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GROWING UP IN THE GOLDEN AGE OF SCIENCE

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I would like to begin by recalling the development of American science over the past 40 years in terms of the experience of my generation. I was lucky as a geophysicist that this was my time "to grow up in science." This period has been described as a "Golden Age of Science" because of the wealth of discoveries in fundamental science and engineering. It was not only a time of great creativity, and wonderful support, but was also a period in which the new knowledge gained led to the creation of new industries and improved our understanding of the environment. For geophysics this was the period when the seafloor was explored with modern technology, when global networks of seismographs were installed, when laboratory experiments could simulate the deep earth environment, and when trace element chemistry could be applied to rock systems. It was the period when other planets were probed and moon rocks were returned to earth. It was the era when the plate tectonic paradigm took hold.

In other fields it was also a time of tremendous progress in unraveling the molecular basis of biology and the nature of diseases. It saw the creation of the green revolution in agriculture. As wise observers have so often pointed out, many of these beneficial applications were serendipitous in that they were not envisaged by the researcher at the beginning of his or her research. (As a sign of our times I should tell you that one cynical senior staffer for a congressional committee important to scientists recently exclaimed to a visitor: "if you mention the word serendipity again I'll scream.")

Before the Golden Age

Many younger scientists may not appreciate that this flourishing of American science in general, and geophysics in particular, was not always the case. Before

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the 1940s, America could be characterized as strong in technology, dominant in industrial production, and relatively weak in science compared to Western Europe. In a sense we were like today's Japan of that period. Basic research was carried out mostly in universities, supported to a great extent by private philanthropy, and in a few government agencies and industrial laboratories. One recalls, as examples of the time, seismology at Caltech and Berkeley, rock physics at Harvard and the Geophysical Laboratory of the Carnegie Institution of Washington (CIW), Earth magnetism at the Department of Terrestrial Magnetism of CIW, and the varied work done at the laboratories of AT&T and General Electric. State universities in partnership with state geological surveys and the United States Geological Survey played important roles in geological mapping. A few oil company laboratories were laying the foundations of exploration geophysics. By and large the government's involvement in the support of basic science was minor compared to that of the private sector, although geology and geophysics may have been an exception because of the Geological Survey and the Bureau of Mines.

In those days the center of world science was Western Europe. Many of the best American students like Oppenheimer and Rabi (who taught me physics) were sent to Europe for postgraduate training.

The Golden Age

However, a remarkable transformation took place as a consequence of the contributions of science to victory in World War II. The important role of American scientists in determining the outcome of the war had its rewards after the war. These war-proven and self-confident scientists continued as influential advisers to the government in the years of rebuilding and growth following the war. Their vision of science as a force for economic growth and national security provided a new rationale for the federal government to become the principal benefactor of science. Vannevar Bush's famous 1945 report, *Science: The Endless Frontier,* became the testament of the new era. With this injunction the military science agencies like the Office of Naval Research (ONR) and the Air Force Office of Scientific Research (AFOSR) laid the foundation of support for basic science in the years after the war and before the ascendancy of the National Science Foundation (NSF) and National Institutes of Health (NIH). For geophysics this set the stage for the expansion of research in seismology and oceanography which began in the late 1940s. Many of today's senior scientists look back fondly on the research administrators of these military agencies who knew how to find the best scientists, including those in fields with little relationship to military matters, and who could provide support with few bureaucratic procedures and almost no restrictions.

With the establishment of the National Science Foundation and later the National Aeronautics and Space Agency, the Department of Energy, and other science agencies, geology, geochemistry, and geophysics had multiple new and larger sources of support. An important element of all of this was the introduction of an honest and efficient peer review system which assured the allocation of funds to the most qualified scientists. Thus, with the government functioning as a group of patrons, the period between the end of World War II and the recent decades became the Golden Age of Science, characterized by explosive growth in the numbers of scientists at work and fueled by seemingly unlimited expansion in the level of government funding. It is no wonder that most American scientists favor a decentralized system of support rather than the equivalent of all-powerful ministries of science that can be found in many countries. The American university system expanded and flourished, and the concept of the research university took hold in which graduate education and research were combined. (An unwritten story is the role of graduate students functioning as working scientists to the extent that in many of the best departments half the papers were coauthored by them.) This was also a time of growth of national laboratories, many of them operated by universities. In a transition unique to the United States, the research university with its teams of faculty, research associates, students, technicians, and postdocs, and many of the national laboratories became the loci for fundamental science. Times of extraordinary creativity and discovery ensued, spanning almost every scientific field. The United States rapidly assumed a world leadership position in science, dominating the world scientific literature, making most of the breakthrough discoveries, and winning most of the prizes. Foreign students flocked to the country seeking the best of scientific training. Many of them stayed on to become valuable contributors. With this record of achievement it cannot be said that American scientists did not deliver an abundance of dividends for the investments of public funds that were made.

