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Science: Our Common Heritage

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A heritage is a present structure originating in the past and transmitted to the future. Ideally, we might be able to identify every subpattern of present structure with a date of origin. In practice, of course, the epistemological problem is severe and we can usually only identify these dates very approximately. Still, a geologist can usually identify the date of a piece of sandstone; a paleontologist, of a fossil; an archeologist, of a ruin; a historian, of a document; a literary critic, of a manuscript; and so on. I am sure that the genetic pattern of my own body was formed sometime in the spring of 1909, though the exact date and time will always remain a mystery.

The heritage is transmitted from its date of origin by two principal methods: one, the survival of equilibrium states, like a crystal or a book; the other, the replication of structures, each example of which is impermanent. The heritage of life involves the replication of DNA and genetic structures. The heritage of human knowledge, including science, involves the replication of information and knowledge structures by such techniques as printing, xeroxing, and recording on phonographs or cassette tapes, and also through the transmission of knowledge structures from the minds of one generation to the next by a learning process. This is what I have called "noogenetic" evolution (*1*), to distinguish it from the biogenetic evolution where the heritage is transmitted through DNA and the genes. Science is primarily a product of noogenetic evolution, although, of course, it is structured in biogenetically produced human brains.

Learning began long before science. The human brain (*2*) has an enormous "autopoietic" potential for mutation of images, or self-structure. The images which it creates need not have any correspondence to structures in the real world. The principal business of the human mind, indeed, is fantasy. Nevertheless, part of the structure of images is their labeling with our belief in their degree of reality. Some images we believe do correspond to the "real world"; others we believe do not. Our information input through the senses, plus internal information generated in the brain in the form of logic, operates as a powerful selective process that tests the labels on our images. Those which in the face of this input turn out to be less stable are eventually detected as error. Those which are stable are identified as true.

From our images we form expectations. When an expectation is fulfilled, it reinforces the image; when it is not fulfilled, and we cannot deny its nonfulfillment or deny the validity of the derivation of the expectation, we are forced to change the image. If I have an image that my bank is open and I go down to cash a check and find it is closed, I revise my image. I learn that it is a holiday or that the bank has failed. Through disappointment, the real world exercises a persistent selective pressure on our images of it, which produces a long-run bias for truth. Illusions can last a very long time, especially when they are of the sort that cannot be tested, but there is always a probability that illusions that can be tested will eventually be found out and relabeled as error. Knowledge increases not by the matching of images with the real world (which Hume pointed out is impossible), that is, not by the direct perception of truth but by a relentless bias toward the perception of error. This is as true of folk knowledge as it is of science.

Furthermore, the same process goes on in human valuations. The knowledge structure in the human brain consists not only of images of "fact," but also of a complex structure of preferences and valuations at least at three levels: preferences, or first-order valuations; ethics, which is an evaluation of preferences, especially those of other people; and ethical critique, which is an evaluation of ethics. These valuations are subject to exactly the same process of selection by which we detect error in fact. There are "bad" valuations which are less stable than others, just as there are "erroneous" images of fact which are less stable than others. The fact that valuations are a property of the human mind in no sense deprives them of objectivity or deprives them of the privilege of being erroneous, for the human mind is also part of the real world and feeds back into itself.

Science is a fuzzy set within the field of human knowledge. Its boundaries are somewhat arbitrary; indeed, I shall argue that it is a much fuzzier set than many scientists think. Nevertheless, there is a core scientific community the world over, and while citizens of this invisible republic are largely self-appointed, for not even the Ph.D. is a certificate of membership, it has moderately clear boundaries, and science is what it thinks and does. Some components of this heritage go back a long way, to Chaldean astronomy, Greek and Indian mathematics, and Chinese technology, for example, and we have even been able to reconstruct extinct science species, such as the astronomy of the builders of Stonehenge or of the Anasazi. What

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might be called the "great acceleration," however, is usually dated from Copernicus. Certainly between Copernicus and Galileo we get a creation of evolutionary potential for science, which sets off an almost continuous expansion in the number of scientists and scientific publications, and also in the complexity and, I think we can say, the truth of scientific ideas and images, the like of which the human race had never seen before and indeed may never see again. The expansion that follows any creation of evolutionary potential always follows something like an ogive curve; nothing can grow forever, except perhaps the whole universe. There is considerable debate today as to where we are in this process, particularly whether we have turned the inevitable corner toward slowdown (*3*).

