SCIENCE, VALUES, AND HUMAN EVOLUTION

by Arnold W. Ravin

The role of science in society is often described today in extreme terms. For some, science is the exclusive vehicle by which the lot of humanity can be perfected; for others, it is the relentless mechanism by which all we hold dear in human civilization will be destroyed. Neither of these polarized attitudes regarding the place of science strikes me as valid. To appreciate both its potentialities and limitations, science must be viewed, it seems to me, as an inextricable part of those human cultures in which it has emerged or into which it has diffused from other cultures. This view, I hope to show, warrants an attitude neither of incautious optimism nor of apocalyptic gloom.

AUTHORITY OF BELIEF

All of the many human societies that have been examined appear to be governed by beliefs, transmitted from generation to generation as a culture, describing how the world operates. In each society men and women believe that which renders consistent and compatible the events they daily observe. They believe that which makes sense and upon which they can rely. If I believe thus and so, it is because my whole world of experience is thereby explained to my satisfaction. I know, moreover, what I may expect to follow from certain actions of men or from certain phenomena of nature, and I have a way of protecting those I care for from injury and of seeking benefit for them instead. Beliefs about the world of nature and man, therefore, influence actions and bear a stamp of authority insofar as they attest to the confidence with which past and present generations have learned and applied them.

Modern science shares this sense of authority with cultural beliefs in general. The authority of science is generated by a fundamental belief in a regularity and order underlying natural phenomena,

Arnold W. Ravin is professor of biology and microbiology, University of Chicago. This paper is a revised version of the author's Sigma Xi bicentennial lecture presented before a number of college audiences in 1975–76.

[*Zygon,* vol. 11, no. 2 (June 1976).]

which scientists attempt to express in the form of "laws of nature." Without such a belief, indeed, scientific research would hardly be possible, for there could be no reliance on past observations for present or future expectations. Because from time to time scientists find they have to revise their formulations of the pattern or order in nature as new observations are made, they claim to have expressed the "laws of nature" only imperfectly in the past and seek a better fit to the perceived order in their current formulation. The ultimate concept all scientists share, however, is that of an eternal (and, they hope, a simple) set of relationships that governs all of nature. These natural laws are supposed to govern independently of man and independently of whether we recognize them or not. This belief sustains scientists when, as we know, certain conceptions of the natural order are invalidated and a search is undertaken for a new conception to replace the rejected one. With firm confidence in the ultimate regularity and order in nature, scientists have always been able in the past to replace discarded theories with newer ones which took better account of the existing empirical information. Thus the Ptolemaic system of celestial bodies came to be replaced by the Copernican and a static conception of living species by an evolutionary model. Science begins, then, with belief in a natural order, which gains authority to the extent that it remains compatible with new experiences.[1]

Insofar, then, as both science and culture in general are contingent upon ultimate a priori beliefs, they are similar. The content of science is greater than its ultimate belief, however, and that part which goes beyond the fundamental assumption of order is relatively open to critical examination and change. In this respect science has evolved from other modes of acquiring belief. Where myth and tradition provide beliefs that readily tend to become dogmatic, science may be tested and challenged anew at any time. In this respect, it is true, science differs only in degree from mythic tradition. For scientific beliefs do not fall or change every day. Thomas S. Kuhn refers to this conservativism as "normal science," in which scientists seek to reinforce the insight into nature they have obtained rather than to overthrow it.[2] Scientists do in fact spend much of their time reinforcing their conception of nature or demonstrating its truth, if you will, by revealing "how it works," how it answers questions and solves puzzles, how it points the way to new findings, how it makes possible the control of phenomena we wish to control.

Conservative as scientists may be in their respect for scientific knowledge, their enterprise is nevertheless a risky one. However much confidence a scientist may have in his theoretical conception of nature, as based on previous experience, he has no alternative but to expose that conception continually to new risks. A good scientific theory must be framed in such a way as to be subject to conceivable tests. There cannot be one instance of its failure to explain, no one prediction that fails of confirmation. Every potential reinforcement of a theory or concept is, in fact, an opportunity for its overthrow. As Karl R. Popper rightly emphasizes, no single verification of a hypothesis is sufficient to assert its eternal truth, but one failure of confirmation, as when the contrary of a predicted outcome actually issues from an experiment, is enough—at least in the ideal case—to discard the hypothesis.[3] In this sense science is open ended.

