Articles

Basic Research and Economic Health: The Coming Challenge

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The United States faces an international economic challenge that can best be met with a renewed emphasis on the basic science and engineering that underlies new technology. For 20 years, however, the nation has not invested adequately in the science and engineering base, with the result that we have too few young people entering science and engineering programs and inadequate facilities and equipment in the nation's universities. We need a fresh infusion of resources into the universities, together with a new emphasis on cooperative efforts between universities and industry. The engineering research centers recently established by the National Science Foundation are an example of how we should proceed.

"The Party views scientific and technical progress as the main lever for the solution of all economic and social issues."—MIKHAIL GORBACHEV, June 1985

"Science and technology have emerged as a universal language for humankind."—YASUHIRO NAKASONE, June 1985

"No nation depends as much as we do on the science base."—RONALD REAGAN, February 1985

THESE THREE QUOTATIONS ILLUSTRATE A CONSENSUS about the importance of science and technology in a modern society. Let me put that more specifically: In a competitive society.

We depend on what we call the science and engineering base—the collection of people, institutions, equipment, and facilities that enable us to do fundamental research in the sciences and in engineering—for economic progress. This dependence is real. And, as those three quotations illustrate, it is recognized all around the world, by leaders of all ideological persuasions. It is surprising that we in the United States are not doing a better job of cultivating the science and engineering base. We are not training enough young scientists and engineers. We are not investing sufficiently in research equipment and facilities. We are not supporting adequately the activities of our basic researchers, especially in the universities.

Inadequate support for the science and engineering base is related to our economic problems. The connection between the two is the subject of this article.

The Importance of Science and Technology to the Economy

The relation between science and technology and economic success has been highlighted many times. It may bear emphasizing again, however. The connections are the same in any modern, competitive society.

1) Since World War II, new technology has been responsible for nearly half of all productivity gains, far more than those due to capital, education, resource allocation, or economies of scale.

2) We cannot be economically competitive without high productivity. It should worry us that our average productivity increase over the 10 years before 1983 was only 0.3 percent. Our major competitors did five to nine times as well during this period.

3) Markets for nearly all manufactured products are now global. In high technology the markets are driven by product innovation. The company with the best product is the one that will succeed. Computers and all sorts of electronics are the best examples.

4) Global markets for low-technology products are driven by price. Price is a function of capital and labor costs and exchange rates—all areas in which the United States is at a disadvantage. But it is also an important function of process innovation. High technology can be applied to the manufacturing process to drive down costs.

5) Too often we have shifted production overseas to take advantage of low labor costs. But this often means slowing the application of new process technology, with negative effects in the long run. We saw this with semiconductor packaging. We moved production offshore, which reduced the rate of adoption of new processes and the reliability of parts. It also let several less-developed countries build an indigenous semiconductor industry that now competes with us in producing the entire product.

6) In both high- and low-technology products, success in the global market means creating and applying new knowledge—which is to say new technology—faster than one's competitors. This is the fundamental law in this competitive world.

7) Many countries that did not have substantial research capability in the past—especially the newly industrializing countries of the Pacific rim—are rapidly developing that capability. They understand that they must if they expect to be able to compete.

8) For whatever reasons, our record in competing has not been very good recently. Our trade balance has deteriorated significantly in the past few years. The record is worst in the older industrial areas, but even in the high-technology areas we are moving from a surplus to a break-even position.

The Health of the Science and Engineering Base

Education. The Nobel Prizes were announced recently and, once again, the United States did well. We should take pride in the fact that our system continues to produce such successes. Unfortunately, the Nobel Prizes are a better measure of the success of past policies than they are an indicator of the future. We will do poorly in science and engineering in the future if we do not train the people that we

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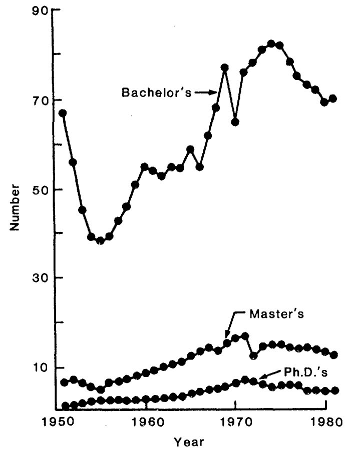


Fig. 1. Degrees in science and engineering per thousand students in the appropriate age cohort.

need. Recent data suggest that we are not doing this well enough.

■ We are attracting a smaller fraction of our best students to the sciences, and the size of the relevant age groups is declining (Fig. 1).

