President's Lecture: The Need for Scientific Communication with the Public

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Most scientists, indeed most people, spend the great majority of their working and thinking time in a relatively small part of what I will call "information space." On some occasions, however, one can be called upon to look out upon the world with a somewhat broader outlook. The presidential address to the American Association for the Advancement of Science (AAAS) is certainly one of those circumstances. Nevertheless, even when I try, I cannot escape from the perspective reflecting the path, both personal and scientific, which I myself have traversed. This will not be an impersonal report, perhaps as could be expected from a committee carefully chosen to cover all possible points of view and all possible concerns. It will be a personal report from me. This is certainly fortunate for you because as an audience, you will clearly want whatever I have to say to come to end in a timely fashion. As the speaker, I too have my own desire, which is, in common with many others before me, that I do not want you to stop listening until I have stopped speaking.

So, here in 1993, what do I see ahead of us as scientists, as citizens or visitors to the United States, and as inhabitants of the Earth?

As you've heard, my own scientific pursuits of the past 20 years have been chiefly concentrated upon some of the physical and chemical aspects of our global environment, upon several of the specific problems of the global atmosphere, and in some instances with progress toward solutions for the observed difficulties. Perhaps inevitably, too, given the nature of these problems, these scientific interests have often crossed apparent disciplinary boundaries. For instance, the individual hydrocarbon compounds observed last fall in aircraft missions over the southern tropical Atlantic Ocean by members of my research group trace their origin to agricultural burning in Africa or South America. Our physical and analytical chemical measurements are registering the consequences of organic chemical transformations on material of biological origin, while the decision to burn has cultural connotations.

Globally, the bipolar world threatened constantly with the possibility of nuclear conflict between two superpowers is rapidly fading into the past, only to be replaced by a world with perhaps as much danger and insecurity but distributed over innumerable small but often quite deadly conflicts. Some of these struggles have arisen or are made worse by deteriorating environmental conditions which actually limit the value of the prize which both sides are attempting to seize. The political and economic problems of the citizens of Haiti are surely made worse by the rapid environmental degradation of their land over the past two decades. Unfortunately, the world can expect more and more refugees whose economic plight has elements of environmental as well as political difficulties.

National and international security in the future have certainly become more complex, and environmental security can no longer be casually assumed. This becomes especially pertinent as the truly global environmental problems such as stratospheric ozone depletion and the accumulation of greenhouse gases have become prominent enough to be regular subjects for public comment. The major atmospheric problems readily cross all national boundaries and therefore can affect everyone's security. You can no longer depend upon the 12-mile offshore limit when the problem is being carried by the winds. An instructive reminder of the international nature of such insecurity was given by the arrival only 2 weeks later in Irvine, California, of trace amounts of the radioactive fission products released by the 1986 Chernobyl nuclear reactor accident in the former Soviet Union. The amounts of fission products were extremely small and not hazardous, but the reminder was there that the atmosphere is a global commons.

Within the United States, we continue to have a very high standard of living for a sizable fraction of our population, including nearly everyone in this audience. Increasingly, however, we cannot avoid noticing the presence all around and among us of another sizable fraction of the population, who are neither sharing in this high standard of living nor have much hope of doing so in the near future. Basically, these extremes of rich and poor should be unacceptable in a democracy and cry out for solutions applicable across the United States. In the rest of the world, we also see a mixture of standards of living but with far more lows than highs. We see a rapidly growing world population, essentially all of whom aspire to a better life for themselves and especially for their children. In the past, and in the present, improvements—or even maintenance—of individual living standards have often been attained in a manner which places serious strains upon natural resources and upon the regional and ultimately the global environments. The national and global agendas thus call for the simultaneous development of the means for bettering the human condition, coupled with new concepts that diminish the accompanying environmental strain.

Obviously, this is a demanding, daunting set of challenges. Of one thing I am sure, however. And that is that success in meeting these challenges will require the application of detailed knowledge—scientific knowledge—ranging across all of the disciplines represented by the AAAS, from social organization to the technological demands of zero by-product engineering. All of us have our roles, and many—probably most—are anxious to participate in meeting these challenges. Individual efforts are already discernible in the direction of such future goals within each of our disciplines. But are there some special difficulties which may impede progress broadly? Any lessons for the future?