The explosion of science as a subculture within the human race was the result of a cultural mutation which created large evolutionary potential. Such cultural mutations take place fundamentally as a result of ethical mutations, that is, changes in the human value system which are then transmitted through the culture that they created from one generation to the next. The origins of the cultural change which produced science are puzzling. It is not unrelated to the Renaissance in Western Europe, which again is related to the rediscovery of the Greeks and the scattering of Greek scholars from Byzantium after the Turkish conquest of Constantinople. It is loosely related to the protestant Reformation and the religious movements which followed it. It is still puzzling why science advanced so rapidly in Christian Europe and not in China, which technologically was more advanced than Europe in many ways; or in Islam, which had preserved the Greek heritage that Christian Europe had lost, and seemed to be on the edge of science in 1200 before it relapsed into a stagnant fundamentalism. One can speculate that it was not wholly an accident that science arose in a Christian society. Christianity was a proletarian religion founded by a carpenter and propagated by a tentmaker and a fisherman, which through Constantine became dominant in the European establishment. This legitimated the world of work and matter in a way that the more aristocratic and "spiritual" religions of the East could not, and made the mutation into science more likely. But even then, why did it come so late? The complex mutual interaction of science and technology, even "folk technology," might give us a clue here.

Curiosity, Testing, and Veracity

We may not be able to explain why it happened, but there is little doubt that it did: that from 1500 on a small, precariously communicating subculture developed in Europe which was distinguished by a very unusual ethos. It put a high value on curiosity, which folk cultures and official political cultures frequently do not. "Curiosity killed the cat" goes the folk proverb. Questioning the legitimacy of an established religion or ruler has been precarious and dangerous in almost any society. Coupled with curiosity was a belief in testing, a belief that the real world not only existed but would itself respond to inquiry, so that the tests for error were not for failure to conform with ancient writings but the test of organized experience and expectation. Coupled with this was a high value placed on a curiously uneasy combination of logic and imagination in forming theories (image mutations) with testing as the selective factor. Without fantasy, science would have nothing to test; without testing, fantasy would be unchallenged. Testing comes both by logic and by organized input of information from outside the person, from the senses directly and from the trustworthy records of others.

Trust in the records of others is crucial to the development of science, so it is not surprising that another important ethical principle in the scientific community was the high value placed on veracity, that is, on not telling lies. This is a sporadic value in folk cultures and a rare value in political culture. In the scientific culture, it is central. One of the few things that can result in expulsion from the scientific community is to be caught out in falsifying one's results. Coupled with this principle of veracity is another, which is the abandonment of threat as a means of changing people's opinions and behavior. It is a fundamental principle of the scientific community that people's minds should be changed by evidence and not by threat. In this it differs from virtually all other communities, especially the political community and many religious communities.

Exceptions can be found to this principle. Students are forced to conform to their teacher's opinions under the threat of failure in examinations. Specific practices which are regarded as too extreme result in threats of expulsion, at least from the organized scientific community. When the scientific community becomes politicized, threat creeps into it, as we saw in the Lysenko tragedy in the Soviet Union, or the creationists' attacks on biology in the United States, and we find traces of this in all societies. Even the American Association for the Advancement of Science is not above using threat, for instance, in changing the location of its annual meeting for political reasons. This should not surprise us, for scientists are also human beings and exist in other communities besides the scientific. Nevertheless, when the use of threats in the scientific community rises above a low level, the existence of that community and the whole culture of science is itself threatened.

