

# Science, Economic Growth, and Public Policy

Richard R. Nelson and Paul M. Romer

*The authors argue that the social returns to R&D investment are large and cannot be captured by any single firm. Therefore, the United States underinvests in research. Encouraging R&D investment is as important as investing itself.*

**M**ajor long-term policy changes often flow from decisions made in times of stress. Thus, choices about how to fight World War II ultimately led to the large-scale sustained support of university research by the federal government that has lasted over the half-century since World War II. The economic threat we face today is less acute than the security threat we faced then. Nevertheless, this threat may lead to a fundamental realignment of science and technology policy and a major change in the economic role of the university.

In the midst of the debate about how government support for science should be structured after World War II, Vannevar Bush prepared his famous report, "Science—The Endless Frontier." Although the specific institutional recommendations from the report were not adopted, it set the terms for the subsequent intellectual debate about science policy. In an analysis of Bush's report, Donald E. Stokes (1995) notes that Bush advocated government support for the kind of abstract science done by scientists such as Niels Bohr, the physicist who played a

pivotal role in the development of quantum mechanics. Bush argued that public support for that kind of science would lead to advances in the work done by someone like Thomas Edison, who takes existing knowledge and puts it to commercial use. (The argument comes from Bush but the examples of Bohr and Edison come from Stokes.)

We are beginning to see a decisive shift on the part of the government toward direct rather than indirect support for the "Edisons." If Edison were alive today, setting up General Electric, he could apply for direct grants from such government programs as SBIR (Small Business Innovative Research), ATP (Advanced Technology Program), and TRP (Technology Reinvestment Program). He could pursue CRADAs (Cooperative Research and Development Agreements) with the National Laboratories. He could form a consortium of for-profit firms and get government matching money to develop a specific technology such as flat panel display screens. The government would also be much more willing to help him establish commercially

RICHARD R. NELSON is Professor of Economics at Columbia University, and PAUL M. ROMER is Professor of Economics at Stanford University. This article is excerpted from a forthcoming book, *Technology, R&D and the Economy*, edited by Bruce Smith and Claude Barfield, a joint publication of the Brookings Institution and the American Enterprise Institute.

valuable intellectual property rights over any fundamental discoveries that he might make. Some policy makers would encourage him to patent the sequence data on gene fragments, the scientific and practical importance of which no one had yet understood.

As many students of science and technology have pointed out, there are good reasons to be dissatisfied with the "linear model" of the relationship between science and practical technology that is implicit in Bush's report. According to this now discredited

---

***The economic threat that we face today . . . may lead to a fundamental realignment of science and technology policy and a major change in the economic role of the university.***

---

model, the government merely puts resources into the Bohr-end of a production line and valuable products come out at the Edison-end. There are, however, equally good reasons to be worried about a strategy that sharply shifts government policy toward direct support of R&D in industry, giving government money to Edison-like activities and strengthening property rights across the board. And the reasons for concern are amplified if such a policy shift involves a drying up of public support for basic research at universities.

One important limitation of the linear model—the one we will focus upon here—is that it is blind to basic research undertaken with practical problems in mind—work in which the Bohrs are directly motivated to lay the scientific basis for the work of the Edisons. In the map laid out by Stokes, such work is epitomized by the research of Louis Pasteur, a scientist whose research was primarily guided by practical problems, which led him to explore fundamental scientific questions. Basic economic analysis suggests that different institutional arrangements be used to support the work of a Bohr and an Edison, but the example of Pasteur indicates that one wants to have strong linkages between the two. Both of these kinds of work are more productive when they rub up against each other.

Universities in the United States have enjoyed unique success in promoting this kind of interaction.

Before World War II, they did this by catering to the needs of the private business sector. They provided the home for new scientific fields such as metallurgy, which was developed expressly to advance steel-making technology. After the war, universities in the United States became world-class centers of Bohr-style science, but they also gained new strength in the Pasteur-like activities. In large part, this took place because such government agencies as the National Institutes of Health and the Department of Defense provided massive support for what came to be called "mission-oriented" basic research.