SOCIALLY MOTIVATED SCIENTIFIC RESEARCH AND UNEXPECTED DISCOVERIES

But there is another sense in which science is open ended. Embedded as it is in human culture, science is not separated from the practical everyday concerns of humanity. Rather, it is a human enterprise regulated by the expression of social needs and values. It has, in fact, an interesting feedback relationship with society: The needs of mankind at any given time serve to guide to a significant extent the pursuit of scientific research, and the consequences of that research impinge upon society and its further evolution. I would like to illustrate this relationship by means of examples from a field of inquiry with which I am familiar, for they will give me the opportunity to explore later the legitimacy of current views of science as an agent of social change.

For my illustration I turn back to the early decades of the present century when two areas of research were proceeding largely independently of each other. The one area of research was genetics; the other, medical microbiology. Let us consider genetics first. The phenomenon of heredity—the tendency of living beings to produce progeny similar to themselves—had intrigued men since the centuries before Christ. The phenomenon was not without its practical interest, however. A long-debated question, for example, concerned the constancy of species. To what extent do new species arise in the course of time, and to what extent does occasional breeding between members of different species create the hybrids from which entirely novel species emanate? These questions were relevant to the concerns of plant and animal breeders who sought to develop new sources of food for human consumption.[4] The questions were undoubtedly responsible for motivating experiments to breed—or "cross," as we now say—organisms with differing characteristics and to examine the qualities of whatever progeny issued from the cross. Despite the accumulation of some hundreds of years of empirical observations, the field of genetics did not mature into a separate discipline and did not receive its distinctive name until the first decade of the twentieth century. This maturation of genetics was due to the realization by the Augustine monk, Gregor Mendel, in 1865 and by other biologists around 1900 that the results of crosses could be explained by postulating the existence of entities—called genes—transmitted from parents to their young. In the first decade of the century little more was known about the nature of these genes than that their postulated existence in pairs within the living body and their segregation during the production of sex cells accounted for the statistical distribution of contrasting parental characters among the progeny of a cross. In the second decade, primarily due to the work of Thomas Hunt Morgan and his group of collaborators at Columbia University, strong evidence was given for the occurrence of genes in linear arrays in the threadlike chromosomes that were seen to occur in structurally similar pairs inside the nuclei of the body's cells. Given a physical residence, the genes were now being increasingly regarded as material entities instead of abstract symbols. But what was the chemical nature of the genes? This became a central question of the rapidly developing field of genetics; yet the answer did not come from a direct frontal assault upon it. The answer came from an entirely unexpected direction, that of a new field of medical microbiology, which had arisen to identify and control the microorganisms discovered not long before to be the causative agents of infectious diseases.

At the turn of the century, pneumonia was one of the foremost killers of human beings. In the United States, for example, it ran a very close second to tuberculosis as the leading cause of fatalities among human diseases.[5] There are a number of forms of pneumonia, but the most common and serious as a cause of death in the early 1900s was that due to infection of the lungs by a spherically shaped bacterium called the pneumococcus. By the 1920s several significant facts about pneumococci were known. Virulent pneumococci—those that invoked fatal disease when injected into susceptible animals—secreted around themselves a coat or capsule of slimy polysaccharide. It was learned, moreover, that there are different types of virulent pneumococci based upon the specific chemical nature of the polysaccharide they secrete. These types were of practical importance, for it turned out that animals immune to one type of pneumonia were not immune to another because their antibodies recognized specifically only the type of capsule they had previously encountered. In the preantibiotic 1920s the control of pneumonia was dependent upon knowledge of the types of encapsulated pneumococci that were being encountered, and that number proved to be very large. Each type of capsule was not only chemically distinct, but the capacity of a pneumococcus to synthesize a given type was a hereditary character which was nearly always transmitted to its descendants when it multiplied by growth and division. Occasionally, however, the ability to produce a capsule was lost by the descendants of originally encapsulated bacteria, especially when the latter were grown in laboratory culture media. It was then discovered that such unencapsulated pneumococci usually fail to cause illness when injected into laboratory animals and are unlike capsule-producing forms in this respect.