From my own experience, I see that the most serious problems are related to faulty communication about science among the various segments of society, including the scientific segment itself. Each of us is bombarded daily by messages from television, radio, magazines, newspapers, and so on. We live in the midst of massive information flow, but those items connected with science itself are often badly garbled, sometimes with potentially serious negative consequences. The remedy must lie in greater emphasis by all of us in increasing both the base level of knowledge of science and communication about science with all levels of society. This is much easier to say than to do, because one does not sense an overwhelming general demand for more information about scientific matters. My predecessor as president of AAAS, Leon Lederman, has been and continues to be an activist in this connection, pushing for more science in newspapers, in magazines,

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on radio, on television—even in prime time. But more effort is required by all of us.

One cause of communication problems is simply the enormous growth of scientific knowledge itself and its accompanying tendency toward narrower and narrower specialties. In my own mind, I exaggerate this trend as the progression from a specialty first in chemistry, then in biogeochemistry, and then paleobiogeochemistry of the third-row elements in eastern Siberian lakes. Each of us faces daily the choice of whether to read within our field or more broadly for general knowledge and perhaps too often chooses the former. Accompanying this development is the observation that almost all scientific journals and magazines are much harder to read now than 20 years ago because of the increasingly specialized nature of the vocabularies used for reporting scientific progress. I do not know how to alter this tendency, but it works to drive away the more general audience at all levels, probably to the overall detriment of the scientific community.

A second cause of communication difficulty lies in our general lack of success in progress toward our often stated goal of a scientifically literate society. Many of you have seen or heard of the documentary film made at a Harvard graduation several years ago in which the majority of the graduates who were interviewed could not provide a knowledgeable answer to the question "Why is summer warmer than winter?" I can confirm from my own observations with a general physical science course taken mostly by nonscience majors in our Irvine honors college that this question stumps a majority of California college students as well. Roughly speaking, one-third of them can give the proper answer, a larger number say it is because the Earth is closer to the sun in the summer, and another group says "I'm not supposed to know that, I'm a humanities major." While often very interested in the phenomena of science, the average person just is not very well informed about basic scientific matters. In the long run, we certainly want to raise the educational base for science. In the short run, we need to work with the reality that successful communication will have to start at a lower level than we would like.

My own strong belief is that understanding of modern technology and science is of extremely critical importance as we approach the 21st century, even more so than in the past half-century. Most of the world now operates on an assumed basis of interlocked technologies. We expect water, electricity, transportation of people, food, and fuel, and rapid communication. Failure of any of these causes significant immediate societal dislocation. We now face and will continue to encounter difficult situations both nationally and internationally, for which the possible successful solutions will often require sophisticated scientific advances within our own community, together with satisfactory understanding and appreciation both by our governmental representatives and by the public at large.

Each of us has had some experience in trying to communicate to laypersons the essence of some new scientific results or at least the conclusions and some grasp of the validity of the knowledge base underlying them. During the past 20 years, such communication has been essentially a daily experience for me with people having a very wide spread of scientific and educational backgrounds and beliefs. Many of these contacts are simply with those who telephone directly with their questions, comments, and concerns, and often these questions range far afield from the original subject which caused them to single me out. Parenthetically, just last week a person called up and said that he wanted to get audio tapes of UFOs and wondered if I knew from whom to get these. I was tempted to suggest Jim Anderson or Susan Solomon and then to add that they really have these tapes but are very reluctant to give them out—that you will have to ask aggressively for the tapes before they will admit to having them. Cumulatively, these communication experiences lead me to the observation that a substantial amount of communication about scientific matters passes around the nonspecialist scientific community through the same distributive processes which are serving the nonscientists. Making the scientific descriptions more difficult in our own publications may just result in the nonspecialist learning about these advances through another, less scientific route.

Clearly many people want to know and understand, but sorting out the scientific details initially and then keeping up with them are both hard work, and not everyone is willing to do it. My personal experience is that the mainstream media—the major newspapers, magazines, the press services, and the national radio and TV networks—are interested, probing, knowledgeable, usually fair, and usually essentially correct. Of course the media make errors, some of them glaring; so do scientists, even without the pressures of imminent deadlines. However, outside the mainstream exist other magazines and books which often have special points of view, ideologies, and axes to grind, and frequently their proponents are unwilling or unable to give the attention to detail necessary for full and accurate understanding. The more the scientific conclusions overlap everyday life, the more likely are these additional information avenues to become important in the broad transmission of science. These messages get transmitted to the lay public and the scientific community as well and illustrate our urgent need for better scientific communication within society.