We now have the opportunity to adjust the set of practical problems that animate Pasteur-style science within the university. We could reduce our emphasis on problems in the areas of defense and health. We could pay more attention to the broad range of scientific and technical challenges that arise in the private sector. This change can be implemented without endangering our national strength in Bohr-style science. It can be accomplished without trying to privatize Pasteur-style science and without creating strong property rights that could impede the free flow of knowledge that is generated by this work. Indeed, our argument is that the preservation, with reorientation, of Pasteur-style science within the university will both strengthen Bohr-style science and help us meet the changing practical demands we are putting on science.

We are concerned that this is not adequately understood. Instead of offering new and different opportunities for the Pasteurs of the university, policy makers may try to convert both the Bohrs and the Pasteurs into Edisons. Fearful of this prospect, the Bohrs and Pasteurs may fight any proposal for readjustment. Government leaders may therefore bypass the university in frustration and fund the Edisons of the private sector directly. Over time, the work that was previously done by Pasteurs in the university will be shifted to the private sector through a combination of direct grants, matching money, and stronger property rights, where it will become Edison work, not Pasteur work. The Bohrs may acquiesce in this privatization and eventual destruction of Pasteur-style science because it buys them protection from political demands for changes in their part of university research. We could end up with the kind of separation that we have avoided until now, with the Bohrs working in isolation from the Edisons, and with little work in the Pasteurs' quadrant. We will then have lost the unique features that made our uni-

versities so successful in generating good science and strong economic growth.

In this paper, we try to outline the economic principles that should guide the choice of which path to take. We start by outlining the forces that brought us to this junction.

## **THE CURRENT POLICY CONTEXT**

Before describing what economists know about the connections between science, technology, and economic growth, it is important to lay out the economic context of the current debate about science policy. This context has been shaped by the erosion of the very large and widespread technological and economic lead that the United States had over other countries during the 1960s and the worldwide slowdown in income and productivity growth since the early 1970s. The erosion of the U.S. lead is easy to explain and probably was inevitable. The slowdown in growth is not well understood.

It is important to recognize that the post-World War II economic and technological dominance of the United States was the consequence of two distinct waves of economic growth. The first wave, which dates from the late nineteenth century, began at a time when U.S. universities were not strong centers of scientific research. The act that created the land-grant college system in the 1870s described the mission of these institutions as the development of the "agricultural and mechanic arts." Such research as did take place tended to reflect this strong practical orientation. European intellectuals were disdainful of the vocational orientation of American universities. And as late as the 1930s, young American scientists who wanted advanced scientific training generally went to Europe to get it.

The early U.S. successes in such industries as automobiles and steel were not the result of any particular American strength in science. Instead, firms here achieved dominance in the techniques of mass production in large part because they operated in the world's largest common market. They had access to many consumers and to ample supplies of inexpensive raw materials. But universities also played an important role. Because of the unusual practical orientation of the U.S. system of higher education, U.S. industry had access to a large pool of well-trained engineers and was able to develop professional managers to a far greater degree than was the case in Europe.

The second major wave of American economic success was in "high-technology" industries. These developed after World War II and were made possible by rapidly developing American capabilities in science. Indeed, World War II was a watershed in American science and technology in several respects. After the war, the federal government became the principal patron of university research. By the middle 1960s, the American university research system had clearly become the world's best across a spectrum that included almost all fields of science. This improvement in the quality of American science was accompanied by major procurement and industrial R&D programs of the department of defense and, for a period of time, NASA. These programs created the initial market for some of the high-technology goods that made the first use of the rapidly developing body of scientific knowledge. On the other hand, in many cases the market for high-technology goods drew forth the science that made these goods possible.

Increased government support for science was accompanied by two other developments. One was the large increase in the number of young Americans earning a university education. While only a small fraction of college majors were in the natural sciences or engineering, the sheer numbers of Americans receiving undergraduate and postgraduate training meant that by the late 1960s the fraction of scientists and engineers in the U.S. work force stood well above the fraction in Europe and Japan. Second, both private and public monies flowing into industrial R&D increased greatly. By the late 1960s, the U.S. ratio of industrial R&D to GNP was far higher than in any other country. All these factors combined to give firms in the United States a commanding position in such high-technology fields as computers, semiconductors, aircraft, and pharmaceuticals.

