The Changing Frontiers of Science and Technology

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The 20th century has often been called the American century. In the course of it, achievements in the United States have led to improvements in the lives of people all over the world. Even in remote places, longevity has increased and famines have been averted. These improvements have occurred as a result of advances in science, engineering, and technology.

For three decades after World War II, U.S. leadership in technology was unchallenged, but in recent years, global industrial competition has become a threat to future U.S. strength. The United States has become the world's greatest international debtor (*1*), and it has a large continuous merchandise trade deficit (*2*). Although it has recently improved its status in some critical technologies, the United States has lost or is losing supremacy in other important fields, and additional strong competitors are emerging in East Asia.

Changes in U.S. science and technology are impacting industry, government, and academia. Here I will discuss some of the global developments that are affecting these sectors now and that will do so in the future, and describe some of the changed circumstances at the frontiers of science. I also suggest a few actions that might be useful in coping with some of the problems that this country will face.

Evolution of Industrial R&D

The circumstances under which U.S. industrial R&D are conducted today contrast greatly with those of the two decades after World War II. The major potential competitors of the United States were recovering from the destruction of their facilities. The United States, on the other hand, was enjoying a large trade surplus and was a net exporter of many items, including steel, automobiles, and petroleum. Companies that used scientific research to develop new products had little foreign competition, and they were able to move inventions slowly from the laboratory through many steps to final production and profitable sales.

During the mid-1970s, I made 2-day intensive visits to 20 major corporate laboratories, including those at IBM, General Electric, DuPont, Dow, Bell Laboratories, and Hewlett-Packard. These corporations gave generous support to their R&D laboratories. Research and development were leading to new products, and long-term studies designed to understand nature were still fashionable. The level of scientific competence was excellent, and to achieve rapid progress toward goals, the best companies assembled interdisciplinary teams of scientists, engineers, and marketing experts. The morale of team members was excellent, and staffs faced the future with confidence.

But in part because of increasing global competition, these happy days at corporate research laboratories came to an end. Downsizing and transfer of R&D functions to business units followed, and some major laboratories even disappeared. Support of long-term research designed to explore nature and lead to innovative products for the future diminished. In 1988, such support constituted 6% of industrial R&D expenditures; by 1994, it had diminished to 1.8%.

Most of the large U.S. companies that engage in R&D are members of the Industrial Research Institute (IRI). In the 1995 annual report (*3*) Charles J. Bishop, president of IRI, stated, "The old way of doing business no longer works. And this includes research and development. . . . We must accept the challenges the world thrusts at us. We must learn to accept, to adapt, and to prosper under the new rules. The business world can be a harsh place and those who do not adapt no longer exist. Of the . . . list of Fortune 500 companies issued in 1955, less than 35% exist today. . . . " Of the 500, more than 325 have disappeared.

The structure and content of R&D in many U.S. companies have been altered in an effort to increase global competitiveness. What is the current U.S. status? An objective source of U.S. information on this matter is provided by the Council on Competitiveness. In 1994 the Council published a report titled *Critical Technologies Update 1994* (*4*). Among 94 critical technologies, the United States had a strong position in 31 and was competitive in 42. Examples of those in which the United States had a strong position were genetic engineering, computers, and computer-aided engineering. The U.S. position was also strong in many other facets involving the use of computers, including information technologies.

Diminished Leadership in Energy

Although the United States is strong or competitive in many critical technologies, its position has atrophied in a crucial field—energy. At one time, America was dominant in petroleum discovery, refining, and petrochemicals, but now it imports half of its consumption of oil or oil products. During the past 10 years major U.S. oil companies moved much of their exploratory activities elsewhere. Already more than 500,000 relatively high-paying U.S. jobs have disappeared. When exploring and drilling in other countries, the major oil companies find it both politically necessary and financially desirable to hire and train foreign nationals in the countries in which oil is produced.

At present, the United States has a substantial favorable trade balance in chemicals, many of which are derived from petroleum feedstocks. But to meet increasing global demand for liquid fuels, companies will install new refineries where labor is less costly and environmental regulations are predictable. No new refineries have been built in the United States during the past 20 years.

The federal government often creates a regulatory climate that is adverse to U.S. global competitiveness. In its report titled *Endless Frontiers, Limited Resources* (*5*), the Council on Competitiveness examined factors influencing the behavior of companies in six different areas of technology, one of which was the chemical industry. The report reminds us of how crucial the products of the chemical industry are to improving productivity and the quality of goods manufactured by many other industries. So far the chemical industry has maintained a large trade surplus, but the report states, "The chemical industry has directed significant amounts of capital expenditures and R&D funding to comply with environmental regulations. Future environmental requirements are expected to be increasingly stringent." In part as a result of uncertainty about future U.S. environmental regulations, the industry is already doing more of its R&D in other countries, and it is only a matter of time before increased production of chemicals there will follow.