At this time Fred Griffith, a medical officer in the British Ministry of Health, was interested in the relation of polysaccharides to the invasiveness of pathogenic bacteria. Reports had been made of enhanced virulence of pneumococci when injected into mice simultaneously with polysaccharide substances. These reports led Griffith to suppose that a similar effect might be observed if live, avirulent (that is, unencapsulated) pneumococci were injected in conjunction with a heavy suspension of dead encapsulated pneumococci.[6] Indeed, that is the result he obtained when he performed the now classic experiment which he described in 1928. When he injected unencapsulated pneumococci (or R pneumococci, as they were called), they caused no disease in mice. Neither did encapsulated (or S) pneumococci if they were first killed by heat. However, if living R bacteria were injected together with heat-killed S bacteria, the result was often a virulent infection that caused pneumonia and death of the injected mice. Moreover, Griffith could find many living S pneumococci in the lungs of dead or dying mice that had been treated in this manner. Now what was at once surprising and significant about Griffith's findings was that the type of capsule synthesized by the pneumococci isolated from the diseased mice was the specific one that had been made by the S cells prior to being killed. It was not the type of capsule that had been made by the S cells from which the R cells had originally descended. Griffith's conclusion was, in brief, that the capacity to produce a capsule, which had been lost by R bacteria, could be reacquired in the presence of cells which had possessed that capacity prior to being killed. Griffith spoke of the phenomenon as being a transformation of R cells into S cells by a capsular "pabulum" furnished by the dead S cells in the mixed inoculum; hence the specificity of the type transformation.

So surprising were Griffith's findings that, in fact, few microbiologists trusted them—least of all Oswald Avery, a physician and microbiologist at the Rockefeller Institute for Medical Research in New York City where he had been instrumental in demonstrating the polysaccharide nature of the type-specific capsule of pneumococci. In

Avery's own laboratory, however, was a young Canadian by the name of Martin Dawson, who had confidence in Griffith's work. Largely on his own, Dawson not only confirmed Griffith's phenomenon but showed it could be produced by mixing R cells and heated S cells in a sterile test tube containing a medium satisfactory for the growth of pneumococci. Living S cells of the same type as that of the killed cells soon appeared in the tube. Avery was now impressed. Another of his young collaborators, Lionel Alloway, subsequently found that one could replace intact heat-killed S cells by a crude, cell-free extract derived from these cells and still induce a type-specific transformation in vitro. From this moment on and for over a decade (1932–44) Avery addressed himself to the question of the nature of the constituent of S cells that was responsible for transforming R cells. This constituent, he realized, was capable of bringing about a directed hereditary change. This constituent, moreover, was reproduced in the transformed cells since the latter contained more of the same substance as brought about the original transformation. It was a material endowed with genetic information—in short, it was like genes. With the help of collaborators, Avery carefully tested every possible constituent in the crude transforming extract derived from S cells and found that it was DNA and no other constituent that was the material responsible for transformation, the material endowed with genetic properties. This result was, to a large extent, a surprise inasmuch as Griffith had suggested the transforming substance was the specific capsular polysaccharide itself and since the only other class of substances known to possess chemical individuality was the proteins, of which specific enzymes and antibodies were composed.[7] The work of Avery's group was the first and still most important piece of evidence we possess that the genes transmitted from parents to offspring are made of DNA. We have good reasons (reasons too time-consuming to detail here) to believe that this conclusion is true not only of bacteria but also of all kinds of plants and animals.

I have taken this long route of tracing the discovery of DNA as genetic material in order to illustrate the unexpected in science. Who would have suspected in 1920 that the chemical nature of genes would be discovered by medical microbiologists interested in the virulence of pneumococci? No one, surely. Yet this is not an isolated instance of the unplanned road to scientific discovery. An equally good example is that of the discovery of antibiotics by Alexander Fleming in 1929. The "accidental" alighting of a spore of the mold *Penicillium* upon a background of bacteria growing in a petri dish resulted in a zone free of bacteria that was visible as a halo around the growing mold colony. This observation in turn led to the guess that the mold was secreting some substance inhibitory to bacterial growth, which supposition generated in turn the search for the chemical inhibitor or antibiotic, and the discovery of penicillin. And after penicillin, in a logically similar manner, streptomycin, neomycin, erythromycin, and all the other antibiotics we know today.