The late 1960s marked another watershed. By that time American economic dominance was clearly beginning to erode, as Japan and the advanced industrial nations of Western Europe began to catch up. There were two basic factors behind this process of catching up. One was the rapid integration of the economies of the industrialized nations. Reductions in transportation costs and the removal of trade restrictions meant that manufactured products and raw materials could move more readily between countries. In addition, increased flows of direct foreign investment let firms from the United States put their knowledge and technology to work in many other countries. The other

---

factor in the process of catching up was the investment that other countries were making in science and engineering education and in research and development. Together these developments made it possible for several countries to achieve rough parity with—and in some cases go beyond—the United States in traditional areas of mass production. The U.S. high-technology industries, however, have generally continued to do well in the face of strengthening foreign competition.

---

***The loss of the dominant position held by American firms has caused the policy discussion to focus on measures that could enhance their competitive position. The productivity slowdown, which manifests itself most dramatically in stagnation of the wages paid to low-skilled workers, has generated additional support for government measures that would directly spur economic growth.***

---

Most economists believe that convergence among the advanced industrial nations was inevitable. In a world where transportation and communication costs are falling and where governments remove artificial barriers, the same forces that operate within the borders of the United States will operate between countries. At the time of the Civil War, economic activity in the southern states of the United States was very different from that in the industrialized Northeast. Because of the greatly increased mobility of goods and firms that has been the result of advances in transportation and communications technology since that time, economic activity in the two regions now looks much the same.

At the same time that the convergence between the industrialized nations was taking place, productivity and income growth slowed significantly from the pace it had achieved during the quarter-century after World War II. This slowdown occurred first in the United States, but is also apparent in the other industrialized economies. Economists are still uncertain as to exactly what lay behind the global slowdown beginning in 1970, or to put the question in another way, why growth that proceeded at unprecedented rates during

the 1950s and 1960s has returned to levels that are closer to historical norms. In any case, economists are nearly unanimous in holding that the rapid growth of other nations was not a cause of the slowdown in growth in the United States.

Nevertheless, the combination of convergence and slow growth blended together to create a public perception that the United States is suffering from a serious relative decline in its economic performance. This perception has changed the nature of the policy discussion in the United States regarding the appropriate role of the government in supporting technology and science. The loss of the dominant position held by American firms has caused the policy discussion to focus on measures that could enhance their competitive position. The productivity slowdown, which manifests itself most dramatically in stagnation of the wages paid to low-skilled workers, has generated additional support for government measures that would directly spur economic growth.

The slowdown has also meant that government revenues have not grown as rapidly in the last thirty years as they did during the 1950s and 1960s. The slowdown in the rate of growth of private income has increased political resistance to increased tax rates. As a result, political support for the strategy of dealing with national problems by spending public money has fallen. Also, as seems always to be the case when times get harder, there has been growing disenchantment with government policies and programs that were widely regarded as appropriate and efficacious during earlier, better economic times.

One important manifestation has been growing dissension about whether the large-scale U.S. government support for basic research, primarily at universities, is worth what it costs. Increasingly, there are suggestions that university research support ought to be more closely targeted on areas and activities that were deemed likely to feed directly into technological innovation.

This dissatisfaction certainly has influenced the design of the new technology programs. Except in the area of defense procurement, the government traditionally has used the university as an intermediary when it wanted to encourage economic and technological development in the private business sector. The new technology programs cited in the introduction largely bypass the university. Many directly influence research activity within firms and, for the first time, attempt to do so in areas where the federal

government will not be the primary user of the goods being developed.

Several other factors further complicate the situation for universities. The end of the cold war already poses a serious threat to existing defense-related support for university research in such fields as electrical engineering, computer science, and materials science. Growing concern about health care costs may soon threaten research support for the biomedical sciences. An increasing number of young scientists who had expected to follow an academic career are finding that path blocked by a lack of jobs. Universities are responding to the feared cutbacks in government research funding by soliciting more support from industry.

At the same time that public support of university basic research has come under attack, some of the private organizations that did path-breaking basic research—Bell Labs, IBM Yorktown, Xerox PARC—have been cutting back on expenditures or reallocating their energies to projects that have quicker payoffs or where the results more easily can be kept proprietary. Some of these same companies also are pulling away from their previous support of academic research.