A similar loss of world leadership is occurring in nuclear energy. During the past decade, no new nuclear power reactor has been contracted for by electric utilities in the United States. Nuclear power has been developed and exploited elsewhere, notably

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in France and East Asia. The South Koreans have achieved a proficiency that is particularly impressive (6).

Merchandise Trade Deficit

With respect to goods produced by some critical technologies, the United States currently has a positive trade balance. In contrast, however, the trend in the U.S. merchandise trade balance has been negative, and for the year 1995 the deficit was $175 billion (2), only partially offset by trade in services amounting to about $60 billion (1). Since 1982, the international financial status of the United States has deteriorated more than $1000 billion. Chronic major factors in the merchandise trade deficit are the costs of imports of petroleum and an imbalance of trade with Japan, which together have contributed annually about $100 billion to the trade imbalance. Big, new increasing sources of additional imbalance are other East Asian countries, which constitute the world's fastest growing economies. The two most technologically advanced of these are South Korea and Taiwan. Other countries that have been making rapid economic progress are The People's Republic of China, Hong Kong, Indonesia, Malaysia, Singapore, and Thailand.

As the economies of South Korea and Taiwan have been expanding, their product mix has been changing rapidly (7). In 1989 the leading export to the United States from Taiwan was footwear. In 1993, the value of Taiwanese exports to the United States of automatic data processing equipment exceeded that of footwear by nearly a factor of 6. A less dramatic but similar pattern existed in exports of other high-tech items, which increased while those of low-tech articles such as clothing diminished. In South Korea, footwear was the leading export to the United States during 1991. Now, high-tech items such as memory chips have become the leaders.

The People's Republic of China has the world's fastest growing economy. Its trade imbalance with the United States has also been the fastest growing of any country. In 1988, it had a net positive trade balance with the United States of $3.5 billion, but by 1995, the Chinese favorable balance was about $34 billion.

Expansion of R&D Elsewhere

The intellectual capital of East Asian countries is being enhanced by students emerging from newly established universities there. Large numbers of engineers who will be essential to the development and improvement of competitive processes and products are being trained. In 1990, six Asian countries produced more than 250,000 first-degree engineers compared with the United States, which graduated 65,000 (8). In the decade ending in 1991, the fraction of engineering Ph.D. degrees awarded in the United States to foreign students grew from 40% to about 55% out of a total of 5000 such degrees. At present, about half of foreign engineering Ph.D. recipients remain in the United States, but as attractive opportunities arise in their homelands, more of them will return home. Many were educated at top U.S. universities and have had industrial experience in such companies as Intel, Hewlett-Packard, and IBM.

Nations in all parts of the world are seeking economic growth and creation of jobs, and the belief is widespread that encouraging science and technology is the path to a better future. Accordingly, many countries are expanding their support of R&D. This comes at a time when the United States is cutting back in federal support and industry is emphasizing short-term R&D. A report recently issued by the U.S. Commerce Department describes accelerated investments in commercial technologies in Europe and East Asia (9). Japan plans to double its government's science and technology budget by the year 2000. Its per capita funding would then be twice that of the United States. Starting from a relatively low level, China is planning to triple its R&D investment by the year 2000, emphasizing computers, software, telecommunications, pharmaceuticals, and infrastructure. A net effect of the contrasting approach to R&D by the United States and other countries will be to hasten the departure of foreign students trained here.

R&D Opportunities

During the past 50 years, hundreds of thousands of scientists have had access to increasingly powerful instrumentation, and they have created an enormous fund of facts. In the physical sciences, the simple and many of the most important phenomena have been investigated. A vast body of knowledge is available to be exploited by scientists and engineers concerned with practical applications. New frontiers in the physical sciences have been identified—for example, physics of condensed matter, materials science, new catalysts, cluster chemistry, applications of lasers, and plasma physics—that potentially can lead to knowledge relevant to global competition.

In the field of medicine the United States is entering a new era in the availability of medicines designed to treat hitherto refractory diseases. The discovery process is being expedited by the use of large quantities of costly but powerful instrumentation, expert data processing and analysis, and new, fast means of synthesis and testing of large families of chemicals. This is leading to large libraries of small molecules of medically important classes of chemicals designed to inhibit crucial enzymes. Detailed information about normal and pathological processes is providing targets for intervention.