The discovery of antibiotics played a useful part not only in the combating of infectious bacteria but also in the development of a new field emerging from the convergence of genetics and microbiology. Ability to synthesize capsular polysaccharide was not the only bacterial character subject to heritable variation. In populations of bacteria in which the vast majority were killed by an antibiotic such as streptomycin some rare variants resistant to the antibiotic could be found. These variants were called mutants because they had undergone a random genetic mutation that caused all of their descendants arising by division to remain streptomycin resistant. Indeed, the S → R change that spontaneously arises at low frequency in certain pneumococcal populations has come to be regarded as the result of random mutation. Since antibiotic resistance was a heritable character like capsule synthesis, it seemed obvious to try to transform streptomycin-sensitive bacteria by providing them with DNA extracted from streptomycin-resistant mutants. In fact, this worked, and soon it was realized that practically any heritable character was subject to mutation and could be transformed in any direction using DNA from bacteria having the desired genotype (gene constitution). If the bacteria undergoing transformation differed in more than a single genetic property from those donating the transforming DNA, bacteria transformed for only a single character were the usual outcome, although multiply transformed bacteria were also found to a lesser extent. Thus DNA contained a heterogeneous assortment of genes, and many of these genes transformed independently of one another. Yet, by studying the frequency of cotransformation by various groups of genes, it could be shown that certain groups were linked to one another and that the entire assembly of genes constituted a continuous, linear structure. Indeed, DNA carefully isolated from bacteria so as to avoid fragmentation of its delicate, lengthy structure proved to be a linear fiber without ends, a closed loop in short.

This discovery of the closed, linear structure of bacterial DNA did not come about exclusively through the study of the transforming action of DNA on bacteria. Shortly after Avery's discovery of DNA as transforming substance, other ways in which genes could be transferred between bacteria were discovered. Joshua Lederberg and Edward Tatum found, for example, that bacteria normally inhabiting our intestines, and called *Escherichia coli,* can undergo a process of conjugation. During conjugation, bridges are formed between bacterial couples, and genes are passed from one member of each couple, the donor, into the other member, the recipient. Analysis of the manner of the transfer of genes during conjugation revealed to the French biologists Francois Jacob and Elie Wollman that the DNA of the intestinal bacterium was a closed loop that opened at a specific point prior to entry into the recipient.

The ability of a bacterium to serve as a donor in conjugation has proved to be due to an agent acting very much but not quite like a virus. While a virus has the capacity to kill its host, the agent responsible for making a bacterium a conjugating donor is not lethal. Nevertheless, it is infectious and will invade and multiply in recipient bacteria which were initially devoid of these agents. This infectious agent is now known to be composed of DNA and may either remain separate or be inserted into the linear continuity of the host DNA. In whichever form it exists within the bacterium, however, it confers a special property upon its host: The host becomes a "male" capable of synthesizing certain fibrillar structures on its surface. These fibrillar structures are not present in "female" bacteria devoid of the infectious "sex" agent and are somehow responsible for the coupling of "male" to "female" bacteria. Other nonviral genetic agents which, like the "sex" agent, can multiply separately from the host cell's DNA have been found in bacteria, and this class of nonviral agents has been called plasmids.

Plasmids have been in the news recently because of a technique that has been developed to open circular DNA and splice DNA from another source onto a free end of this opened linear structure. Given this technology, it has been possible, for example, to splice a specific piece of the DNA of a toad onto the DNA of a bacterial plasmid and then cause bacteria that would have hosted the normal plasmid to be infected instead with this widely hybrid DNA produced by "genetic engineering."[8] The outcome of this experiment is that the piece of toad DNA multiplies inside the infected bacteria, indicating that the mechanism for replication of genetic material is essentially similar in all living organisms.

The wedding of genetics and microbiology has obviously expanded our basic knowledge of heredity. That wedding led to the fundamental discovery that genes are made of DNA, paving the way for the determination of the chemical structure of DNA, which James Watson and Francis Crick achieved. The determination of that structure in turn has had an enormous impact upon our understanding of how genes replicate, mutate, and direct the biochemical activities of the cells of which they are a part. Because the story of modern molecular genetics has rapidly become an integral part of the teaching of biology in high schools and colleges, many persons are now familiar with the explanation that the sequence of the four kinds of building blocks in the long DNA polymer represents an encoded message which, upon being decoded, results in synthesis of specific kinds of proteins that play specific roles in the economy of the cell. Thus the genes ultimately determine the metabolic pattern of a given cell. What may not be so commonly known, however, is the conclusion drawn from numerous experiments that the genetic code is universal. That is to say, the instructions for decoding—the instructions that give meaning to the specific sequences of the building blocks in DNA—are the same in all kinds of living things from viruses and bacteria to algae, ferns, and oaks as well as flies, mice, and men. The universality of the genetic code, taken together with the universal mode of genetic replication, is fundamental evidence for the essential unity of living things on this planet and their probable derivation from a common ancestor.