The evolutionary potential of this small subculture and its ethos turned out to be very large. Scientists are still a very small proportion of the human race—perhaps less than one per thousand. Nevertheless, science is universal. Probably no country in the world fails to have in it somewhere a classroom with the periodic table of the elements on the wall, and this periodic table is the same whether a society is Muslim, Catholic, Communist, or Buddhist. Nevertheless, science occupies a specialized habitat—universities, laboratories, institutes—which exist in the middle of a social ecosystem that does not conform to its values, although it supports science economically, whether this is the church, the state, the business organization, or the philanthropy. There is a constant potential tension between the scientific community, with its peculiar ethic, and the social environment in which it finds itself and which supports it. The tension rarely surfaces in open conflict, but it has surfaced at times in the past and there is no guarantee that it will not do so in the future.

Threats to the Legitimacy of Science

The heritage of science is so well established and so secure today that it seems almost absurd to discuss possible threats to it which might prevent, in some degree, its transmission to the future. The dynamic of legitimacy, however, dominates all others in social systems, as we have just seen in Iran, and it is often precarious and unpredictable. One should never assume, indeed, that any legitimacy is 100 percent secure. Even if the legitimacy of science is 99 percent secure, we still have to worry about that 1.0 percent, and that 1.0 percent might be an underestimate. Science occupies a socioecological niche, the boundaries of which are very largely determined by the image of science in the minds of nonscientists, especially those who make decisions about budgets, whether in government, education, or industry. If this image changes unfavorably, the niche will begin to close. This could happen either because of the spread of illusions about science or, what may be more dangerous, the spread of adverse realistic images. The scientific community, therefore, should be deeply concerned about the images of science that lie outside it and even those that lie within it, for the probability of adverse changes in these images is at least large enough so that ignorance about them would be unwise. It is entirely consistent with the ethic of the scientific community to try to dispel illusions about it, especially by better processes of testing. It is also within the ethic of the scientific community to detect failures of that ethic within the community itself and to correct them.

It is important, therefore, to try to detect possible illusions about science. One illusion, held even within the scientific community and by many outside it, is that there is a single "scientific method," a touchstone that can distinguish what is scientific from what is not.

Within the scientific community there is a great variety of methods, and one of the problems which science still has to face is the development of appropriate methods corresponding to different epistemological fields. Methods that work in one field do not necessarily work in another. There has to be constant critique and evaluation of the methods themselves. Perhaps one of the greatest handicaps to the growth of knowledge in the scientific community has been the uncritical transfer of methods which have been successful in one epistemological field into another where they are not really appropriate. Furthermore, many scientific methods are not peculiar to science. The alchemists had experiment, the astrologers had careful observation, the geomancers and diviners had measurement, the theologians had logic. These methods are not peculiar to science and none of them define it.

Special and General Methods of Science

Observation and experiment are "special" methods. They are not incompatible, but some sciences have more of one and some more of the other. The earliest special method of science was not experiment but careful records of observation in time and space, beginning with astronomy, going on into geography, Linnean biology, archeology, recorded history, national income statistics in economics, and so on. This is appropriate wherever there is an orderly pattern in space-time, whether in temporal sequences or in spatial structures. Experimental science is appropriate for the study of systems that have events of high probability, stable parameters, and isolable subsystems. Within these epistemological fields, it has been very powerful, as we see especially in chemistry, physics, and molecular biology. The stability of parameters is important both for observational and for experimental science, and success in prediction depends upon this stability. Celestial mechanics, for instance, was successful mainly because the evolution of the solar system had virtually ceased so that its parameters were stable. The space-time patterns of the system could be constructed from observations, and highly successful predictions were a result. The success of experimental physics and chemistry depends also on the stability of their parameters in currently unfamiliar regions of the systems involved.