I shall give you two examples from my own experience which make me realize just how tenuous scientific understanding can be even within the scientific community and why this situation needs to concern us all. Both will be taken from our experiences in trying to understand the depletion of stratospheric ozone by chlorofluorocarbons. One can be quickly stated, but the other will need to be discussed in some detail in order to see the progression from hypothesis to major error. In this instance, as is often the case, the fine points are an intrinsic part of the scientific understanding. If I did not provide them, then you in the audience could rightfully conclude that others had made certain statements with which I disagreed, and you would be left without the underlying science which guides my particular conclusions. These details are needed for your conclusions as well, if the decisions are to be scientifically and factually rather than personality-based. One of my somewhat disconcerting observations from the past two decades is how frequently conclusions labeled as scientific rely on inaccurate or erroneous interpretation or manipulation of the original sources.

So, first a simple case. Most scientists know that gravity acts in proportion to the molecular weight of molecules, with the result that those which are heavier than air tend to sink toward the floor when released in a quiescent laboratory. This well-known circumstance often leads the newcomer to atmospheric problems—many of my fellow chemists, for example—toward the conclusion that a heavier molecule, such as the chlorofluorocarbon trichlorofluoromethane—also known as CFC-11, with molecular weight 137.5, almost five times as heavy as air—would have great difficulty reaching the upper atmosphere. In the more radical but sometimes asserted hypothesis, such heavy molecules could never penetrate into the stratosphere.

The atmosphere, however, is not a quiescent laboratory, and its mixing processes are dominated to altitudes far above the stratosphere by the motions of large air masses which mix heavy and light gaseous molecules at equal rates. Throughout most of the atmosphere, all gaseous molecules go together in very large groups, independent of molecular weight. The first experiment which began to provide information along this line was carried out in 1804 by two French scientists, Gay-Lussac and Biot. That the atmosphere mixed in this fashion was already well established 25 years ago prior to any measurements of CFC-11 or any other halocarbon in the stratosphere (*1*). When CFC-11 was first detected in

1970 in air samples collected at the Earth's surface, it was therefore logical to assume that such molecules would soon begin to penetrate into the stratosphere as well.

By 1975, stratospheric air samples had been obtained with both balloon and aircraft platforms and had been shown regularly to have CFC-11 present in them. During the past 17 years, CFC-11 and more than a dozen other halocarbons have been measured in literally thousands of stratospheric air samples by dozens of research groups all over the world.

Naïvely, one might assume that the transport of CFC-11 to the stratosphere would now be a fact accepted by all scientists. Not so. A scattering of letters and articles by persons identifying themselves as scientists continues to be printed in scientific news magazines or other major media which say that (i) molecules such as CFC-11 cannot reach the stratosphere because they are much heavier than air and (ii) no measurements have been made that show the CFCs to be present in the stratosphere (*2–4*). Scientific progress is usually described as occurring through the formulation and testing of hypotheses, discarding those that fail to meet the test of observation. What is not so often remarked upon is the reluctance which many have to accept the results of observation or even to bother determining whether any pertinent observations have been made.

This first example is a rather straightforward case of ignorance and misinformation. Some other standard questions have always existed—for instance, "Why don't we just ship ozone-rich Los Angeles air into the stratosphere?" Actually, there is far more ozone in the stratosphere already, and Los Angeles air would dilute the stratospheric ozone concentration rather than enhance it. Let me now give you a second example which those of us concerned with stratospheric ozone depletion encounter essentially every time we speak on the subject. During the last 2 or 3 years, a new generic question appears regularly which runs more or less as follows: "Don't volcanoes cause the Antarctic ozone hole?"

A simple answer of course is that the very large losses of ozone over Antarctica during October—now exceeding 60% each Southern Hemisphere spring—first became noticeable around 1980 in measurements conducted continually since 1956 and became public knowledge in 1985 (*5*). Because volcanoes have been around for geologic time, with no unusually violent activity during the past decade, they can't be the direct cause of these Antarctic ozone losses.

This answer, however, is usually not satisfactory by itself because some of the doubters are not prepared to accept that there has been any springtime loss of ozone over Antarctica and put their dissent as an assertion that volcanoes are the primary source of stratospheric chlorine, totally overshadowing any possible effect from man-made compounds. Asserting this to be so, they then conclude that there cannot be an Antarctic ozone hole and therefore the whole ozone depletion story is a hoax.