We have seen that basic advances in molecular genetics were initially helped by research concerned with the practical mitigation of human disease. How these advances in our basic knowledge have come to redound to the benefit of society is perhaps not as well known as it should be. Let me give some examples of the benefits. Consider how research on bacterial mutations to antibiotic resistance has aided therapeutic strategy in medicine. We know that resistance to very low levels of certain antibiotics may be conferred by each of several independently arising mutations. When these individual mutations are compounded within the same bacterium as the result of successive mutations or of gene transfer, very high levels of resistance are acquired. Thus it is a good piece of strategy when combating an infection by bacteria susceptible to these antibiotics to use a very high concentration of antibiotic—as high as the human patient can tolerate. The chance that the infection contains a mutant bacterium containing a compound of mutations, each arising independently at a low frequency, is very small indeed. Penicillin is used effectively according to this strategy. Similarly, resistance to one antibiotic usually arises by mutation independently of resistance to another antibiotic. Thus, if an infection is caused by a bacterium susceptible to two or more antibiotics or drugs, it is sometimes useful to employ a number of them, for the chance that the infection contains a mutant bacterium resistant to all of the antibiotics is exceedingly small, considerably smaller than the chance of its containing a mutant bacterium that is resistant to only one antibiotic. Tuberculosis has been considerably diminished as a cause of fatal illness through the strategic use of multiple antibiotics.

Nevertheless, the history of antibiotic therapy is not one of unalloyed joy. Mutant bacteria resistant to specific antibiotics actually arise in nature as well as in the laboratory. It should be no surprise, therefore, that antibiotic-resistant bacteria are being increasingly encountered in human infections. With the extensive use of antibiotics, resistant mutants are being inadvertently but quite naturally selected. Such mutants now represent an important hazard in many of our hospitals and clinics. The need to reintroduce aseptic techniques in the care of infected patients has been emphasized by local epidemics of resistant bacteria. Such epidemics would not in themselves be very serious if we possessed a large repertoire of antibiotics and if a given species of bacterium resistant to one antibiotic were still sensitive to a number of other antibiotics. Thus mutants selected for resistance to one antibiotic could still be effectively eliminated by treatment with another. Our problems have grown more difficult, however, with the appearance and spread of pathogenic bacteria that used to be sensitive to a wide spectrum of antibiotics but are now resistant to a large number of them. Multiple resistance to antibiotics has turned out to be due to a new form of bacterial plasmid. Somehow, possibly through removal of resistance-causing genes from the DNA of a succession of hosts, certain plasmids have acquired in their own DNA the genetic information for resistance to a large number of antibiotics. Any bacteria acting as hosts to such plasmids become, ipso facto, multiply resistant. What makes matters worse is that these plasmids are often promiscuously infectious, being passed efficiently between many very different species of bacteria. Thus the evolution of multiply resistant plasmids is very rapid. We are still learning to cope with this situation.

Perhaps I have dealt with enough concrete examples to be able to return to my original themes. What we have seen is the significance of social concerns upon discoveries of a fundamental nature and, conversely, the impact of these discoveries upon society. We have seen, too, that, although the research leading to basic discoveries may be motivated by social concerns, the discoveries themselves are often unanticipated. Such unexpected discoveries have effects that are not part of any original social design, effects that may in fact create new problems and motivate further inquiry.

We have come to realize, therefore, that movement in science is not inexorably straight and forward along a single track. Like evolution, science is an expanding radiation of pathways, some of which may come to interact with others in ways that could not possibly be foreseen in advance. This unpredictability exists because each of many steps along these pathways has only a less-than-100 percent likelihood of occurring or, in brief, because there is an indeterminate or stochastic element in evolution. What, for example, if Griffith had never become a bacteriologist or had never conceived of the (now defunct) idea that R bacteria might become virulent in the presence of capsular polysaccharides? The answer is probably not that DNA would never have been discovered to be the material stuff of genes. If we accept the reasonable view that there exists external to our senses a reality the ordered structure and regular processes of which are knowable through our cumulative experience, the genic nature of DNA would possibly have become known even without Griffith's experiments.[9] But the precise way in which it became known, the actual paths by which the discovery was made, would be quite different. The time, the place, the social and intellectual context in which the discovery was made, as well as the impact it had on other events, would be far different. Supporting this conjecture are the occasional examples of a fundamental scientific conception (such as the statistical laws of hereditary transmission) being discovered at separate times and places with quite different consequences issuing from the separate discoveries.