Measurement and logic are "general" methods found in all sciences, in varying qualities. Measurement has been particularly important in enabling science to expand human images of the world beyond the human scale toward the very large (for instance, in cosmology) or toward the very small in the molecule of the atom, the proton, electron, and now even smaller elementary structures. Measurement is a function of technology, and it could well be, indeed, that technology has contributed more to science historically than science has to technology. There is at least a constant feedback between them. Measurement is important in testing, especially as we move beyond the human scale. The Michelson-Morley experiment on the velocity of light only established that this was constant within the range of measurement. If the range of measurement had been, say, 10 percent of the velocity, the experiment would not have been very conclusive.

It must be emphasized, however, that the numbers which result from measurement are properties of the human mind, not of the real world. There are some quantities in the real world that are independent of the human mind, such as π, e, the velocity of light, Planck's constant, and so on. There are numbers that can be obtained by counting, the written expression of which depends on the scale of notation, but which represent a given size, no matter what the scale, as do numbers that are derived from measurement of arbitrary units. There are also the famous numbers of psychological perception, seven plus or minus two (*4*). For the most part, however, the real world consists not of numbers but of shapes and sizes. It is topological rather than quantitative. Quantification for the most part is a prosthetic device of the human mind, though certainly a very useful one. Anyone who thinks that numbers constitute the real world, however, is under an illusion, and this is an illusion that is by no means uncommon. It could be argued, indeed, that quantification is simply a result of certain defects in the human nervous system that do not permit us to form complex images of topological structures. Fortunately, the principle that topological structures can be mapped into a set of numbers enables us to perceive relationships in the topological structures of the real world, even of great complexity, by mapping numbers into them. Still, however, it is the topological structures that we are really trying to perceive. A simple example of this would be the computer, which has the latitude, longitude, and altitude of a large number of points on the surface of the world and can use this information to print out maps that the human mind can readily appreciate as structures in topology. If it printed out only the numbers, it would mean very little to us, even though they represent the same informational structure as the map.

Logic is perhaps the most general methodological component of all human inquiry. A widespread illusion about science is that its basic theoretical images and paradigms are the result of inductive reasoning from observations and experiments. It would be truer to say that science is the product of organized fantasy about the real world, tested constantly by an internal logic of necessity and an external public record of expectations, both realized and disappointed. The theories are the mutations in this evolutionary ecosystem of mental species; testing by logic and by disappointed expectations is the selective process.

The selective process begins, however, with internal logic, consisting essentially of the perception of truisms or identities. Contrary to Aristotle, we perceive these as capable of taking degrees. One can then classify the images, theories, and paradigms of the scientific community according to the degree to which they are truisms. At the core of science are the logical truisms, beginning, of course, with mathematics, and all of these truisms are obvious once they have been pointed out. Anything that is not ultimately obvious cannot be mathematics.

The next stage is what I would call the "empirical truisms," perceptions of the way in which our image of the real world "has to be." Even in mathematics we have things like Playfair's axiom, which is the foundation of Euclidean geometry, that only one line can be drawn through a given point parallel to a given line. I personally do not see any other way in which the ordinary world in which I live can be. I am prepared to accept the logic of non-Euclidean geometries, and even prepared to admit that the Einsteinian world beyond my personal experience conforms to them, but I am not really sure that I really believe this deep down.

Empirical Truisms

Many of the "great laws" of science are empirical truisms. Thus, the law of conservation says that if we have a fixed quantity of anything, all we can do is push it around; more of it here must mean less of it there. The second law of thermodynamics can also be stated as a special case of a general truism. If we translate negative entropy (5) as "potential," we can state it in the form that, if anything happens, it is because there is a potential for it happening, and after it has happened that potential has been used up. There may even be a generalized third law, that the closer we are to anything, the harder it is to get any further. This looks a bit like Zeno's paradox, and one can visualize exceptions to it. The law of inverse squares on which so much of physics is based is a truism, resting on the logical mathematical proposition that the surface of a sphere is proportional to the square of its radius, so that any effect as it spreads out from a point is spread out over a sphere. Ohm's law, that current is proportional to potential difference divided by resistance, is hard to deny if we define resistance properly. The Fisher equation in economics, that the volume of transactions times the price level at which they are made is equal to the money stock times its velocity of circulation, again falls back on a truism that the value of what is bought is equal to what is paid for it. The law of diminishing returns is demonstrated by the empirical truism that we cannot grow all the world's food in a flowerpot. The laws of scale and allometry (that we cannot make an exact scale model of anything, and change in scale requires well defined change in structure) depends on the truism that doubling the linear dimensions quadruples the areas and octuples the volumes of any structure.