In discussing this scientific situation in some detail, I am ultimately raising a cause for great concern over the role of science in a democracy in which the general population has not enough understanding of science itself; does not entirely trust "science experts" and does not want to; and is left with no way to distinguish between the competing claims of apparent experts on both sides of any question. Another interjection: One of my colleagues at the University of California, Irvine, the late chemist Don Bunker, was called in more than a decade ago by the Securities and Exchange Commission (SEC) to investigate what was clearly a perpetual motion machine, a magic "catalyst" claimed to be capable of decomposing water into hydrogen and oxygen without using any energy, allowing the hydrogen then to be burned as a power source. The SEC became concerned because the inventor had sold partial rights to an entrepreneur and he in turn had sold the rights to this new power source to a major home-building company. Rumors were rampant, the stock was rising very rapidly, and the SEC suspended trading and started calling in scientists to find out about the validity of these claims of a new energy source. Shortly after the investigation began, the whole balloon burst and one more perpetual motion machine was unmasked as nonoperative. As my colleague said afterward, "It is not necessary that a perpetual motion machine actually work for its proponents to bring in large sums of money."

The volcanic chlorine question is part of a background which has been confronted over the past 20 years in atmospheric chemistry and which asks the extent to which "natural" processes have contributed chlorine-containing chemical species to the stratosphere. Here, the word "natural" is usually contrasted with the word "anthropogenic." "Natural" is thus loosely defined as not being influenced by the activities of mankind, although obviously human beings and their activities are very much part of the natural world. Sunspots, volcanoes, most oceanic biology, primeval forests—these are among the processes which are clearly designated as natural.

The general consensus of the active atmospheric scientists on a worldwide basis, after 20 years of study, is that the major chlorine sources to the stratosphere in 1993 are almost entirely compounds that contain both carbon and chlorine and are released at the Earth's surface (*6, 7*). Furthermore, the great majority of these are man-made chlorocarbon compounds such as carbon tetrachloride and the chlorofluorocarbons, or CFCs, together representing now about five times as much chlorine as carried by the only significant natural source, methyl chloride. The possible inorganic sources such as hydrogen chloride or sodium chloride from the evaporation of ocean spray dissolve in cloud droplets and are removed by rainfall, with negligible quantities reaching the stratosphere.

Twenty years ago, before the question of depletion of stratospheric ozone by CFCs had been considered and before stratospheric measurements had been made of any chlorinated molecule, a reasonable scientific hypothesis could be made that a major natural source of stratospheric chlorine might well exist—for example, that substantial amounts of hydrogen chloride could be transported into the stratosphere by the largest volcanic explosions. One estimate from 13 years ago began with two basic observations made upon the solid particles isolated from the ashfall from the 1976 Alaskan volcanic eruption of Mount Augustine, Alaska: More chlorine, approximately 0.5% by weight, was found in glassy inclusions within the ash than was trapped in the ash itself (0.25% by weight) (*8*). The hypotheses were put forth that (i) the glassy particles were representative of the pre-eruption volcanic magma; (ii) the ash had less chlorine than the glass because the difference had been released as a hydrogen chloride gas; and (iii) this hydrogen chloride had been injected directly into the stratosphere. When this fractional weight of chlorine lost from the volcanic magma (0.5% minus 0.25%) was then multiplied by the estimated amount of material released in the entire eruption, the conclusion was drawn that 82,000 to 175,000 tons of chlorine had been directly released into the stratosphere. This release was then evaluated as the equivalent of 17 to 36% of the industrial production of chlorine in the form of CFCs in 1975.

This overall hypothesis was then further extended by calculating how much hydrogen chloride could have been released in the enormous volcanic eruption 700,000 years ago, which left the Long Valley caldera in California, if its composition had been similar to that of the Alaskan volcano. This calculated, long-ago emission of hydrogen chloride directly into the stratosphere came to 289 million tons and was stated to be 570 times the 1975 release of chlorine as CFCs. Not surprisingly, very little experimental information is available about this volcanic eruption 700,000 years ago, with none at all about its chlorine content.

