longer to be our chief goal and ambition. The once sacred rights of man must alter in many ways. Thus, in an overpopulated world it can no longer be affirmed that the right of the man and woman to reproduce as they see fit is inviolate. On the contrary, if my own additional child deprives someone else of the privilege of parenthood, I must voluntarily refrain, or be compelled to do so. In a world where each pair must be limited, on the average, to two offspring and no more, the right that must become paramount is not the right to procreate, but rather the right of every child to be born with a sound physical and mental constitution, based on a sound genotype. No parents will in that future time have a right to burden society with a malformed or a mentally incompetent child. Just as every child must have the right to full educational opportunity and a sound nutrition, so every child has the inalienable right to a sound heritage.

Human power is advancing with extraordinary rapidity in this realm of control over the genetic characteristics of the unborn. Perhaps, as Carl Becker so pregnantly stated, our race, far from having any aversion from power, will welcome this power too, will seek it, fashion it, and grasp it tenaciously. Unlimited access to state-regulated abortion will combine with the now perfected techniques of determining chromosome abnormalities in the developing fetus to rid us of the several percentages of all births that today represent uncontrollable defects such as mongolism (Down's syndrome) and sex deviants such as the XYY type. Genetic clinics will be constructed in which, before long, as many as 100 different recessive hereditary defects can be detected in the carriers, who may be warned against or prohibited from having offspring. Preliminary efforts to synthesize genes and to introduce a sound gene by means of a carrier virus into a child or fetus bearing only the defective allele at the same position in the chromosomes are promising. They may make it possible not merely to correct a genetic defect while leaving intact in the individual the defective gene to be passed on, but actually to substitute the sound gene for the defective gene in the reproductive cells of the treated person. This procedure will be unquestionably most effective if carried out during the early embryonic stages of development, or in the just-fertilized egg itself before it has begun its cleavage into numerous cells. Hence we must look with expectant attention at the startling progress that is being made in the laboratory of R. G. Edwards at Cambridge University, England, and in a few other places, since the number of biologists engaged in such studies is still astonishingly low.

Dr. Edwards and his collaborators (*9*) have succeeded in obtaining considerable numbers of oocytes from human females, culturing them in media that permit their maturation, fertilizing them with fresh spermatozoa, and observing normal development of the embryos so produced to the blastocyst (hollow ball) stage at which they normally become implanted in the wall of the mother's uterus. The way is thus clear to performing what I have called "prenatal adoption," for not only might the selected embryos be implanted in the uterus of the woman who supplied the oocytes, but in that of any woman at the appropriate time of her menstrual cycle. Edwards cautiously limits the application of his developing techniques to the provision of a healthy embryo for a woman whose oviducts are blocked and prevent descent of the egg. It should be obvious that the technique can be quickly and widely extended. The embryos produced in the laboratory might come from selected genotypes, both male and female. Preservation of spermatozoa in deep frozen condition could permit a high degree of selectivity among the sperm donors, who so far have been limited to the husbands of the women donors of the oocytes. Sex determination of the embryos is possible before implantation; and embryos with abnormal chromosome constitutions can be discarded. By checking the sperm and egg donors with a battery of biochemical tests, matching of carriers of the same defective gene can be avoided, or the defective embryos can themselves be detected and discarded. By preserving the reproductive cells obtained from young persons under conditions which minimize mutation, those same individuals may have offspring at a relatively advanced age without incurring the higher probability of adverse gene and chromosome defects that normally increases with age. In the future age of man it will become possible for every person to procreate with assurance that the child, either one's own or one prenatally adopted, has a sound heritage, capable of fully utilizing the opportunities provided by society for optimal development.