A little closer to empiricism comes what might be called the "aesthetic truism," a pattern that simplifies expectations, images of the world that may not be logically necessary but which are aesthetically pleasing. The role of such images in science is probably larger than most scientists would like to admit. The Copernican image of the solar system is aesthetically more satisfying than that of Ptolemy, with its innumerable epicycles. The periodic table of elements is an aesthetic delight, which we could have deduced as a truism from electron ring stabilities if we had known about them earlier. Mendelian genetics is more aesthetically satisfying than Darwinian. As we move into modern physics, the poetry of paradox manages to dominate the scene, with particles that are pieces of waves, and that move when we ask them where they are. Even the language that produces quarks and charm is verging dangerously near to poetry. Ironically, science seems to be turning into an activity for finding out the way things almost have to be.

At the bottom of the list, there is the "empirical regularity," or constant connection. As Hume observed, this is not at all the same thing as necessary connection. Statistics has become a large-scale device for discovering regularities with a probability that they are not produced by chance, but this usually throws very little light on what does produce them. Empirical regularities sometimes lead to the discovery of theoretical necessities, as happened in celestial mechanics, but science can never be satisfied with empirical regularities unless it can discover the theoretical necessities behind them. The idea that science consists merely in the discovery of empirical regularities is a total misunderstanding of its methods and its power. Without logical necessity, empirical regularity is little better than superstition.

Secure and Insecure Science

Another image of science, widely held within as well as outside the scientific community, but which I regard as an illusion, is the common taxonomy which differentiates the hard from the soft sciences, and the sciences from the humanities, in a descending order of truth or validity. A far more important distinction is between the "more secure" and the "less secure" sections of the whole sphere of human knowledge. All the traditional disciplines have secure images which are not going to change much, and less secure ones which are subject to change. Classical physics, the chemical elements, the structure of compounds, classical price theory in economics, classical genetics, and so on, are not going to change much. By contrast, all the historical sciences and disciplines are extremely insecure, simply because of the inadequacy of the historical record, which in the first place is a very small sample of the total field, and then is strongly biased in unknown directions by durability. All we know of the past is the record of it, and new discoveries of durable records may constantly upset our whole image of the past, whether in cosmology, paleontology, geology, or human history.

A field of knowledge is likely to be insecure if the available data only cover a small part of the total field and if the actual structures and relationships in it are extremely complex. Thus, our knowledge of individual human behavior is insecure because of the extreme complexity of the field of the human brain and body, and the great difficulties we have in sampling it. Cosmology, likewise, is likely to be very insecure, simply because it studies a very large universe with a very small and biased sample. We have only been looking at it carefully for a very small fraction of its total time span and we know intimately an even smaller fraction of its total span in space. Any field of knowledge which deals with rare events is also likely to be insecure. Those fields which study events that are common and repeatable-at-will, as in the experimental sciences, are likely to be fairly secure. The experimental sciences, however, are only a fraction of the total potential field of human knowledge.

The concept of the security of a field of knowledge practically erases the distinction between the sciences and the humanities. Human history is almost certainly a more secure field than paleontology, simply because the record is better and closer in time, even though the field itself is more complex. The study of literature, likewise, especially as we approach the present, covers a large part of the total field and is likely to be quite secure. "Folk knowledge" of our ordinary daily life is also apt to be fairly secure. Our image of the town where we live, our relationships with the people we know, and so on, rarely change very much.