Thus the uniqueness of each scientific discovery is owing to the unfixed and stochastic paths of science. The same element of indeterminacy means, of course, that we have no means of foretelling the end of science any more than we can foretell the end of evolution. Indeed, we can have no certainty that there is an end—that what there is to be known can fill a box of finite dimensions and that we are busily engaged in gradually filling that box, however slowly. The fundamental laws upon which all natural phenomena depend may be simple and immutable and yet may generate a continuously evolving world containing novel and unpredicted entities and processes. Man is not omniscient. However broad, deep, and complex his understanding of nature becomes, he never seems to reach the point of knowing everything since he may at any time learn something new that he never suspected and that may actually threaten the validity of ideas he has come to accept.

To concede the open-ended, incomplete nature of science is in no way to denigrate its accomplishments. The structure of knowledge that scientists have created is truly beautiful and stirring and as remarkable an achievement of human potentiality as the greatest artistic creations of human history. In this respect, too, science is similar to biological evolution of which it is an integral part. Evolutionary theory explains how beautifully adapted microbes, plants, and animals—in their subtle and extraordinarily complex interactions with one another and their physical environment—are the result of random, indeterminate genetic changes occurring in a world of limited resources. A remarkable structure of diverse living forms seemingly designed for the kinds of lives they pursue—a living world of marvelous, even if imperfect, order—indeed can be the consequence of stochastic processes in a system of finite resources.

INTERDEPENDENCE OF SCIENCE AND ETHICS

The incompleteness of science and the limitations of human knowledge in general are apt to make men humble and cautious, and this cannot be entirely bad. On the other hand, acceptance of human limitations does challenge the idea of progress, which has held sway over the minds of men since the late Renaissance. At that time radical ideas concerning the possibility of improving the human condition were strongly reinforced by the development of science and technology which gave men extraordinary powers to manipulate their environment. In time these very powers gave rise to the arrogant view of the human species as the acme toward which all of evolution is striving: Since man has, among living creatures, unique powers of acquiring knowledge, he is in a position to dominate nature rather than to be a mere part of it. Moreover, if man can dominate nature, he can dominate himself. In short, he could arrange nature and guide his own evolution so that there would be perfect harmony among men and between man and nature. Presumably, this was the end of evolution. Indeed, a naturalistic ethics arose in the belief that, as men study nature and learn its laws, we would know how men ought to be in order to correspond best with those laws. There is, however, a fallacy in reasoning from "is" to "ought," which was pointed out first by Hume and later by G. E. Moore. When applied to human affairs, it too often consists in accepting prevalent human institutions and behavior as how they ought to be.

So deep rooted was the hope that science could be an agent of progress that still a new form of science-based ethics appeared after the Darwinian revolution. This new ethics was based on the idea, promoted by Herbert Spencer and argued with more sophistication in recent times by Julian Huxley and C. H. Waddington, that the study of evolution illuminates trends that may serve to guide men in their own evolution. Waddington in particular tried to escape the judgment of philosophers that the new evolutionary ethics are as fallacious as the older naturalistic ethics.[10] Waddington claimed with much persuasion that the ethicizing of man—that is, human judgment based upon concepts of "good"—is the consequence of the mechanism of sociogenetic or cultural transmission, which originated uniquely in human evolution. This mechanism is actuated early in the life of human individuals as they perceive the "authority" of parental figures, who for their part are transmitting information as to acceptable limits of behavior, that is to say, traditional values. The same authority-perceiving mechanism is the one by which all subsequent knowledge is acquired either through the formal education of students by teachers or through direct individual inquiry of the authority or order of nature. With the acquisition of new knowledge culture evolves, for there are new ways of viewing the world and of man's place in it.

The insight that a sense of external authority—the sense of something beyond ourselves—underlies both science and ethics may prove to be very fruitful, for it suggests a link between the cognitive and the evaluative. This connection, however, may not set one prior to the other so that science informs ethics unidirectionally or conversely. Thus, while there is much to recommend the notion that ethicization is a product of human evolution, and that ethics evolve as human societies do, it does not follow that knowledge of what has happened in evolution can serve as a criterion for choosing between ethical systems, as Waddington believed.[11] He supposed that ethicization has a function—that of promoting further human evolution. In the sense that ethical values help us to select among possible courses of action, it is obvious that human evolution is guided by ethics. But to decide that the ethics is better which promotes the evolution of a better man or which more efficiently steers evolution on its proper path is to suppose that we already know, from what has happened in evolution, what makes man better or what is the proper direction of evolution.[12] The notion of the perfectibility of man has crept in by the back door and with it the unwarranted assumption of the absolute certainty of human knowledge.