My own experience as a scientist reflects this history. The work of my team led by Maurice Ewing at Columbia University and afterwards at the Lamont Geological Observatory, as it was then called, began with support from private sources such as the National Geographic Society and the Geological Society of America. With growing government involvement, private sources were superseded with funds from all of the federal agencies mentioned above. The largess of the federal government enabled us to use advanced equipment, ships, planes, and spacecraft. We could map the seafloor and sample its rocks over large areas. It was possible to deploy arrays of seismographs, and ocean bottom instruments, to explore the oceanic and continental crust and mantle using elastic waves generated by explosions and earthquakes. New instruments were designed to expand the spectrum of seismic waves that could be analyzed. We could conceive and carry out sea floor experiments involving multi-ship operations. All of this meant that we could obtain geophysical data of a quality and amount that enabled more detailed exploration of the Earth's interior than had hitherto been possible. This led to such discoveries as the absence of continental crust under the oceans, mantle surface waves, the Earth's free oscillations, and the ability to describe the structure of the crust and mantle on both a regional and global basis.

The cold war had a profound effect on geophysics as it did on most science. In geophysics the need to detect and identify nuclear explosions led to major developments in the use of computers and the applications of signal processing to arrays of detectors. The precise location of epicenters and determinations of earthquake mechanisms with these new techniques played an important role in the development of plate tectonics—namely, the precise delineation of plate boundaries and the description of the plate movements that characterize these boundaries. The Consortium for Continental Reflection Profiling (COCORP), the Incorporated Research Institute for Seismology (IRIS), and grand experiments like the Deep Sea Drilling Project evolved naturally from these beginnings.

This was a period when just about every qualified American scientist with a creative idea could receive a research grant. It enabled young scientists like me to work as independent investigators, to pursue our own ideas, to design and field new instruments, to acquire the new computers that were just becoming available. We were able to assemble and support a team of technicians, graduate students, and postdoctoral fellows, all of whom became our partners in research. We could participate in international scientific congresses and workshops and could conceive and engage in joint research with scientists from other countries. All of this served to increase our productivity as scientists. Tens of thousands of American scientists can describe their own careers in these terms. Wordsworth's line written for another occasion is an apt characterization of those days: "Blessed was it to be alive, but to be young was heaven."

This is the essence of the Golden Age of American Science. But it was also a golden age for the applications of science to human betterment.

A Golden Age of Applications

A great nation has among its obligations the support of science as a cultural endeavor: as an intellectual quest for new knowledge. However, history shows that the collateral beneficial fallout from research more than pays for the initial investment in basic science and engineering of the kind that takes place in the research universities. This can be measured in economic terms such as improved productivity or the creation of new industries, and in human terms such as better methods to diagnose and treat disease, better understanding of the environment and of natural hazards, or in helping developing countries to become self-sufficient in food. Together with many scientists, we found that our work in the basic geophysical sciences had important social and economic consequences. The team exploring the seafloor, led by Maurice Ewing, in which I participated as a young scientist, was motivated entirely by a desire to understand the workings of nature. Collaterally, we pioneered the technology of offshore oil exploration and helped create an industry. The arrays of detectors that geophysicists used to explore the continental crust and mantle became the basic technology for predicting volcanic eruptions, for trying to predict earthquakes, and for detecting violations of a nuclear test ban treaty.

Since World War II, new technologies spawned in science have accounted for more than half of the increases in per capita economic productivity in this country. Many of these technologies originated not only in the applied research and development done in industry but significantly in the more fundamental research done in universities, and in a few national and industrial laboratories.