Human knowledge becomes particularly insecure when we move into unfamiliar regions of a field or system. Experimental science tends to deal with the familiar, for the laboratory, after all, is a clear descendant from the kitchen. This may sound a little insulting to the practitioners in the cathedrals of high energy physics, which move into unfamiliar regions of size (in this case the very small), but even this region of experimental science can only deal comfortably with events that are common within the field of the experiment. In extreme positions even of relatively familiar fields strange things happen, such as Prigogine's dissipative systems, far from equilibrium (*6*). The evolutionary process itself indeed is one in which rare events in unfamiliar parts of the field are of extreme importance in explaining the overall pattern in time, where the sciences of the familiar are not very much help. Improbable events in a small field cannot be studied in laboratories. This is perhaps why experimental social psychology seems to be running into a severe crisis, because in fields where extreme positions are highly significant the experimental method may be of limited value and indeed be quite inappropriate. One of the unfortunate effects, indeed, of correlational statistics has been to divert attention from extreme cases, which are simply rejected as deviations, whereas they may contain important knowledge about extreme positions of the field. The uncritical transfer of statistical techniques which are entirely appropriate in some epistemological fields, into fields in which they are quite inappropriate, has been the source of a great deal of wasted scientific effort, especially in the social sciences. Statistical significance is by no means the same thing as epistemological significance, and one of the underexplored frontiers in science is the tailoring of statistical methodology to particular epistemological fields.

It is clear that the scientific community has some internal methodological problems that deserve careful attention in the next generation. It should be possible to handle these problems, however, within the framework of the moderately familiar. There is nothing within them which cannot be profitably handled within the general method of science itself, certainly within the ethic of science. Nevertheless, implausible as it may seem at the moment, the world scientific community may find itself in danger in the next few decades because of threats to its legitimacy within the larger framework of the social system.

The Interaction of Science and Technology

Its internal dynamic makes science what it is. Its external results in technology—"know-how" rather than "know-what"—and in the impact of technologies on social systems, are what mainly lead to its support by the rest of society. The impact of science on the economy and on technology came surprisingly late. It was very small before about 1860. The so-called industrial revolution of the 18th century in England owed very little to science; it was still largely a continuation of the long improvement in folk technology in Europe which began after the fall of Rome. The steam engine, for instance, owed nothing to thermodynamics. Thermodynamics owed a great deal to the steam engine.

After 1860, however, we get an extraordinary period, in which the know-what of science is increasingly translated into the know-how of technology. This perhaps begins with aniline dyes and the chemical industry, which the alchemists could never have produced because they got the elements wrong, but which was almost inevitable once we had the periodic table and theory of valency. In the 1880's, we get the electrical industry (the first modern power station was constructed in 1888), which would have been impossible, I suspect, without Clerk Maxwell. A by-product of chemistry was improvements in steel production, which led to the steel-frame building and the skyscraper, also beginning in the 1880's. The automobile, which produced such an enormous social change, beginning in the 1890's, does not come out of any great scientific principle, though it does come out of constantly improving mechanical technology, for instance, in the exact drilling of cylinders. The niche for the automobile, however, was created by the oil industry, which originally produced gasoline as a by-product in the production of kerosene for lamps. Yet without chemistry and geology, I doubt whether the oil industry would have developed in the way that it did.

The telephone, again the 1880's, radio after 1920, and television after 1950, were, in a sense, by-products of the electrical industry and of physics and some chemistry. The airplane, beginning in 1908, would have been impossible without aerodynamics, though in the beginning there were still certain elements of folk technology about it. The enormous increase in agricultural productivity on which a great deal of our development depends would have been impossible without scientific genetics, resulting, for instance, in hybrid corn and other crops and improved livestock breeding, and depended also on large inputs of energy from fossil fuels, especially oil. The difference between the technological sophistication of the oil industry and the "folk technology" quality of the coal industry is a striking example of the impact of science. Utilization of nuclear energy is even more striking. No amount of folk technology would ever have produced it. It would have been impossible without Einstein, Bohr, and Rutherford and the advance of nuclear physics and chemistry.