Some plausibility existed for this hypothesis, and the report was published in 1980 in the AAAS journal *Science* (*8*). I should also note in fairness to its late author that the Antarctic ozone hole had not yet been discovered, so the cause-and-effect mismatch which now exists for volcanoes and observed ozone depletion was not yet a dominant consideration. Nevertheless, one should note three potential weaknesses in this hypothesis at the time of its publication. For one, the glassy particles that were different from the ash after the eruption could also have been different before the eruption and might not have been characteristic of the pre-eruption magma. In this case, the differences in chlorine content between glass and post-eruption ash might not signify any release of hydrogen chloride at all but simply a difference in original composition. However, if this potential major flaw is set aside, two other facts remain: first, volcanic eruptions also emit enormous quantities of water in the form of steam, which later condense in the rising volcanic plume as water droplets into which hydrogen chloride might dissolve, subsequently to rain out; and second, actual data on chlorine concentrations were obtained only from the solid fragments of glass and volcanic ash. Chlorine measurements were not made in the water rained out from the volcanic plume and, most critically, not in the stratosphere itself. In reality, then, no actual evidence was presented in this *Science* paper to show that any hydrogen chloride had really reached the stratosphere in this volcanic plume—it was just a hypothesis based on ashfall data.

If, as seems likely to me, some hydrogen chloride was released from the volcanic magma, then another, at least as plausible, hypothesis is that this hydrogen chloride subsequently dissolved in the volcanic water and rained out, with little or none left to reach the stratosphere. Because atmospheric hydrogen chloride from other ground sources has been observed to appear in rainwater, at least some loss to this pathway is extremely plausible. But, no measurements were made of the chloride ion concentration in the rain from the Alaskan volcano.

Obviously, confirmation of the hypothesis of volcanic delivery of hydrogen chloride into the stratosphere, or a decisive choice between these two hypotheses, is not possible without further experimental information not available from that Alaskan eruption. As you all well know, the progress of science depends on the formulation and testing of hypotheses, discarding those which are not consistent with the accumulating mass of observations.

In this case, the appropriate stratospheric experimentation has been carried out over the past 15 years through observations of the global accumulations of stratospheric hydrogen chloride with infrared spectrometers operated from aircraft, from the ground, and from space. These observations showed only a small increase, less than 10% (*9, 10*), in total stratospheric hydrogen chloride accompanying the major eruption of the Mexican volcano El Chichón in April 1982 and have shown even less increase from the other recent large volcanic eruption, that of Pinatubo in the Philippines in June 1991 (*11*). Furthermore, the measured amount of stratospheric hydrogen chloride has increased regularly over this time period (*9–11*). If stratospheric hydrogen chloride is increasing with chlorofluorocarbons as the major source, an obvious corollary question is whether hydrogen fluoride is also on the increase. A severalfold increase in stratospheric hydrogen fluoride since 1977 has been observed by infrared techniques, and the amounts of both hydrogen chloride and hydrogen fluoride are consistent with expectations from the stratospheric decomposition of chlorocarbon and chlorofluorocarbon compounds—in other words, the stratospheric evidence does not support any other significant input to the stratosphere of either chlorine or fluorine (*10, 12*). The working atmospheric science community has therefore rejected volcanoes as an important source of chlorine (and fluorine) for the stratosphere, at least for the past few decades and specifically for the past 15 years during which significant ozone depletion has been observed.

Again, you might think this would largely settle the matter, but not so (*13*). This is far from the end of the volcanic chlorine story, as indicated by the fact that we atmospheric scientists continue to receive "volcano" questions whenever we speak on the subject. The trail of escalating statements behind many of these current questions is both informative and instructive. First, the hypotheses from the report in *Science*—that is, the calculated releases of the 1976 Alaskan volcano and the extrapolation to the far larger Long Valley eruption of 700,000 years ago—were then quoted not as hypothesis but as fact in a skeptical article on the ozone question (*14*). They were later repeated by the same author in a book (*15*) which then goes on to claim that the campaign to eliminate the chlorofluorocarbons is part of a capitalist plot, led chiefly by the Du Pont Company.