The current debate about government support for science and technology reflects all this. Decisions made now will determine how scientific research in universities and technological development in industry will evolve, perhaps for decades to come. Behind every position in this debate there lies a set of assumptions about the relationships between science, technological innovation, and economic growth. It is to these relationships that we now turn.

## TECHNOLOGY AND ECONOMIC GROWTH

From the very beginning, economists have appreciated the importance of technical advance. One of the most striking parts of Adam Smith's pioneering analysis of economic principles, *The Wealth of Nations*, was his famous description of productivity improvement in the making of pins. A good part of that description involved technical advances.

From the beginning, technological advance was seen as the force that could offset diminishing returns. Diminishing returns—the notion that the marginal benefits decrease as the effort in any activity increases—is fundamental to any explanation of how a

market economy allocates resources. Classical economists reasoned as follows: the amount of food produced by each agricultural worker is very high when there are few workers on a given area of land. Output per worker diminishes as more people work the given amount of land. This kind of reasoning leads to a very pessimistic view of the prospect for sustained economic growth. As Thomas Malthus and others pointed out, in the absence of some offsetting influence, diminishing returns in agriculture implies that the output of food per person will fall as the population increases. The inevitable outcome would be famine and starvation.

By the end of the nineteenth century, it was clear that this dismal forecast was completely wrong. Population and food output had each increased dramatically. Economists observed that discovery and invention kept Malthus's bleak prediction from coming true. With a fixed set of technological opportunities, the return in any activity did indeed diminish. But over time, new techniques of production have been introduced. Initially, these new activities offered high returns. As resources were shifted into them, the returns fell, but new discoveries and new techniques kept the process going.

Economists were preoccupied with other questions during the first half of this century, especially with macroeconomic stabilization because of the worldwide disruptions experienced during the interwar period. When they returned to the study of long-run trends in the 1950s, both the empirical studies and the theoretical writings affirmed the importance of technical advance to economic growth. Technological change was understood to have a direct effect on growth by increasing the amount of output that can be produced with fixed quantities of capital and labor. The direct effect is what economists try to measure with estimates of "total factor productivity growth" or the "growth accounting residual." Early estimates attributed most of the growth in per capita income to this effect alone. More recent estimates have attributed a larger fraction of growth to the accumulation of physical and human capital and have reduced the fraction directly attributable to technology.

In any case, estimates of this direct effect of technological change tell only part of the story. Technical advance also has an indirect effect because it raises the return on investments in physical and human capital. If there were no technological advance, returns on both of these types of capital would be reduced to zero.

Capital accumulation would stop. In a fundamental sense, all economic growth, even the growth that is directly caused by capital accumulation, can ultimately be attributed to technological change.

A second line of work tried to measure the rate of return on investments in technology. In one famous and revealing calculation, Zvi Griliches showed that the investment in agricultural research that produced hybrid corn generated benefits that were about seven times larger than the costs and yielded an internal rate of return of about 40 percent. Other calculations found similar rates of return on research investments in other parts of agriculture and in manufacturing. These estimates measure the social rate of return because the entity that does the research—either the government or the private firm—often fails to capture all of the benefits. In the jargon of the field, much of the benefit comes in the form of “spillovers” that are captured by others.

The existence of a differential between private and social returns is essential if we are to understand why high rates of return on research and development could persist. If all firms could capture all of the benefits and earn 40 percent return on investments in R&D—a return that is much higher than returns on other forms of investment—many firms would increase their R&D investments. As they did, the return to research would be driven down to a more normal level. Because large returns to investment in research apparently still are available, we can infer that private investors have difficulty capturing all of the benefits from their investments.

The divergence between the private and social return to R&D investment provides an important justification for policies that would encourage R&D. From the point of view of society, the income-maximizing strategy is to invest first in those activities that offer the highest rate of return. From the point of view of society as a whole, this criterion suggests that we are not investing enough in the activities that generate technological advance. To address the question of how this deficiency could be resolved, we need a precise understanding of what these activities are and what the government can do to influence them.

## THE ECONOMICS OF SOFTWARE

Although economists have long appreciated the centrality of technical advance in the process of economic growth, a complete understanding of the key processes, investments, and actors that combine to produce it has not come easily. Indeed, these processes are very

complex and variegated. Economists broadly understand that the advance of technology is closely associated with advances in knowledge. It also is clear that new knowledge must be embodied in practices, techniques, and designs before it can affect an economic activity. Beyond this, different economic analyses focus on or stress different things.