Margaret Thatcher, in a speech to the Royal Society, characterized the value of basic science this way:

> First, although basic science can have colossal economic rewards, they are totally unpredictable. And therefore the rewards cannot be judged by immediate results. Nevertheless the value of Faraday's work today must be higher than the capitalization of all the shares on the stock exchange.... The greatest economic benefits of scientific research have always resulted from advances in fundamental knowledge rather than the search for specific applications... transistors were not discovered by the entertainment industry... but by people working on wave mechanics and solid state physics. [Nuclear energy] was not discovered by oil companies with large budgets seeking alternative forms of energy, but by scientists like Einstein and Rutherford....

And I would add: Scientists have given us modern American agriculture, the stored computer program, antibiotics, biotechnology, industries based on new materials, lasers, modern communications, and much more.

The Commerce Department's own list of emerging technologies, mostly growing out of science, is projected to account for a trillion dollars of new business worldwide by the end of the decade. And although the monetary value is incalculable, we should add the contributions of those scientists whose work did not create new industries but who provided early warning about greenhouse gases or who discovered the ozone hole. Scientists created the green revolution that helped wipe out famine in much of Asia, and they found and described retroviruses, including the one that causes AIDS.

The Counterculture

Yet a very different view has lately been gaining ground—at least among a small but influential group of social scientists who study scientists, and among staffers in Congress. It contends that scientists have very little to do with economic progress or with the many other benefits that we often ascribe to them. As one of them said recently: "All of their discoveries did little to help America solve its economic and social problems." According to this group, which I have described as a counterculture, scientists are members of a self-interested, conflicted constituency that cannot be trusted to set priorities or advise on the allocation of government funds. They say that scientists are more interested in the practice of their profession, in gaining grants, in enriching themselves, than in improving the life of the American people who support them. The disdain I have for this view and the ignorance it reveals on the history of science matches Pauli's famous remark about a theory that was obviously doomed: "It is not even wrong!"

IDNDR—An Example to Counter the Counterculture

I would like to draw an example from my own career that illustrates the dual nature of fundamental science as an intellectual endeavor, but also as an activity that can improve the human condition in unanticipated ways. I have spent almost all of my research activities in basic science. However, I believe that my most important contribution as a scientist may well be in an application—a proposal I made in 1984 to organize the International Decade for Natural Disaster Reduction (IDNDR). In addition to my work on the mechanism of earthquakes, I knew of the remarkable progress in geophysics, geology, hydrology, meteorology, earthquake and structural engineering, and related fields. It was therefore natural to propose a worldwide program of dissemination and application of this new knowledge to reduce the tragic losses of natural disasters. The timing was right and it was not difficult to marshal the enthusiastic support of thousands of scientists and engineers in launching the IDNDR.

The IDNDR, launched in 1990, is now a program of the United Nations involving some 140 participating countries. At a mid-decade conference in Yokohama, Japan in May of 1994, all of these nations were represented. Each had organized a national committee, most for the first time, to assess their nation's risk and to use modern technology based on new scientific understanding to reduce their country's vulnerability to natural disasters. A tenet of IDNDR is that the less developed countries where most disaster casualties occur would be aided by the more advanced nations.

The potential for the IDNDR to reduce the tragedy of disasters can be appreciated by citing a few statistics and a case history. During the past twenty years, earthquakes, floods, storms, volcanic eruptions, and other natural disasters have killed about three million people worldwide. More than eight hundred million people have been adversely affected. They have suffered homelessness, ill health, severe economic losses, and personal tragedies. The impact of these hazards is growing worse by the year despite our increased understanding of them. This is true for several reasons. First, the world's population is continuing to grow and many people are settling in areas of high risk, such as flood plains, coasts, seismic zones, or mountain slopes susceptible to landslides. There are 20 megacities in the world with populations exceeding 10 million people. When an event occurs now in these areas, not only are more people hurt immediately, but critical life-support systems are interrupted, leading to further health problems. Economic development is set back as scarce resources are diverted to emergency and recovery efforts.

These case histories describe the events surrounding two volcanic eruptions. In 1985 at least 22,000 people perished in mudflows in Colombia following the eruption of Nevada del Ruiz, South America's northernmost active volcano. Scientists predicted the eruption weeks in advance and notified the government, but people remained in their homes. They remained, and they perished. As the British philosopher John Locke observed, "Hell is truth seen too late."