■ Equally disturbing is the decline in the number of engineering Ph.D.'s since the early 1970's and the increasing proportion of degrees awarded to those who are not U.S. citizens. Since 1981, more than half of all Ph.D. degrees in engineering in the United States have been awarded to foreign students. This proportion has risen in recent years. The figures for mathematics and physics—the core disciplines of a technological society—are not much different.

■ Between 1980 and 1983, full-time graduate enrollment in science and engineering rose 6 percent overall. But enrollments of U.S. citizens rose only 1 percent, while foreign student enrollment rose 23 percent. Foreign students accounted for 85 percent of the total growth in this period.

Many of these graduates stay in the United States and enrich our society. We can be proud of an open system that is able to attract so many highly qualified people. But overdependence on a resource that is not under our control is a serious danger.

Graduate enrollments have been lagging in part because industrial positions are so attractive to recent baccalaureate recipients. This is a serious problem, for without graduate enrollments the faculty shortage will increase and reduce the ability of the universities to enroll undergraduates, which will perpetuate the problem.

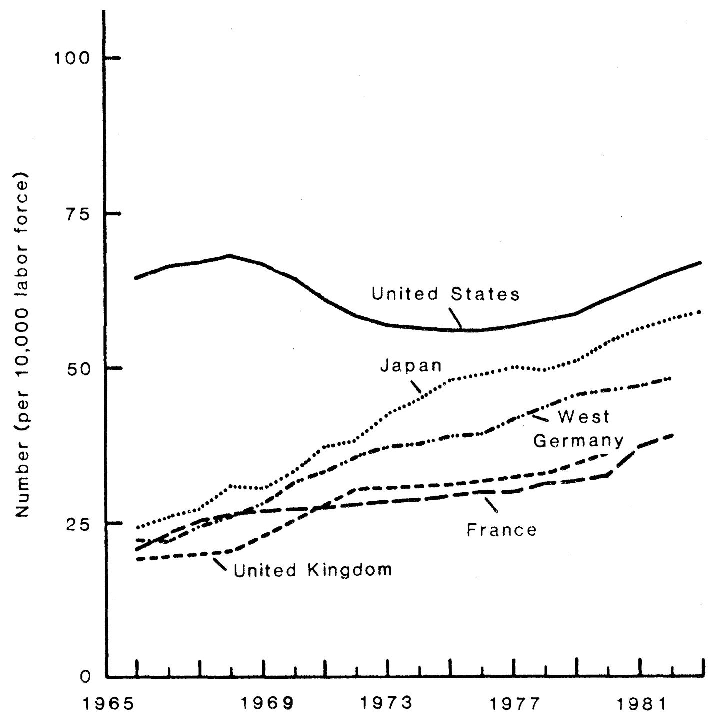
There is no way to establish conclusively the numbers of technically trained people that a modern society needs. Looking at the numbers required for specific jobs will not be sufficient, because we are always finding new ways to use people with technical skills. But the society is becoming more—not less—dependent on technology. It stands to reason that we should be training more technical people. As the world becomes more and more technologically oriented, no country will be able to keep up without an adequate number of technically trained people.

In the past 10 years the number of Ph.D.'s in industry in the United States has increased at more than twice the rate that it has in academia. Despite this increase, the proportion of our population engaged in science and engineering has declined markedly relative to our trading partners (Fig. 2). We have given up the very large lead that we had 20 years ago.

I am concerned mainly about quantity because that is easier to measure than quality. But we can and do, to some extent, make up for a lack of quantity by stressing excellence in everything we do. In a time of tight resources that is a saving grace, but it may not be enough by itself.

Research inputs. As with educational levels, there is no objective way to establish the "right" level of spending on research and development (R&D). But just as we did with educational data, we can look at trends. We can look at ourselves over time and compare ourselves with other industrial nations.