Benefits and Costs of Science

The impact of this development on the human race has been very large. The population explosion began in 18th-century Europe, produced by what might almost be called "eoscientific" advances in agriculture, nutrition, and medicine; this became a worldwide phenomenon, especially in the tropics, after 1950, with the development of DDT and the control of malaria and the tremendous decline in infant mortality which resulted. The increase in the number of human artifacts has been spectacular since 1860, summarized very roughly in the gross national product (GNP). For 25 percent of the world population at least, GNP per capita has been doubling almost every generation since 1860. This has not happened except on a small scale for the large populations of the tropics. On balance, however, at least in terms of increasing expectation of life and per capita real income, which are certainly important components of the overall human welfare function, though not the whole thing, the benefits of the applications of science to technology seem to be substantial.

With all the benefits, however, almost inevitably there come large and perhaps increasing costs. Some of these may be illusory, though this does not prevent the illusion having a large effect on the behavior of those who hold it. Some of them, however, are unquestionably real. There is, for instance, an increasing fear, often by no means unjustified, of many of the products which science has helped the human race to produce. Chemistry and the chemical industry have produced tens of thousands of new compounds with which the biosphere has never had to deal before. There is always a chance that one of them might have catastrophic consequences. The intense fear of recombinant DNA, the fear that the biological sciences could let loose previously unknown plagues which will decimate the human race is perhaps only 99 percent irrational, and the 1.0 percent is worth worrying about. The movement against nuclear power by any long-term cost-benefit analysis is hard to justify in the light of the probably greater dangers of greatly expanded use of the available alternative, coal. It derives partly from the fear of unknown complexity, though this might only be 90 percent irrational! This fear is reinforced, by no means irrationally, by the association of nuclear power with nuclear weapons, loose though this association may be.

Undoubtedly, the greatest social cost of science has been its use in the development of weapons and the means of destruction. Weapons have always been part of human technology. The rise of science-based technology did not break this connection but resulted in a profound change in the nature of war, mainly because of the increase not so much in the destructiveness as in the range of the deadly missile. The area which can be defended with weapons depends on this range, and on the degree to which it can be reduced by defensive measures. Threat-based political institutions have to adapt themselves to these parameters. Science-based weaponry, particularly the long-range missile with the nuclear warhead, has done for the national state what gunpowder did for the medieval baron. Just as gunpowder made the medieval castle indefensible, so the nuclear missile has destroyed the unconditional viability of the national state.

The defense policies of the major powers are now officially based on nuclear deterrence, appropriately described as MAD (mutually assured destruction). There is an extraordinary illusion, even in the scientific community, that deterrence can be stable. It can indeed be stable in the short run, but there must be a positive probability of it failing; otherwise it would cease to deter. My own guess is that the international system is about as stable as the San Andreas fault, and the probability of it failing within, say, 100 years is very uncomfortably high. This means essentially that the system of unilateral national defense has broken down. Its original justification was that it preserved an area of peace internally by pushing war to the boundaries of the society. The nuclear missile has destroyed this system. Civilian populations are no longer defended by their armed forces; they are merely hostages to them. We live in a system that has a noticeable positive probability for virtually total, perhaps irrecoverable, disaster. The temporary stability which deterrence yields should surely be used for a massive effort to reduce this probability of catastrophe to zero. It could be done by a transition to a system of stable peace. War, like science, is a learned activity of the human race, and so is peace. There is no nonexistence theorem about constructing a system of stable peace. Indeed, in many parts of the world we have already done so, and what already exists is clearly possible.

It is the greatest tragedy of the scientific community that so large a proportion of its activity is devoted to the learning of war and so little to the learning of peace. It could well be that because of this the overall long-run impact of science is to bring closer the day of human extinction.