A better story can be told about the volcano Mount Pinatubo in the Philippines. In this instance, not only were warning systems available, but also the infrastructure was in place to alert government officials and to evacuate the endangered population. Mount Pinatubo is a remarkable success story where a team of international volcanologists accurately predicted the climactic eruption, evacuation was carried out, and tens of thousands of lives were saved.

Fundamental science and the technologies they have spawned are poised to make a historic contribution to reduce the tragedies of disasters that have plagued humankind since the beginning of civilization.

After the Golden Age

Many American institutions are in a period of restructuring. Industry is reorganizing to become more efficient in production to improve quality and lower costs. Universities are adjusting to demographic changes and reduced government support. The end of the cold war and large deficits have stimulated debate on new priorities for the allocation of resources. In this environment the institutions of fundamental science are not exempt. It is generally agreed that the "golden years" which saw exponential growth in the support of science and in the numbers of practitioners cannot be sustained. Nevertheless, a nation that has built a world leadership position in science and technology should not follow policies that would diminish what may be its sole comparative advantage. I would argue that growth in science and the number of scientists at work will be needed as we enter what undoubtedly will be a technological millennium. Growth at the rate of the gross national product can easily and justifiably be maintained as a floor. Other changes may be in order. For example, it may now be time to review the nature of graduate education. The next generation of scientists may have to be trained more broadly so that they have many more career options open to them beyond their thesis area.

Recently, in response to the arguments of the counterculture, a committee appointed by the National Academy of Sciences (NAS) and the National Academy of Engineering undertook a broad reexamination of the federal rationale for investing in science and technology. In a sense they were updating the Bush report to reflect current conditions. This was the last report issued during my term as President of the NAS, and it may have been our most important one because it addressed the issue of science and technology policy appropriate for the post–Golden Age era. The report, entitled *Science and Technology and the Federal Government,* is a statement that argues, as I have, that the sole comparative advantage of the United States in the years ahead will be the scientific strength that has derived from the Golden Age. It raises the question of how many scientists does a nation like the United States really need. It sets out performance goals that for the first time provide policy makers with a yardstick to gauge how much to invest in science. This is the gist of the recommendations:

> The first goal is that the United States should be among the world leaders in all major areas of science. Achieving this goal would allow this nation quickly to apply and extend advances in science wherever they occur.

That the United States needn't be first in all fields of science is a change from the past. However, that the country should perform well in all fields of science is in recognition of the unpredictability of which fields will become important. It keeps open the option of assuming a leadership position should a field suddenly take off because of a new technique, a revolutionary paradigm, or an important application. High-temperature superconductivity is often cited as an example. The breakthrough occurred in Switzerland but those nations with competent, ongoing research programs caught up in a matter of months.

> The second goal is that the United States should maintain clear leadership in some major areas of science. The decision to select a field for leadership would be based on national objectives and other criteria external to the field of research.

This recommendation recognizes that there are key fields where preeminence can be justified. Among the criteria might be extraordinary intellectual levels of achievement, potential for important contributions to the economy, to national security, or to the welfare of people. My own list of fields that would be chosen today are astronomy, condensed matter physics and materials, biology and biotechnology, and earth and environmental sciences. However, the selection is appropriately within the province of elected officials and their staffs.

> In implementing these goals the performance of U.S. research in a major field would be assessed by independent panels of experts from within and outside the field.

This recommendation would avoid self-serving assessments by practitioners.

Science is an international, cooperative endeavor and some readers may question these recommendations as unduly chauvinistic and divisive. However, each country has to find its own route to improve the standard of living, the security and the health of its people, and to see that the cultural and intellectual life of the nation thrives. For the United States with its world role and its many problems, the path is made easier because of the great research university and national laboratory system that it has built and the world leadership position in science and technology that has evolved. For our country to look away from the lessons of the Golden Age of Science and not recognize its achievements nor build on them for the future would be a mistake of historic proportions.

American scientists should be proud of their accomplishments. They deserve accolades for their past contributions and for laying the foundations for the future success of our nation, and for that matter, for all nations. The Golden Age has come to a close with much turmoil, but I have no doubt that it will find a necessary and appropriate reentry through another opening.