As an example of the difficulty we could get into by relying upon the past course of evolution as a key to guiding human evolution, consider the emergence of increasing levels of integration that is generally accepted as a basic feature of evolution: Molecules and molecular aggregates were at some early time in evolutionary history assembled into integrated organizations which today we call cells; at a later time cells became parts of multicellular assemblies, and, as the constituent cells became more tightly integrated, the assembly usurped the organismal features of the cell itself. Still later in evolution multicellular organisms became spatially noncontiguous parts of a larger whole, the society. In some insect societies, indeed, individual autonomy has been sacrificed to such an extent that the reproducing organism appears to be the social group itself. If, then, emergence of organisms of increasing level of organization is a fundamental feature of evolution, should we conclude therefore that human societies ought to evolve, in accordance with this inevitable principle, in the direction of greater integration, meaning lesser autonomy for individual men for the sake of society as whole? If so, what becomes of individual freedom upon which artistic creativity and scientific creativity have depended in the past? How much individual freedom can we afford to abandon and yet retain the kind of humanity we cannot imagine living without? Can we even conceive of the suppression of individual consciences and their replacement by a social conscience, presumably a logical next step in the evolution of the fully emergent human society? Even were such a replacement conceivable, should our private wishes be subservient to this perceived evolutionary imperative?

Nor is it any more valid to claim that the ultimate ethical criterion, derived from evolution, is survival of the species. If this criterion is to be applied to humans, we must ask what kind of species we want to survive. When confronted by the choice of submission to a perceived immoral command or death, the moral individual will choose death. Thus did martyrs like Dietrich Bonhoeffer choose when forced by the Nazis to act against their moral precepts. As I have suggested elsewhere, the meaning of humanity may very well be the tolerance of life within moral bounds.[13]

Anthropologists reinforce this view of man's moral nature. They inform us that all of the diverse human societies are governed not only by beliefs as to how the world operates but also by beliefs as to how man ought to behave in such a world. Even so, moral beliefs are not the same in all human cultures. The culture of a given human group comes to differ from that of others according to the group's geography, climate, and unique history. Yet it is remarkable, as Clyde Kluckhohn has pointed out, that certain moral concepts, being part of every human culture that has been studied, appear to be essentially universal.[14] For example, every culture has a concept of murder, that is, a specification of conditions under which homicide is unjustifiable. Every culture has a taboo upon incest and usually other regulations upon sexual behavior. Similarly, all cultures hold untruth to be abhorrent, at least under most conditions. Finally, all have a notion of reciprocal obligation between parents and their children. These universal or near-universal ethics cannot be regarded as absolutes that will never change in time, but they do indicate some profound and fundamental needs in all men to behave within certain limits or ethical boundaries.

Expressed in such prescientific cultures as those of the Navajo, the Eskimo, and the Fiji Islander, these ethical needs have obviously preceded the origin of Western science. Science, therefore, operates within a moral culture. The virtue of truth telling, which J. Bronowski liked to remind us was a supreme characteristic of the scientific endeavor,[15] happens to be one of those ethical universals I have already referred to. Its universality is readily understood, for cultural transmission is hardly conceivable in the absence of confidence in human communication, any more than science could work without confidence in the honesty of its practitioners. The view I am expressing of the interdependence of morality and science is entirely consistent with the observation that moral standards may change in the light of new scientific knowledge. For example, when scientific technology makes it possible to keep biologically alive human beings who have irreversibly lost consciousness or capacity for voluntary action, human societies may and do alter their definition of the circumstances in which it is justifiable to deprive beings of biological life.

In observing that moral views change under the impact of scientific change we do not admit thereby that science is autonomous and produces its own morality. Just as a scientist never begins his work with a cognitive tabula rasa, he does not embark with an ethical tabula rasa. There have already been some moral "givens" at the time and place he starts his investigations. Griffith and Avery were undoubtedly moved to work on the pneumococcus out of consideration of the value of preventing human suffering. Certain experimental research has also been avoided on similar grounds. For example, we possess today the knowledge by which one could take the DNA of viruses that probably cause cancer in humans and splice that DNA onto the DNA of plasmids that normally infect the intestinal bacterium *E. coli.* Although the linking of DNA of human cancer viruses to plasmid DNA could possibly be useful in making large amounts of viral DNA available to researchers and might be even useful in telling us something about how such viruses act in causing malignant growth, scientists recently banded together to place a self-imposed moratorium upon such experimental investigations.[16] The fear that laboratory cultures of *E. coli* might colonize the intestines of human beings, thereby launching the propagation of plasmid-borne cancer viruses, prompted scientists to speak out and seek agreement against such hazardous research without communally acceptable safeguards. An ethical judgment was obviously being made in this case: The most rapid route for the extension of human knowledge is not acceptable when it is at a likely cost of cruel mental anguish and physical pain inflicted upon human lives.