Some discussions stress the “public good” aspects of technology, seeing new technology as ultimately available to all users. Others treat technology as largely a “private good,” possessed by the company or person that creates it. Many economists have studied research and development as the key source of new technology. Those that have focused on R&D done by private, for-profit business firms naturally assumed that the technology created through corporate R&D is, to some extent at least, a private good. By contrast, economists who have stressed the “public good” aspects of technology have focused on government investments in R&D, “spillovers” from private R&D, or both. (These spillovers are another manifestation of the divergence between the public and private returns noted above.) Still others argue that a single-minded emphasis on organized R&D as the source of technical advance sees the sources too narrowly. They point to evidence that learning-by-doing and learning-by-using are important parts of the processes whereby new technologies are developed and refined.

Another matter on which economists have been of different minds is whether technical advance and economic growth fueled by technical advance can adequately be captured in the mathematical models of economic equilibrium that economists developed to describe a static world. Joseph Schumpeter and economists proposing “evolutionary” theories of growth have stressed that disequilibrium is an essential aspect of the process. By contrast, recent theories that descend from neoclassical models presume that the essential aspects of technical advance and economic growth can be captured by extending the static equilibrium models.

While we do not want to underplay the important open questions about how economists ought to understand technical advance, a workable consensus for policy analysis seems to be emerging from these divergent perspectives. Technology needs to be understood as a collection of many different kinds of goods. These goods can have the attributes of public goods and private goods in varying proportions. Some are financed primarily by public support for R&D, others

---

by private R&D. Both business firms and universities are involved in various aspects of the process. Other parts of technology are produced primarily through learning-by-doing and learning-by-using, both of which can interact powerfully with research and development. There are aspects of the process that are quite well treated by equilibrium theories, with their emphasis on foresight, stationariness, and restoring forces. Still other aspects are better suited to the evolutionary models, with their emphasis on unpredictability and the limits of rational calculation.

---

***At the same time that public support of university basic research has come under attack, some of the private organizations that did path-breaking basic research—Bell Labs, IBM Yorktown, Xerox PARC—have been cutting back on expenditures or reallocating their energies to projects that have quicker payoffs or where the results more easily can be kept proprietary. Some of these same companies also are pulling away from their previous support of academic research.***

---

One way to summarize this emerging view is to focus on three types of durable inputs in production. We will take our imagery and language from the ongoing digital revolution and refer to these three different types of inputs as hardware, software, and wetware. Hardware includes all the nonhuman objects used in production—both capital goods such as equipment and structures and natural resources such as land and raw materials. Wetware, the things that are stored in the “wet” computer of the human brain, includes both the human capital that mainstream economists have studied and the tacit knowledge that evolutionary theorists, cognitive scientists, and philosophers have emphasized. By contrast, software represents knowledge or information that can be stored in a form that exists outside of the brain. Whether it is text on paper, data on a computer disk, images on film, drawings on a blueprint, music on tape—even thoughts expressed in human speech—software has the unique feature that

it can be copied, communicated, and reused.

The role of software, hardware, and wetware can be discerned in a wide variety of economic activities. Together they can produce new software, as when a writer uses her skills, word processing software, and a personal computer to write a book. They can produce new hardware, for example, when an engineer uses special software and hardware to produce the photographic mask that is used to lay down the lines in a semiconductor chip. When an aircraft simulator and training software are used to teach pilots new skills, they produce new wetware.

These three types of inputs can be discerned in activities that are far removed from digital computing. In the construction of the new city of Suzhou in mainland China, the government of Singapore says that its primary responsibility is to supply the software needed to run the city. The hardware is the physical infrastructure—roads, sewers, buildings, etc.—that will be designed according to the software. The wetware initially will be the minds of experts from Singapore, but eventually will be supplied by Chinese officials who will be trained in Singapore to staff the legal, administrative, and regulatory bureaucracies. The software comprises all the routines and operating procedures that have been developed in Singapore, examples of which range from the procedures for designing a road, to those for ensuring that police officers do not accept bribes, to instructions on how to run an efficient taxi service.

