Graduate Education and Research for Economic Growth

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Scientific and engineering research in the United States is undergoing radical change. Driving this revolution are two forces (1). One is increasing global competition, which has highlighted the widening gap between the needs of industry and the expertise of academia. The second is the balanced budget movement, which will reduce overall federal research and development (R&D) funding and may drastically cut the federal support of commercially relevant R&D. How should these forces affect the doctoral-level training of industrial researchers, who are the main link between the U.S. economy and academic research (2)?

Industry in the United States is the largest customer for engineering and science doctorates. It continues to need researchers for critical activities, including the practical exploitation of new fields of science and engineering. About 56% of all U.S. graduates with a Ph.D. in the physical and computer sciences or electrical and chemical engineering work in industry. In 1992, 61% of all the new potentially permanent positions held by graduates with new Ph.D.'s in physics were in industry or federally funded R&D centers (3, 4). Industrial researchers must be able to understand scientific research and communicate its consequences to technologists and their sponsors. These scientists must identify those lines of inquiry that can have economic and social value as well as intellectual challenge. How this challenge to graduate education can be met over the next decade has been the subject of much study (2, 5). We believe that the need is not for new kinds of degrees but a fine tuning of the existing educational process. Foremost of these changes are (i) increasing the opportunities for greater breadth and choice for students before they embark on their dissertations, (ii) providing a broader range of experiences for students during their research projects, and (iii) increasing the rewards for effective teaching by graduate students. Making these changes will require conscious efforts from academia, government, and industry but probably not much new money.

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Science for National and Corporate Needs

Research in the United States over the last 40 years (as opposed to development) has had a strong academic flavor, even in industrial and government laboratories. Basic scientific principles were more important than production-based design rules.

These values have changed recently. In *Science in the National Interest*, the Clinton Administration said, "We acknowledge the intimate relationships among and interdependence of basic research, applied research, and technology, appreciate that progress in any one depends on advances in the others, and indeed recognize that it is often misleading to label a particular activity as belonging uniquely to one category" (6). This synergy was reflected by James C. McGroddy, head of IBM Research, when he said, "In any institution, it is the job of the researchers and those who manage researchers (to the degree that they can and should be managed) to take full responsibility for capturing the value produced by research. A novel DRAM cell must be integrated into a potentially manufacturable process. An architectural innovation for a processor will not succeed by itself . . . " (7).

The new demands on graduate training are driven by the increase in technological sophistication worldwide. The United States and U.S. companies no longer dominate technology and can no longer expect to reap the benefits of scientific knowledge, independent of how long these benefits take to arrive (8). Many companies around the world have the ability to exploit scientific breakthroughs and technical advances. Anybody that invests in leading-edge research and leaves the results on the table invites others now to realize the benefits first. In spite of all the difficulties of technology transfer, there are times when it "is very hard not to transfer it," when the other party is interested, sophisticated, and knowledgeable (9). This now describes the scientists and managers in many competitive industries and nations. The idea that corporate research can and must serve identifiable, strategic, commercial ends is now essential but is not fully appreciated in many research universities.

The identification of potentially useful scientific problems requires great familiarity with the details of the problems. The quality of choices decreases monotonically as the decision maker becomes further removed from the laboratory (10). Commercial investments in research make sense only if the researchers themselves try to anticipate how their work can impact the marketplace.

Corporate research requires the excellence that characterizes outstanding science because these problems can be as demanding as any in academic research. However, unlike their academic counterparts, industrial researchers will be best supported if they understand the technologies that are relevant to their research. They must also appreciate the problems of the customers who use these technologies. Customer needs can be a fertile basis for scientific research and a powerful stimulus for the solutions to basic problems. The interaction of this triad of curiosity-, technology-, and customer-driven knowledge must be at the heart of industrial research.

Implications for Higher Education and Training

The emphasis on detailed knowledge and hands-on experience in the personal solution of a scientific or technical problem gives graduate education its value and is fundamental to a new Ph.D. graduate's success. The national concern (2) about graduate education centers on whether it unnecessarily narrows the interests of the student. Students must excel in a discipline, but in industry, the world cannot begin and end with that discipline. Industry needs researchers who recognize and solve critical problems and can quickly realize the practical implications of their scientific solutions.

There are many examples of where the active involvement of industrial scientists in both research and development has been critical for the early identification of important new technologies and their implementation. Magnetic storage devices are fundamental to information technology. High bit densities and data transfer rates at reasonable costs help differentiate IBM products in the marketplace. In 1988, researchers in Europe reported that films of very thin alternating layers of Fe and Cr showed anomalously large changes in resistivity with applied magnetic fields. However, the fields needed were too large for magnetic storage applications. Nevertheless, this inspired IBM scientists to extend the original results obtained on Fe/Cr films to many other materials, and observe new physical phenomena, including the giant magnetoresistive effect at the very low magnetic fields characteristic of high-density magnetic recording systems. This work helped make IBM a leader in this field, motivated work throughout IBM, and laid out a clear technology road map for the continued development of magnetic storage devices into the 21st century. In this and other cases, researchers took purely scientific questions and identified those areas that had an impact on their company's products and services. Obviously, not all efforts to pursue "strategic" objectives are so successful, but the efforts are essential.