Nevertheless, science is also the greatest hope of the human race. It is highly probable that we are entering a period of increasing difficulty what with the technological arms race, increased politicization of human life, the impending exhaustion of cheap fossil fuels, growing scarcities of water and other materials, and a population explosion that is almost certain to lead to a doubling of the human population before it can be controlled. Under the conditions of social and political stress which these movements presage, scientists may have a rough time, along with other segments of the human race. The increased political repression which disorder so often brings about is itself a threat to science. We saw this in the destruction of genetics by Stalin, the crippling of science in China during the Cultural Revolution, and what looks like the total destruction of whatever scientific community there was in Cambodia. Class war is very destructive to science. There is no way in which scientists can avoid being mandarins, or at least middle class. Like feudal lords, they have to have their laboratory castles and their entourage of research assistants and students.

Nevertheless, the heritage of science is a heritage of hope. By greater understanding, not only of the physical and biological worlds but also of ourselves and the world of human society, we can push the evolutionary parameters toward human betterment and build a happier world for the human race even out of the fires of catastrophe. But, if this hope is to be realized, the scientific community itself must evolve. It needs a renewed sense of its mission and its ethic. It needs to develop a pattern of appropriate epistemological methodologies, and to gain a sense of the unity of human knowledge bridging the present "two cultures" gulf between the sciences and the humanities. It needs to develop within it a discipline of "normative science" which will take the study and critique of human valuations seriously. It needs a livelier sense of itself as a worldwide movement transcending values of nationality and culture, but also concerned to preserve national and cultural variety as one of the keys to human evolution. Perhaps, in another generation, this Association might be willing to change its name to the Association for the Advancement of Human Knowledge, with a worldwide membership. A fantasy, perhaps, but fantasy is part of the appropriate methodologies of all fields of human knowledge.

By a curious coincidence, this lecture was delivered on the Twelfth day of Christmas, which the Western church celebrates as the Day of the Magi, or the Three Wise Men. These old stories have a very persistent symbolic value. We might think of the Magi as an early precursor of the American Association for the Advancement of Science. In the first year of the child, they came bearing gifts, and strangely enough these are deeply symbolic of the gifts of science. Gold symbolizes the great increase in riches that science produces, and perhaps its dependence on the monetary aspects of the grants economy. Frankincense symbolizes the joy of science, the sheer delight of discovery, the excitement of the Mars pictures, the volcanoes on Io, the double helix. Myrrh symbolizes the bitterness, the wormwood and the gall, the chemical wastes and the nuclear weapons, the agonies of doubt. Perhaps we have to have all three. But also there is hope: that we can lessen the third, increase the second, and control the first.

References and Notes

1. K. E. Boulding, *Ecodynamics: A New Theory of Societal Evolution* (Sage, Beverly Hills, Calif., 1978).
2. I do not discuss here the mind-brain problem that has bothered philosphers for so long. Our image of the brain as a physical structure of neurons is very different from our image of the mind as a structure of images of the world. I have some confidence that there are one-to-one relationship patterns between the physical structures of the brain in which are coded the images of the mind, but we understand very little about how this coding is done. I bypass this whole problem by simply assuming that the mind and the brain are a single field, even though we perceive them in such different ways.
3. N. Rescher, *Scientific Progress: A Philosophical Essay on the Economics of Research in Natural Science* (Univ. of Pittsburgh Press, Pittsburgh, 1978).
4. G. A. Miller, *Psychol. Rev.* **63**, 81 (1956).
5. Entropy is a most unfortunate concept, almost as bad a phlogiston, which turned out to be negative oxygen. Entropy is negative potential, and a law of decreasing potential, thermodynamic or otherwise, would seem to be much more attractive than a law of increasing entropy.
6. G. Nicolis and I. Prigogine, *Self-Organization in Nonequilibrium Systems: From Dissipative Structures to Order Through Fluctuations* (Wiley-Interscience, New York, 1977).