The next stage came when the Alaskan and California volcanic details from the 1989 article were quoted in a 1990 book discussing environmental problems but with the major error that the extrapolated estimate for the enormously large 700,000-year-old eruption was now attributed to 1976 in Alaska, with absolutely no room for doubt: "the eruption of Mt. St. Augustine in 1976 injected 289 billion kilograms of hydrochloric acid directly into the stratosphere. That amount is 570 times the total world production of chlorine and fluorocarbon compounds in the year 1975. . . . So much is known" (*16*). Incidentally, those same authors have identified as one of the major contributing factors to scientific misinformation the unwillingness of respected scientists to speak out on such subjects through their professional organizations (*17*). I am pleased to attempt the correction of a major source of such misinformation, although it will be difficult for my message to catch up with their misstatements of the atmospheric facts. Their erroneous conclusion about the stratospheric importance of volcanic chlorine is now being widely quoted in other magazine articles and books, including one of the current national best sellers, although these authors more often assign the blame for the CFC ban not to the capitalists, but to environmental ecoterrorists with anticapitalist motivations. So, a plausible, but fallible, hypothesis subsequently disproved by stratospheric observation has been elevated into major error by successive conversion of the failed hypothesis into purported fact and then into gross exaggeration of the faulty conclusion.

The central problem here is not that science should not be discussed in books for the lay public—we need much more of such discussion. It would certainly help if books written by scientists and claiming to tell how science can help were not the source of such massive errors. The problem for me is that it is now quite common to run into scientists who are relying, often unquestioningly, upon such fourth-hand descriptions of the volcano problem, rather than going back to the original literature. The world is a very complex system, the amount of information we have about it grows exceedingly rapidly, keeping up requires great effort, but I know of no easy way: you just have to do it. Meanwhile, the combination of some but not enough intelligence, plus considerable amounts of both ignorance and arrogance, can easily lead to being badly wrong in full voice and, worse yet, with a considerable following.

Let me turn now briefly to an example of another kind. The description this winter of the proposed space station as the nation's premier science project seems truly bizarre when the scientific community is almost entirely united in believing that the space station has very little scientific utility and certainly none remotely compatible with a $30-billion price tag. Once the economic aspects loom large enough, the question of whether or not any actual scientific advances might come from a science project becomes practically inconsequential in comparison to the employment and construction factors. This situation is both truly sad and ultimately dangerous because I believe that we are entering into several decades or more in which, whether we like it or not, we are going to have to seek scientific and technological remedies to pressing national and world problems, some of which have arisen from scientific and technological errors in the past and some of which are exacerbated by the rapid increase in global population. If we, as a society, are unable to discriminate between useful, intelligent opportunities for scientific and technological advancement with real problem-solving possibilities and relatively useless, big price tag projects labeled as science, then our overall national economic limitations will guarantee that some important problems with major scientific components do not get solved. I believe that we in the scientific community have even lost control of what gets described as science—the designation "scientific" often is applied as a kind of public relations cover for projects whose true origin is in economic activity unable to prosper on its own merits.

An even greater problem is associated with the difference in perception within and outside the scientific community as to whether basic research has intrinsic value. Within, especially in that part concerned with basic science, we each find individually in almost all of our own scientific fields an enormous forward impetus—remarkable progress over the past decade, so much that we now know as compared to 1983 or 1973. At the same time, for most of us the onrush of information in our own field, combined with the fixed number of hours in the day, has made it harder than ever to know what is happening even in adjacent areas of science.

We are also finding, usually with dismay, that the society which surrounds us and which has supported us quite generously in the past seems less than fully appreciative of what we see as our tremendous successes. So much so, in fact, that they are considering reducing, or have already reduced, the resources which are made available to us. For most, even a cost-of-living budget is in effect a reduction in support because the cost of science, especially in instrumentation, parallels the cost of health care in rising much more rapidly than the other factors in the cost-of-living calculation.

During the past year too, more and more general comment, especially in Washington, D.C., has been directed toward a notion which can be approximately stated as "After World War II, the scientific community told us that if the federal government and the general population supported them in fundamental research efforts, then not only would great progress be made in basic knowledge, but this increased understanding would be accompanied by, and incorporated into, major advances which would be highly useful to all levels of society." This wording, however, is mine and does not correspond to the common current statement of the "problem" of basic science. Instead, the latter part now seems to read, "that this increased understanding would lead inevitably to world economic leadership by U.S. industry." With this reading, it follows immediately that if and when the economic leadership role of the United States is placed seriously into question—as it certainly has been in the 1990s—then we must reexamine the role of basic research in the national picture because it has not led to permanent international economic leadership by the United States.