We human beings are neither omnipotent nor unwitting foils of powerful forces over which we have no control whatsoever. We do live in a world of limits, both physical and human. In such a world unmitigated optimism is reckless. Our problem today is in learning to live with limits, limitations in the physical resources of the planet we live upon, limitations in our knowledge and our capacity to control events. Our human limitations do result indeed in the generation of new problems even as we solve old ones. Are we therefore to be bereft of hope? The answer depends upon the magnitude of our ambitions. If we seek nothing less than a guarantee of creating a lasting and perfect world, the world of our dreams, we are doomed to defeat. Our joy must be found rather in those individual acts by which we exercise our unique human capabilities to eradicate what we abhor and to promote that which we value and cherish; our hope must reside in the expectation that, even as we act to change our world, its evolution will afford novel opportunities for human joy in the generations to come. If we scale our ambitions to a human level, we can find a satisfactory meaning to human life and a justification for the human enterprise. In this enterprise we can abandon neither the use of reason nor the application of values.

NOTES

1. Indeed, Gunther S. Stent argues that this Platonistic doctrine of a unifying monistic pattern accessible to reason is the equivalent of the concept of God for science ("Molecular Biology and Metaphysics," *Nature* 248 [1974]: 779–81). It is questionable, however, whether the idea of a rational order conveys the image of a personal, concerned Being that God possesses in the Judaeo-Christian tradition.
2. Thomas S. Kuhn, *The Structure of Scientific Revolutions* (Chicago: University of Chicago Press, 1962).
3. Karl R. Popper, *Conjectures and Refutations: The Growth of Scientific Knowledge* (New York: Harper & Row, 1963), chap. 1.
4. See, e.g., H. F. Roberts, *Plant Hybridization before Mendel* (Princeton, N.J.: Princeton University Press, 1929), and R. C. Olby, *Origins of Mendelism* (New York: Schocken Books, 1966).
5. U.S. Bureau of the Census, *Statistical Abstract of the United States* (Washington, D.C.: Government Printing Office, 1951), p. 69, table 74.
6. I am indebted to Stuart D. Elliott, who was a colleague of the late Griffith, for the explanation of what led Griffith to do his famous experiments on pneumococcal virulence. I am further obliged to René Dubos, who is writing a biography of Oswald Avery, for the information about the reception of Griffith's work in Avery's laboratory.
7. The surprise undoubtedly caused Avery to proceed most carefully if he was to convince his scientific colleagues, and it forced him to put off his well-planned retirement, as described in a letter dated May 17, 1943, to his brother Roy, quoted by L. C. Dunn, "Genetics in Historical Perspective," in *Genetic Organization,* ed. E. W. Caspari and Arnold W. Ravin (New York: Academic Press, 1969).
8. An informative and generally accessible account of these experiments is contained in S. N. Cohen, "The Manipulation of Genes," *Scientific American* (July 1975), pp. 24–33.
9. Thus the molecular geneticist S. Spiegelman remarks: "Science involves discovering a truth that already exists. If you don't find it someone else will. It is not the job of scientists to create a universe. It is simply their job to describe it" (as quoted by J. S.

Farer, "I Would Rather Have Been Born a Bach than a Spiegelman," *Columbia Today* [September 1975], p. 9). This view, of course, derives from the ultimate belief in the existence of a rational order in nature knowable to but independent of man. See above.

10. C. H. Waddington, *The Ethical Animal* (London: Allen & Unwin, 1960).

11. For a full philosophical critique see Antony Flew, *Evolutionary Ethics* (London: Macmillan Co., 1967).

12. It is difficult to resist quoting B. A. W. Russell in this regard: "If evolutionary ethics were sound, we ought to be entirely indifferent as to what the course of evolution may be, since whatever it is is thereby proved to be the best" (*Philosophical Essays,* rev. ed. [London: Allen & Unwin, 1966], p. 24).

13. Arnold W. Ravin, "An Evolutionist's Ethics" (review of Lewis Thomas's *The Lives of a Cell* and of *New Theology No. 10* edited by Martin E. Marty and Dean G. Peerman), *Zygon* 10 (1975): 431–38.

14. Clyde Kluckhohn, "Ethical Relativity: Sic et Non," *Journal of Philosophy* 52 (1955): 663–77.

15. J. Bronowski, *Science and Human Values* (London: Hutchinson, 1961).

16. See Cohen.