We do not know enough about the more complex aspects of human nature, such as intelligence and personality, to exercise strong selection wisely. However, if every couple were permitted to have only two children, or to exceed that number only upon special evidence that the first two are physically and mentally sound, a mild eugenic practice would be introduced that is probably all mankind is prepared to accept at this time. Let us insist, in any case, upon avoiding any measures that might decrease the extent of human genetic diversity. The intelligence of man is an evolutionary product of natural selection for adaptability to great variation of surroundings, to tremendous vicissitudes of experience, as Bergson concluded 60 years ago. That intelligence depends upon a genetic pool in the populations of man to which many genes contribute, in ever-shifting combinations produced by the patterns of heredity and reproduction. A pure line, no matter how perfectly selected for special excellence under given conditions, could be well adapted only to particular conditions. Unless man's power produced a world not only stable but unvarying and unvaried, the maintenance of human diversity should be a paramount aim. As long as our brave new world presents an abundance of choices and as long as we have freedom to choose, so long will human intelligence based upon genetic diversity remain a primary requirement.

Intelligence without integrity will fail. Roderick Seidenberg, in a later book, *Anatomy of the Future* (*10*), puts it well. ". . . The means rather than the ends of life are in our command." Man requires a challenge and a quest if he is to avoid boredom. The Golden Age toward which we move will soon look tawdry if we no longer see endless horizons. We must, then, seek a change within man himself. As he acquires more fully the power to control his own genotype and to direct the course of his own evolution, he must produce a Man who can transcend his present nature. The Erect Ape-Man had little vision of the power that his 20th-century descendant would wield in really so short a span of evolutionary time. For the Erect Ape-Man a club was the acme of power. Even so, if Man can avoid the ultimate follies which our present powers have bestowed upon us, and can survive a few centuries more, we today can little perceive what he may be. Perhaps the Golden Age of no progress will be but a passing phase and history may resume. We can only hope.

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Dormancy of Trees in Winter

Photoperiod is only one of the variables which interact to control leaf fall and other dormancy phenomena.

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Dormancy phenomena in trees include the yearly loss and renewal of leaves which provide both the scientist and the layman with a fascinating pageant of brilliant colors in the fall and a sequence of delicate green traceries in the spring. The leafless tree in winter is commonly said to be in a condition of rest or dormancy; lack of apparent growth and resistance to injury by cold are characteristics of this period.

Careful observations reveal that "dormancy" involves many unsynchronized phenomena. Terminal buds are formed 2 or more months before active growth in diameter ceases and leaves fall. Leaf primordia are formed inside terminal buds during late summer and early fall. Bud scales can grow minutely during every winter month. Roots can grow whenever soil temperature and moisture content are high enough. Photosynthesis, respiration, transpiration, and other physiological activities continue year-round.

The transitions from a phase of active growth in the early summer to a phase of quiescence to a phase of winter rest, and back to a phase of active growth in the spring are gradual. Different species and different genotypes within species vary in their dormancy phenomena. All of the above facts combine to make the task of defining when a plant is in a dormant state or in a state of active growth just as difficult and just as arbitrary as defining whether an organism is dead or alive. Cautious specialists avoid making a highly restrictive definition for the term dormancy. However, some definitions are necessary for intelligent discussion of a subject; for the purpose of this review, a dormant plant is defined as having two attributes: (i) a period of markedly reduced growth rate with few, or in some cases no, cell divisions in the terminal and lateral meristems of the plant and (ii) a winter chilling requirement. Even when exposed to an environment which favors active growth, a dormant plant is unable to renew promptly active growth without exposure to winter cold, chilling, or other special treatments. Not all authors define dormancy in the same way.

Dormancy can be induced and broken both naturally and artificially by a variety of agents that range from controlled photoperiods and winter cold to urine and gibberellic acid; these various agents evidently act to turn some genes on and turn others off. The understanding of dormancy in plants promises to aid in understanding more general mechanisms of genetic control of growth and development. A Pandora's box of over 2000 references related to dormancy and growth substances is opened by reading a selection of review papers (*1–7*). Indeed, the maze of conflicting observations and reviews concerning dormancy and the related field of plant hormones and growth substances is overwhelming.

This article attempts to review the

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