Reexamination of past dogma must always be welcome, especially by scientists; such questioning is equally needed outside the scientific arena. We always must be able to accept searching commentary and listen to what it tells us. However, any comparison of life in the United States in 1993 with that of 1948 must certainly conclude that almost unbelievable changes have taken place in the day-to-day life of the average citizen: television; microsurgery; air conditioning in the office, automobile, and home; lasers; computers; CAT scans; jet airplanes; polio vaccine; satellites, including the daily weather prediction; birth control pills; and on and on. I will not argue that all of these changes have resulted in improvements in the quality of life, but many of them clearly have. Others at least have that potential, and each of our lists of the actual improvements undoubtedly differ. Most of the citizens of the United States are pleased to have many of these as advances in their daily life. We also live in a world severely threatened by a new scourge in the form of AIDS. This plague did not arise from scientific activities, but the world would be even more threatened if the scientific knowledge of viruses and microbiology now stood where it did in 1948 or even 1973.

Our world has, in addition, hydrogen bombs, extensive cocaine addiction, and automatic weapons in the inner city, and a substantial number of people would willingly go back if they could to a society without these. The decision to support fundamental scientific investigations, indeed most extensions of knowledge, always has had certain consequences which some would term Faustian. We cannot go back to 1948 even if we wanted to, and we can go back selectively to those times only if we succeed in understanding the behavior of human beings better than we have so far. The knowledge that nuclear weapons can be built cannot be unlearned, and the 21st century will have as one of its problems the continued control of nuclear weapons, including their proliferation to an ever larger number of countries. Some U.S. scientists were members of the United Nations teams sent to Iraq after the Gulf War to investigate and evaluate the suddenly discovered Iraqi nuclear weapons program. One of them (Dr. Jay Davis of Lawrence Livermore Laboratory) responded to a question about whether such countries had the capability to create nuclear weaponry with the sobering comment that the United States of the 1940s which created the first atomic weapons was in present-day terms essentially a Third World country—no lasers, no computers, no microelectronics, and so on. Nuclear proliferation is a problem that we are going to have to live with. Once a genie is out of the bottle, there is no return.

But in the end, where do we stand?

A year ago, the London *Sunday Times* ran an eight-part series in which they listed the 1000 individuals who had most changed the world during the 20th century (*18*). In recognition of just how much the world has been altered during the past 100 years, approximately 40% of those listed by the *Sunday Times* were scientists, when all phases of medicine are included. Probably more than half of these made their contributions during the latter half of the century. There can be no question: During the time since World War II, science has certainly transformed the world. As scientists, we believe we have tried to do our best and believe that cumulatively we have done well. Certainly the performance can be improved. Almost certainly the promise of science has been oversold. And it won't do just to say to others, "If only you understood . . . ." One of our responsibilities is to try very hard to help others to understand, and I think in general we have failed badly in that task. It is not enough that other scientists in our own subspecialty understand and be excited. We need to be communicating on all levels. This association is in fact one of the few places within which the scientific community is valiantly trying to communicate across disciplines to all of the other members of the community.

In closing, I am going to return briefly to the problem of stratospheric ozone depletion by chlorofluorocarbons. Despite the misinformation problems that I described earlier, an international scientific consensus has been achieved and has been accepted by all of the major nations and most of the minor nations in the world. Since 1987, a United Nations agreement, the Montreal Protocol, has been in force which calls for worldwide controls on further emissions of the chlorofluorocarbon molecules. In its 1990 modification, the protocol called for total elimination of such releases by the year 2000, and the 1992 modifications moved the date of termination to 1996.

What is more, we know from actual measurements in the atmosphere all over the world that the nations and industries and people of the world are complying with the terms of the Montreal Protocol. The emissions of chlorofluorocarbons during the 1990s show a rapid decrease from the rates of the 1980s. Collectively, we have found out that it is possible to get international cooperation on a global scientific problem on the basis of scientific observation and consensus. The protocol, of course, does not stop the ozone damage from molecules already released, but it does place a lid on the eventual concentrations in the atmosphere of these damaging molecules.

Perhaps this global agreement can be a harbinger of the future; science and technology must play major roles in solving the problems we see all around us, and we all must continue to tell this not just to our colleagues, but to our representatives and to the general public, and we must be prepared to do it over and over again because the understanding is necessary.

And it is still the most exciting game in town.