Although educational institutions continue to produce outstanding graduates with Ph.D.'s who do this, the prolonged narrow disciplinary focus of today's education produces too many students who believe that academic research is the goal of their graduate training. In fact, graduate education fosters important values in two directions. At the crux, it fuels the natural curiosity that is at the heart of any scientist's questions about the world. On one axis, graduate education rewards a restlessness that spurs challenges to accepted wisdom and a feeling for intellectual adventure in learning about new problems. On the other axis, it provides an appreciation for what it means to understand a problem deeply, a dedication to quality symbolized by the personal character of scientific work, the ability to collaborate in small teams, and leadership skills as one moves from a beginning to a senior student. However, Ph.D. candidates who only acquire a narrow disciplinary identity during their graduate education can be handicapped when faced with the broader themes and issues of technology and the marketplace.

Opportunities

The development of these "T-shaped" researchers has been the subject of many commentaries (*2*, *11*, *12*). In their education, students must learn that ideas for exciting research come from a wide variety of sources, including one's discipline, the technologies that grow from these disciplines, and customers' questions that can appear to be far removed from a particular discipline. How can graduate education teach this?

1) *More fellowship and less research assistant support*. In the years following Sputnik, many graduate students were supported by federally funded fellowships. In 1991, only 3500 of the total 30,000 graduate students in the physical sciences were on fellowships compared to 12,200 research assistantships (RAs) (*11*). Although the final phase of a graduate education can be supported by RAs, today too many students begin their graduate careers as RAs. This places pressure on students to specialize too early, limits their freedom to explore the boundaries of their academic environments, and increases the pressure on them to work on campus for their advisers, even during the summers when they are still doing course work. These constraints all limit their ability to look at the world about them and at scientific and technical challenges beyond those of their theses problems. A change in how students are supported need not involve new money but a decrease in the amount of support for RAs in research contracts and a matching increase in money for graduate fellowships. Symposia and conferences have concluded that there should be a shift in graduate student support from RAs to fellowships and traineeships (*12*).

2) *More opportunities for research at off-campus, nonacademic sites and other new types of collaborations*. At the predoctoral level, many students benefit from cooperative study programs in industry. These range from work-studies with university-like industrial research labs to time on real factory floors. This area is ripe for further development by both academia and industry. These improvements will only occur if industry invests its own time and money and universities encourage and reward initiative and flexibility on the part of professors and departments.

Exciting new opportunities were developing recently in this area. The Mathematics and the Physical Sciences Directorates of the National Science Foundation (NSF) now allow Postdoctoral Research Fellowships in Mathematical and Physical Science to be held at industrial sites. Programs such as the National Institute for Science and Technology's Advanced Technology Program and the Department of Energy's Cooperative Research and Development Agreements could provide significant new chances for students, faculty, and industrial researchers to collaborate. At this historic crossroads, industry and the academic community must seize these new opportunities to enrich the education of graduate students in ways that will make them more relevant to the industries that will employ them. A major question today is whether the federal government will aid or hinder these collaborations.

3) *More opportunities for teaching*. Universities should use teaching to broaden the intellectual range and sensitivity of research students. Although teaching assistantships constitute over 39% of all graduate support in the physical sciences (*13*), those involved often have little if any preparation. Teaching is often viewed as pure drudgery and a costly diversion from the real work of research. Graduate students should not replace faculty in teaching undergraduates. However, when they teach undergraduates and other graduate students, and many of them must, the importance of a highly motivated, quality effort must be made clear. The synergy between research and effective teaching must be guided and encouraged by faculty.

Teaching is the best test of one's grasp of a subject. It also prepares graduate students for the real world where not everyone cares passionately about their particular discipline. Such experiences force one to look at his or her academic discipline from an outsider's perspective and to understand the goals of nonspecialists and skeptical consumers. Researchers, as well as the managers of research, have not communicated well with the public at large or their corporate sponsors about the value of basic research. Making teaching a valued part of doctoral education can help develop these essential skills.

Conclusions

Many companies in rapidly developing, high-technology industries understand the value of research for both their near and long-term success. However, they can no longer automatically expect to reap the benefits of the research they sponsor. In order for companies to capitalize on their investment, their researchers must choose problems based on a broad perspective that recognizes inputs other than the purely disciplinary; they must also be willing to work on deployment of their ideas in real technology. The critical need in graduate education today is to train researchers who are interested, sophisticated, and knowledgeable about their studies and the wider world in which their research resides.

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