The curve describing the proportion of our gross national product



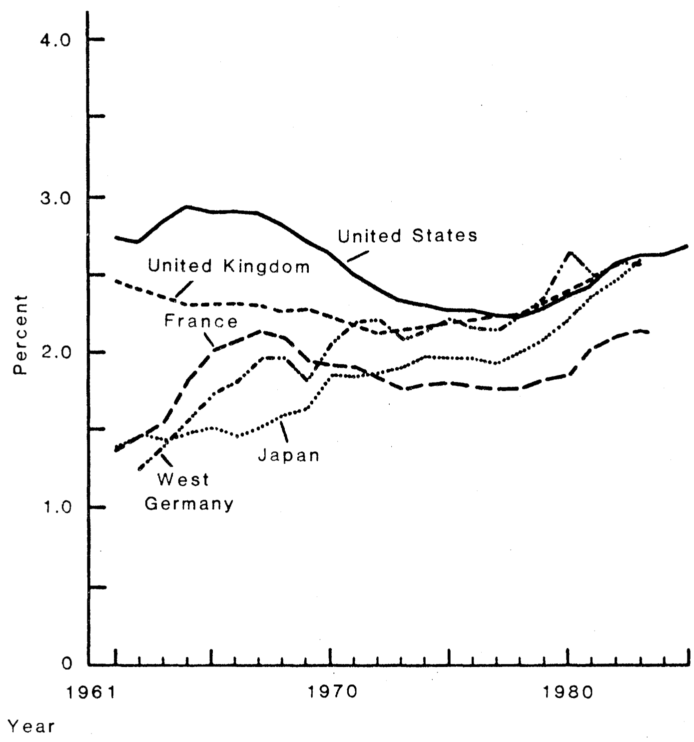


Fig. 2. Scientists and engineers engaged in R&D in different countries.

Fig. 3. National expenditures for the performance of R&D as a percentage of gross national product by country.

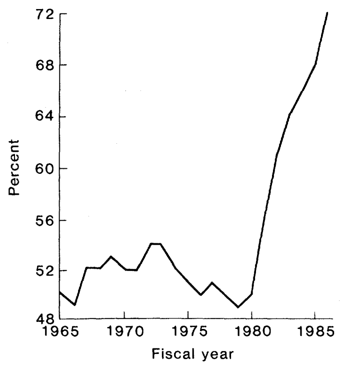


Fig. 4. Military R&D as a proportion of all federal R&D.

that we spend on R&D (Fig. 3) resembles the one that describes the proportion of our population engaged in science and engineering (Fig. 2). Again what is interesting is that the shape of our curve is so different from that of our competitors. The comparison indicates the relative emphasis that our trading partners have been putting on R&D over that past quarter-century.

The United States carries a defense burden that other countries do not. If we remove the defense-oriented work from the R&D figures, our civilian R&D level is below that of both West Germany and Japan. The division of the federal R&D effort between the civilian and defense sectors is also changing in an important way. In the 1960's the civilian effort rose rapidly, and then for about 15 years there was a rough parity between civilian and military efforts. In the past 5 years the balance has shifted strongly toward the defense side again. At present, only a little more than a quarter of the federal R&D effort goes into civilian research (Fig. 4).

Arguments can be made that put an optimistic light on these trends. The balance between military and civilian research may not be that important. The strategic defense initiative (SDI), for instance, is clearly focused on the most advanced technologies, and that should result in a significant payoff for the economy.

But it is also true that outside of SDI and the Defense Advanced Research Projects Agency (DARPA), most of the military effort is focused on fairly short-range development efforts. For a decade or two after World War II, military research sought technologies that were important to the civilian world also, especially computers, semiconductors, and nuclear power. But as a rule, that is no longer the case. In computers and semiconductors today, for instance, the civilian side is leading.

The proportion of military R&D funding that is devoted to basic research has been declining ever since the Mansfield Amendment, in 1971, limited the Defense Department's role in R&D to projects that could be specifically tied to a military need. Although the amendment no longer applies, the attitudes it engendered live on.

Research outputs. The National Science Board has been concerned for some time with developing indicators of the output of the R&D enterprise. This is not an easy task, because the real output of science and engineering is important new insights, and we have no direct way to measure or count them.

But we do have a few indicators that can serve as barometers. The U.S. share of world scientific and technical literature declined in most fields between 1973 and 1982. The most striking declines were in mathematics, 23 percent; physics, 18 percent; and biology, 17 percent.

It is natural that the U.S. share should decline when the research efforts of the rest of the world are increasing. But the citation ratios—the extent to which U.S. literature is cited in proportion to its volume—are also declining. The most striking declines are in engineering, mathematics, and biology. This suggests that the quality of research in competing nations is improving relative to ours.

The rate at which U.S. residents apply for patents in foreign countries—a measure of how aggressively we are commercializing our ideas abroad—has also been declining. On this measure only the Japanese have been advancing steadily, but they have closed the gap with us substantially in the last 15 years.

As sparse as they are, these data do not tell us anything conclusive. But the general pattern is consistent with the other data we have.

Science Policy and Science Organization Since World War II

The federal government supports R&D and the education that goes with it for three basic reasons. (i) We support a certain amount of basic science for its intellectual value. Research on the origins of the universe or of humankind fall into this category. No direct economic payoff is expected. (ii) The government itself needs new knowledge and new technology to carry out specific missions such as defense. This is the largest part of the government's R&D effort. (iii) The nation's economic well-being requires research investments in basic science and engineering, which only the government has the incentive and sometimes the ability to make.