Traditional models of growth describe output as a function of physical capital, human capital, and the catch-all category, “technology.” The alternative proposed here has the advantage of explicitly distinguishing wetware (i.e., human capital) from software. This is an essential first step in a careful analysis of the intangibles used in economic activity. The next step is to identify the reasons why software differs from both hardware and wetware.

Economists identify two key attributes that distinguish different types of economic goods: rivalry and excludability. A good is rival if it can be used by only one user at a time. This awkward terminology stems from the observation that two people will be rivals for such a good. They cannot both use it at the same time. A piece of computer hardware is a rival good. So, arguably, are the skills of an experienced computer user. However, the bit string that encodes the operating-system software for the computer is a nonrival good. Everyone can use it at the same time because it



---

can be copied indefinitely at essentially zero cost. Nonrivalry is what makes software unique.

Although it is physically possible for a nonrival good to be used by many people, this does not mean that others are permitted to use it without the consent of the owner. This is where excludability, the second property, comes in. A good is said to be excludable if the owner has the power to exclude others from using it. Hardware is excludable. To keep others from using a piece of hardware, the owner need only maintain

---

***Technology needs to be understood as a collection of many different kinds of goods. These goods can have the attributes of public goods and private goods in varying proportions.***

---

physical possession of it. Our legal system supports each of us in our efforts to do this.

It is more difficult to make software excludable because possession of a piece of software is not sufficient to keep others from using it. Someone may have surreptitiously copied it. The feasible alternatives for establishing some degree of control are to rely on intellectual property rights established by the legal system or to keep the software, or at least some crucial part of it, secret.

Our legal system assigns intellectual property rights to some kinds of software but not others. For example, basic mathematical formulas cannot be patented or copyrighted. At least at the present time, there is no way for the scientists who develop algorithms for solving linear programming problems to get intellectual property rights on the mathematical insight behind their creation. On the other hand, the code for a computer program, the text of a novel, or the tune and lyrics of a song are examples of software that is excludable, at least to some degree.

The two-way classification of goods according to excludability and rivalry creates four idealized types of goods. Private goods and public goods are the names given to two of these four types. Private goods are both excludable and rival. Public goods are both nonexcludable and nonrival. The mathematical principles used to solve linear programming problems are public goods. Because they are software, they are nonrival; it is physically possible to copy the algo-

ritms out of a book. Because the law lets anyone copy and use them, they are nonexcludable.

In addition to private goods and public goods, there are two other types of goods that have no generally accepted labels but are important for policy analysis. The first are goods that are rival but not excludable. The proverbial example is a common pasture. Only one person's livestock can eat the grass in any square foot of pasture, so pasture land is a rival good for purposes of grazing. If the legal and institutional arrangements in force give everyone unlimited access to the pasture, it is also a nonexcludable good. Frequent allusions to "the tragedy of the commons" illustrate one of the basic results of economic theory: Free choice in the presence of rival, nonexcludable goods leads to waste and inefficiency.

The fourth category, and one of central importance to the study of technical advance, is of nonrival goods that are excludable, at least potentially. We stress the term "potentially" here because society often has a choice about the matter. It can establish and enforce strong property rights, in which case market incentives induce the production of such goods. Alternatively, it can deny such property rights. Then if the goods are to be provided, support through government funding, private collaborative effort, or philanthropy is needed. Many of the most important issues of public policy regarding technical advances are associated with this latter choice. For rivalrous goods, establishing and enforcing strong property rights is generally a good policy (although there are exceptional cases.) But for nonrivalrous goods, the matter is much less clear.

By and large, society has chosen to give property rights to the kind of software commonly called "technology" and to deny property rights but provide public support for the development of the software commonly referred to as "science." Establishing property rights on software enables the holder of those rights to restrict access to a nonrival good. When such restriction is applied—for example, by charging a license fee—some potential users for whom access would be valuable but not worth the fee will choose to forego use, even though the real cost of their using it is zero. So putting a "price" on software imposes a social cost—positive-value uses that are locked out—and in general the more valuable the software is to large numbers of users, the higher will be the cost. To cite just one example that influences the choices of working scientists, there are experiments that could be carried out using PCR (polymerase chain reaction)



technology that would be done if the scientists involved could use this technology at the cost of materials involved. Some of these are not being done because the high price charged by the current patent holder makes this research prohibitively expensive.