REFERENCES AND NOTES

1. "U.S. Standard Atmosphere, 1962," National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, U.S. Air Force, Washington, DC (1962); "U.S. Standard Atmosphere, 1976," National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, U.S. Air Force, Washington, DC (1976).
2. "CFCs are heavy, complex molecules. There has yet to be published a single scientific paper which presents any documented observations of large numbers of these molecules rising to the stratosphere. It is especially difficult to see how they can rise as high as 30 km, where the greatest concentration of ozone is located. Present claims are based solely on the supposition that CFCs will rise to the stratosphere because they are not water-soluble molecules" [R. Maduro, *Exec. Intell. Rev.* **27**, 18 (1989), p. 19].
3. "Incidentally, CFC molecules are heavier than air, and their concentration in the upper atmosphere at extremely low temperatures must be infinitesimally small" (R. A. Beck, *Chem. Eng. News*, 26 June 1989, p. 62); "Since CFCs are heavier than air, how do they get into the stratosphere in quantities large enough to cause ozone depletion? . . . If CFCs are responsible for the destruction of the ozone layer, why has their presence never been detected in the stratosphere?" (R. S. Bennett, *Wall Street Journal*, 24 March 1993, p. A15).
4. "How does CFC rise when its molecules are four to eight times heavier than air? All experience with freon and related CFCs shows that they are non-volatile and so heavy that you can pour CFCs from a container and if some of them spill, they will collect at the lowest point on the ground, where soil bacteria will decompose them. Of course, some molecules will be caught in upward air eddies or otherwise carried upwards, but this is a very small fraction of the total" [D. L. Ray and L. Guzzo, *Environmental Overkill* (Regnery Gateway, Washington, DC, 1993), p. 35]; "As already pointed out, CFC molecules are (depending on which CFC is considered), four to eight times heavier than air molecules; most CFC that escapes into the atmosphere falls to the earth. There soil bacteria decompose CFCs within a few days or weeks" (*ibid.*, p. 47).
5. J. C. Farman, B. C. Gardiner, J. D. Shanklin, *Nature* **315**, 207 (1985).
6. U.S. National Academy of Sciences reports: *Halocarbons: Effects on Stratospheric Ozone* (1976), *Halocarbons: Environmental Effects of Chlorofluoromethane Release* (1976); *Stratospheric Ozone Depletion by Halocarbons: Chemistry and Transport* (1979); *Causes and Effects of Stratospheric Ozone Reduction: An Update* (1982); *Causes and Effects of Changes in Stratospheric Ozone: Update 1983* (1984).
7. World Meteorological Organization, Global Ozone Research and Monitoring Project Reports: *No. 16, Atmospheric Ozone 1985* (1986); *No. 18, Report of the International Ozone Trends Panel 1988* (1989); *No. 20, Scientific Assessment of Stratospheric Ozone 1989* (1990).
8. D. A. Johnston, *Science* **209**, 491 (1980).
9. W. G. Mankin and M. T. Coffey, *J. Geophys. Res.* **88**, 10776 (1983); *Science* **226**, 170 (1984).
10. World Meteorological Organization, Global Ozone Research and Monitoring Project Report *No. 18, Report of the International Ozone Trends Panel 1988* (1989), pp. 582–587; W. G. Mankin, M. T. Coffey, M. C. Abrams, paper presented at the International Association of Meteorology and Atmospheric Physics, 19 August 1991, Vienna, Austria.
11. W. G. Mankin, M. T. Coffey, A. Goldman, *J. Geophys. Res. Lett.* **19**, 179 (1992).
12. R. Zander *et al.*, *J. Atmos. Chem.* **15**, 171 (1992).
13. ". . . [E]vidence is firming up that volcanoes, and perhaps salt spray and bio-chemical emissions from the oceans, contribute substantially to stratospheric chlorine, and thus dilute the effects of CFCs" [S. F. Singer, *Natl. Rev.* **41**, 34 (30 June 1989); the quotation is cited on p. 37].
14. R. Maduro, in (*2*), pp. 20–22.
15. R. A. Maduro and R. Schauerhammer, *The Holes in the Ozone Scare* (21st Century Science Associates, Washington, DC, 1992).
16. D. L. Ray and L. Guzzo, *Trashing the Planet* (Regnery Gateway, Washington, DC, 1990), p. 45.
17. ______, *ibid.*, p. 13.
18. "1000 Makers of the Twentieth Century," *Sunday Times* (London), 22 September 1991.