Any piece of research may serve more than one of these goals, but the three are conceptually distinct. They need to be kept in mind when one is thinking about the way the federal government goes about supporting R&D.

Federal science and technology policy has gone through four distinct phases since World War II. The first lasted until 1957 and was characterized by reliance on the mission agencies for most R&D support. In the physical sciences the key agencies were the Department of Defense and the Atomic Energy Commission. They supported research because it served their missions, but the system worked fairly well for the country as a whole because the technologies they sought were important to the industrial sector as well.

In this first period a small National Science Foundation was responsible for meeting the first goal—intrinsic value. No one was responsible for the third goal.

The second period followed the launching of Sputnik in 1957. The Soviet success in placing the first satellite in orbit was a major shock and revealed weaknesses in the science and engineering base that needed attention. The result was a major increase in support for our universities and colleges. The federal government in this period accepted responsibility for the base, and the goal of economic competitiveness was well served.

But after 1968 the momentum of Sputnik was spent, and national attention shifted to social problems: housing, energy, crime. This was the heyday of "relevance," and research was directed toward these efforts, with little concern for economic competitiveness.

The effects of these periods on funding for the science and engineering base can be seen in Fig. 5. Funding increased rapidly between 1957 and 1968, and leveled off thereafter.

Investment in the equipment and facilities necessary for research declined markedly after 1968 (Fig. 6). To a large extent, increases in support for research in this period were made possible by reductions in such investment. We are now seeing the effect of this long period of lessened support for facilities in a huge demand for replacement of obsolete buildings and equipment.

The fourth period of postwar science policy began about 1980 with an increased recognition of the need to support the science and engineering base. In the past few years, the appropriate roles of government and industry have been better defined with the result that federal support of development in the nondefense area has been

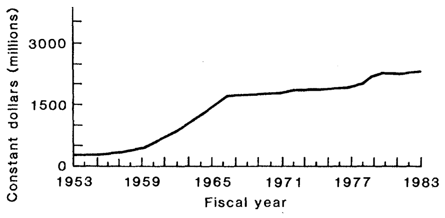


Fig. 5. Federal R&D expenditures at universities and colleges.

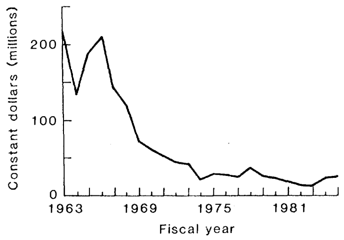


Fig. 6. Federal obligations to universities and colleges for R&D plant.

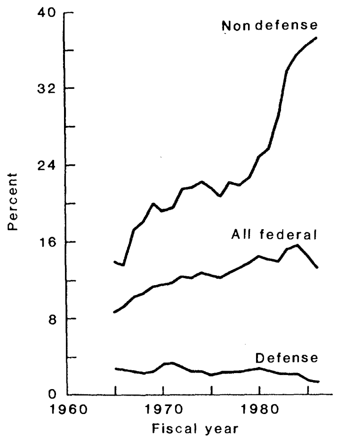


Fig. 7. Basic research as a proportion of all R&D, by category.

cut substantially, and basic research support has been increased. Figure 7 shows how nondefense support has been shifted toward basic research. Yet the dominance of defense R&D in the federal effort is such that, overall, the proportion of basic research has declined slightly in the last 2 years.

What Is to Be Done?

Except for the brief period after Sputnik, there has not until recently been a clear recognition of the responsibility of the federal government for the science and engineering base. During most of the postwar period, primary reliance was placed on the mission agencies to support research, with a resulting inherent bias toward research that is relevant to these missions and away from basic work.

We now recognize what the federal government should do. We understand the three goals of federal R&D support. The system serves the goals of intellectual value and of support of government missions well. But we need to put mechanisms in place to serve the goal of economic competitiveness equally well.

What is such a mechanism? It is easier to say what it is *not*. It is not a program in which the government targets selected basic research areas for special emphasis. Science and engineering move much too fast for any government to be able to do that effectively.

It is also not a program in which government coordinates the research efforts of industry, academia, and its own research laboratories. Industry reacts to market forces, as it should. Government laboratories respond to government needs. And academia properly responds to intellectual opportunity. Trying to coordinate activities to meet these different needs is bound to fail.

What government must do instead is ensure that each sector has the resources and the freedom to respond to its own needs and that each sector has the means and the incentive to cooperate with the others. For these reasons, we are proposing a major shift of resources toward the nation's universities. The universities have always attracted the most inquiring minds. They combine research and education in a way that is impossible in other settings. That is important because we must have education programs to provide researchers, and we cannot have effective advanced education in science and engineering without having students directly involved in research.