Note that this is very different from what is entailed in establishing property rights on rival goods. Only one user can make use of a rival good at any one time. So property rights, or options to sell them, encourage the rival good to be used by those to whom it is most valuable.

Our legal system tries to take account of the ambiguous character of property rights on software. We give patents for some discoveries, but they are limited in scope and expire after a specific period of time. For rival goods this would be a terrible policy. Imagine the consequences if the titles to all pieces of land lapsed after seventeen years. For some nonrival goods, such as works of literature or music, we grant copyright protection that lasts much longer than patent protection. This can be rationalized by the argument that costs from monopoly control of these goods creates relatively little economic inefficiency. For other goods, such as scientific discoveries and mathematical formulas, the law gives no protection at all. This presumably reflects a judgment that the cost of monopoly power over these goods is too high and that we are better off relying on such nonmarket mechanisms as philanthropic giving and government support to finance and motivate the production of these types of software.

One important distinction between different types of software is the difference in the amount and variety of additional work that needs to be done before that software makes an actual contribution that consumers would be willing to pay for. Property rights on software that is directly employed by final consumers can lead to high prices—consider the high prices on some pharmaceuticals—and cut out use by some parties who would value use, but will not or cannot pay the price. For software such as this, however, that is close to final use, it is possible for users to make reasonably well founded benefit-price calculations.

It is quite otherwise with software whose major use is to facilitate the development of subsequent software. Any market for software, such as mathematical algorithms and scientific discoveries far removed from the final consumer, would risk being grossly inefficient. Over time, many producers have to intervene, making improvements and refining the basic

idea, before such software can be finally embodied in a technique, practice, or design that produces value and is sold to a final consumer. Economic theory tells us that the presence of monopoly power at many stages in this long and unpredictable chain of production can be very bad for efficiency.

In the worst case, property rights that are too strong could preempt the development of entire areas of new software. In the computer software industry, people capture this dilemma by asking the rhetorical question, "What if someone had been able to patent the blinking cursor?" The point applies equally well to many other important discoveries in the history of the industry—the notion of a high-level language and a compiler, the iterative loop, the conditional branch point, or a spreadsheet-like display of columns and rows. Extremely strong property rights on these kinds of software could have significantly slowed innovation in computer software and kept many types of existing applications from being developed.

In the production of computer software, basic software concepts are not granted strong property rights. Software applications, the kind of software sold in shrink-wrapped boxes in computer stores, is protected. This suggests a simple dichotomy between concepts and final applications that mirrors the distinction noted in the beginning between the search for basic concepts by a Niels Bohr and the search for practical applications by a Thomas Edison. As the work of Pasteur would lead us to expect, this dichotomy hides important ambiguities that arise in practice. At the extremes, the distinction between concepts and applications is clear, but in the middle ground there is no sharp dividing line. Courts are forced to decide either that software for overlapping windows or specific key sequences should be treated as essential parts of an application that are entitled to patent or copyright protections, or that they are basic concepts that are not given legal protection. In the realm of software, there are many shades of gray. The simple dichotomy nevertheless serves as a useful framework for guiding the economic and policy analysis of science and technology, for science is concerned with basic concepts, and technology is ultimately all about applications.

## SCIENCE AND TECHNOLOGY

One of the dangers in drawing sharp policy distinctions between basic concepts and applications arises because progress in the development of both types of

---

software is most rapid when they interact closely. The ideal policy treatment of these two types is different, but if badly designed policies interfere with this interaction, they can do great harm.

Most important, new technologies come into existence in an embryonic and imperfect form. In many cases, people have only a limited understanding of both the underlying basic concepts and of the range of possible applications. It took some time and effort after the "discovery" of the transistor at Bell Labs before transistors were developed that could be used in practical applications. It took many years for the transistor to evolve from its early free-standing state into collections of transistors in integrated circuits and many more for the development of higher-density and faster circuits. Many researchers working in many different firms contributed to these developments. In the beginning, no one anticipated the many uses to which it would be put. If Bell Labs had had extremely strong property rights over the use of the transistor, many of the most important improvements in design and new uses for it might never have been discovered.