In the biological sciences great progress has been made in the study of living creatures. But the complexities of many of life's processes is such that they will not be quickly fathomed. Only about 1% of marine microorganisms have been identified, and only about 1% of soil microorganisms have been cultured. Our food supply is to a considerable extent dependent on the outcome of continuing subsurface biological warfare, and the status of the warfare, in turn, is dependent on conditions in the soil, some of which could be controlled by humans if the crucial knowledge were available. Opportunities also exist for increasing food, energy, and materials supplies by altering plant genomes. Genomes of major crops have been changed gradually over the past thousands of years, but with the application of genetic engineering techniques, the rate of change will drastically increase.

Problems at Research Universities

I have mentioned some of the pressures encountered by industry in responding to global competition and other realities. Academia has been facing a different set of changed circumstances. Federal funds for research are no longer expanding and, in fact, are predicted to decrease substantially. Many universities have undergone restructuring, which has entailed measures such as eliminating departments and firing tenured professors. An atmosphere of gloom and doom is widely prevalent. The research universities have been criticized to a greater degree than ever before, criticisms such as tuitions are excessive and insufficient attention is being paid to undergraduate teaching, and a host of others. The criticizing has been overdone, but it has often affected public attitudes and state support.

In spite of the criticisms, universities have many assets: They have loyal alumni who are giving increasingly to alma mater, and their invaluable role in educating young scientists is widely recognized. Many industrialists have stated that a stream of well-educated students is the university's uniquely valuable contribution to society.

Federal Support of Research

The departments and other segments of the federal government are subject to a highly variable will of Congress. In turn, Congress is sensitive to the public clamor of the moment, and perceptions are often more important than facts. The physical sciences and engineering have no substantial organized influential constituency, unlike the health and allied sciences. Because of its role in dealing with human health, the National Institutes of Health leads a relatively charmed life. Everyone is in favor of better health, and journalists know that a story about new results of health research is likely to receive front-page attention. The National Science Foundation is more subject to vicissitudes and micromanagement by politicians, and is less visible to the public than NIH; nevertheless, the NSF enjoys goodwill among those who are aware of its policies and activities. It has avoided bureaucratic ossification by its policy of recruiting rotating scientists to participate in evaluation of grant proposals, and it has been steadfast in seeking to promote the nation's competence in science and engineering. The NSF has also conducted meritorious experiments, one of which has been the creation of Engineering Research Centers that foster interdisciplinary work and collaborative activities with industry. Some of the centers have as many as 40 sponsoring companies. Another experiment has been to foster self-examination by states that have not been receiving substantial numbers of grants for research. This program has often stimulated constructive activities.

Further experiments of this sort are desirable. The earlier system of awarding grants to researchers in universities had unintended consequences, including high prestige to specialized research, low priority for teaching, and barriers to interdisciplinary work. If NSF were to modify even slightly the criteria on which proposals were to be judged, the effects on attitudes at universities could be very great. For instance, if the success of a professor in placing students in jobs were to be even a minor factor in the evaluation of a proposal, preparation for those jobs would receive serious attention.

This country should conduct more experiments on how best to support and conduct exploratory research leading to globally competitive products. Some of the experiments should take place in circumstances other than in a university. Not all gifted researchers are competent at teaching, and in fact, some are dreadful at it. They would serve society much better elsewhere. Many of the small biotechnology companies in which the researchers have no teaching responsibilities have been successful in creating a highly productive environment. I was a staff member for many years at the Carnegie Institution of Washington, one of five people doing world-class work in what was then the new field of molecular biology. Later, I was impressed with the creativity that was evident in Germany at the Max-Planck and the Fraunhofer laboratories. Other scientists have recently told me of world-class R&D being conducted in Taiwan and in The People's Republic of China. Perhaps we could learn something from them.

Conclusions and Recommendations

The peoples of East Asia are highly motivated to improve their standards of living. After a few years of continued economic growth, East Asian countries will be consuming large amounts of oil. They will be able to pay for it by trading high- and low-technology products that they could price competitively with ours. As a consequence, it takes no great stretch of the imagination to envision a future severe U.S. liquid fuels crisis. The U.S. Department of Energy, which has not taken prudent steps to minimize the probability of a drastic emergency, should devote a larger fraction of the budget to R&D on liquid fuels.

The problem of this country's huge merchandise trade deficit has not been effectively addressed. The balance could best be achieved by cost-competitive production of what are now low-tech items. Additional support for R&D designed to help reach this goal should have a high priority. The United States has abundant resources of land and potential human talent, but at the moment the politicians seem determined to diminish the country's ability to compete in what has become a global jungle. Educational pipelines containing gifted students cannot be turned off without leaving lasting damage. People of my generation were privileged to live in a unique golden age of science, technology, and increasing national prosperity. As the "American century" draws to a close, many changes are occurring, and history tells us to expect further changes. Some of them will be drastic and unexpected, and some will involve technology. This nation's ability to cope with externally generated problems will be dependent on its maintaining a high level of competence and competitiveness in science and technology.

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