We must apply these new resources in ways that will encourage the necessary cooperation. Last year the National Science Foundation made six awards in a new kind of effort: the Engineering Research Centers. Each center focuses on an important area of engineering, and each brings together researchers from different disciplines and from both academia and industry. The problems they have chosen—in such fields as telecommunications, biotechnology, robotic systems, advanced materials, and systems research—are both intellectually exciting and of potentially great economic importance.

These centers will be successful because they meet a real need with a genuinely innovative approach. They bring together various disciplines to address important problems in the real world. In so doing they also institute change in the universities, reducing their organizational dependence on a disciplinary structure that is, for some purposes, no longer ideal.

The centers also bring together industry and academic researchers, with beneficial effects for both. The academic scientists gain the perspective that comes from working on problems of genuine economic consequence. With industry support, they gain access to research equipment that few universities can provide. The industry scientists also gain from access to the most creative minds among the faculty members and graduate students and through contact with approaches and ideas that provide fresh perspectives.

The Foundation began with six centers, but the idea has been tremendously popular. We had 140 proposals last year, and we have another 100 proposals in this year's competition, although we will be able to support only a handful. The idea need not be limited to engineering: many areas of science could benefit from the same approach.

We hope to move ahead with a major effort to fund centers of this sort. George Keyworth, the President's former science advisor, calls them Basic Science and Technology Centers because they would do basic research but with the eventual aim of creating the technology that the nation needs.

Like the Engineering Research Centers, Basic Science and Technology Centers should be multidisciplinary. It is at the intersection between the disciplines that one finds the most exciting work. For example: (i) Is biotechnology an extension of biology, or chemical engineering, or chemistry? Obviously, it is all of these in varying degrees. (ii) Computational science and engineering includes mathematics, operations research, computer science, information science, and no doubt other elements. (iii) Any other new or emerging field will have this same character of bridging the established disciplines.

Although we must not minimize the importance of the established disciplines in maintaining quality in research and especially education programs, we must also recognize that new demands often require a new approach to social organization. This is as true in the universities as it is anywere else.

At least as important is that these centers will provide more of the cooperation that we need between industry and academia. We have made a good start on this in the past few years, but we are a long way from the point at which this will be taken for granted—as it should. We do not need a coordinated program in which the government chooses the lines of inquiry to pursue. But genuine cooperation, in which all participants can gain, is a major strength that we should exploit. This should be the United States' answer to the nationally coordinated programs of other countries.

Cooperation along these lines will also achieve another important goal: that of leveraging tax dollars. Government should not do everything in these areas. In our Engineering Research Centers and in other similar new programs we have insisted on substantial support from industry, and this should also be a requirement in Basic Science and Technology Centers. The support can take the form of money, but even more important is a commitment from industry to provide people, equipment, and ideas.

We must also create mechanisms to improve the academic infrastructure.

- We must attract the best and the brightest of our young people to faculty life. Industry should help in this, for it is in their interest as well. We have made a start recently with the Presidential Young Investigators program, which has attracted 500 faculty members in the areas of greatest shortage.
- We must find ways to use the latent talent of women and minorities that are now underrepresented in science. There is an equity issue here, and that issue has been the focus of attention. But progress on this issue is also important in economic terms. No society that expects to remain competitive can afford to allow talented people not to be fully utilized.
- We must find ways to invest sufficiently in reseach instrumentation. Like other government agencies, the Foundation is spending an increasing proportion of its budget on instrumentation. These awards make available to university researchers such things as supercomputers, synchronous light sources, nuclear magnetic resonators, and other major equipment.
- We must also find ways to provide the academic facilities that so many universities need. The demand for laboratories and other facilities for both teaching and research has been building for two decades.

Conclusion

In recent decades we have moved away from the synthesis of theory and practice that the best scientists and engineers have always exemplified. We have let science become too much the property of those who define their subjects narrowly and who fail to seek connections between their sciences and other disciplines or between their ability to know and other's ability to accomplish a practical end.

There are signs that we are coming to understand the dangers of this trend and the truth of the observation of the 18th-century philosopher Georg Christoph Lichtenberg: "He who understands nothing but chemistry does not truly understand chemistry either."

We must do everything we can to further this process of recognition and change. Priorities must be set; the fact that we cannot do everything must not prevent us from doing the most important things. If institutional change is necessary, we must embrace it.

Above all we must analyze our situation objectively and make choices, or they will be made for us. The competition of the modern world demands our best efforts, in science and technology perhaps more than in other fields. How best to accomplish this, so that we may realize the potential that advances in knowledge hold for us must be everyone's problem.