The story of the laser follows along similar lines. When it was first invented, AT&T, which had rights to the invention, could not see a way in which it would ever be used in the communications business. Successive generations of the laser have turned out to have a wide range of applications, the vast majority of them outside the telephone system. One important application, however, has been in fiber optics, which currently is revolutionizing that system.

In the cases of both the transistor and the laser, the history of technological development is marked by great uncertainty and considerable differences of opinion regarding how to make the technology better. It took wide participation in the process of refinement and exploration to produce the many applications that consumers now buy.

In most of the technologies whose development has been studied in detail, technical progress proceeded through a lengthy, complex evolutionary process. At any time, there were a number of different actors who were attempting to develop variants or improvements on prevailing technology. They competed with each other and with prevailing practice. Some turned out to be winners, and others were losers. The winners often enjoyed wide market success. At the same time they provided a new base from which subsequent technological advance, often made by others, could progress.

Most innovations that arise in the private sector are

a mixture of new concepts and applications that are ready for sale. Successful inventors can make a profit, at least for a time, on the sale of applications, because they generally are protected. Even if the legal system does not provide effective protection, first-mover advantages and secrecy are often enough to let someone earn a profit by selling a new application. In almost all cases, the basic concepts became public software, available for the rest of the technological community, both in the private sector and in the university, to build on.

---

***Most important, new technologies come into existence in an embryonic and imperfect form. In many cases, people have only a limited understanding of both the underlying basic concepts and of the range of possible applications.***

---

As the discussion from the last section suggests, strong property rights that interfered with widespread participation would reduce the diversity in the evolutionary process and slow progress. But weak property rights create spillovers. They reduce the private incentives for doing research and induce a divergence between the social and private rates of return to research. An effective social system for inducing technological progress will therefore tolerate weak property rights on basic concepts but will subsidize some types of research to offset the tendency for a research effort to be too low. Because both the search for concepts and the search for applications can lead to important new discoveries, both are candidates for subsidies. Since World War II, a significant portion of the subsidies in the United States have taken the form of unrestricted support for university research into basic concepts (as provided, for example, by the National Science Foundation), but an even larger fraction was devoted to support for research in basic concepts that were relevant to practical applications in the areas of defense and health.

Before the war, there was research support from the government in the field of agriculture and private philanthropic support for some areas of basic science. The bulk of the subsidies, however, were directed at training scientists and engineers, most of whom went to work in the private sector. Some of this support

came from the federal government, through its grants of land to the states. Some came from the operating budgets of the states themselves. Important support also came from the philanthropic activity of such people as George Eastman and Arthur D. Little (who helped create chemical engineering at MIT) or such organizations as the Carnegie Foundation and the Rockefeller Foundation (which fostered the development of physics, the social sciences, and molecular biology).

In the cases of both the laser and the transistor, fields of scientific study grew up around the new technologies. The advent of the transistor provided a whole new agenda for research for electrical engineering and materials science. The laser has had a major effect on such fields as physical chemistry and has revitalized the field of optics. These scientific fields worked backwards from applications and tried to uncover the basic concepts that helped explain how and why they worked.

In both of these cases, the original inventions drew extensively on scientific knowledge. After their achievement, the technologies themselves became the subject matter of scientific research. In turn, the growing body of scientific understanding about the technologies provided important inputs into their refinement and further development.

Technological progress was quite rapid both before and after World War II, in environments that provided very different kinds of support for science and technology. The history of specific technological areas shows that the development of basic concepts and applications are intimately intertwined. Both of these observations suggest that it is pointless to ask whether applications or basic concepts are the prime movers in generating scientific and technological progress. Since each can encourage the other, neither can be singled out. This has not, however, stopped people from trying.

In the 1950s and 1960s, scholars studying technical advance debated the relative importance of "perceptions of demand" or "opportunities opened by science." Implicit in this debate were two different views about policy options for stimulating technical advance and economic growth. The interpretation based on scientific opportunity was associated with a science-push policy: Support scientific research, and the economic and technical benefits will follow. The perceptions of the demand view seemed to suggest that measures designed to increase economic activity in the private sector should be given the highest priority.

A number of studies indicated that if one looked into

the perceptions that motivated the initiation of particular projects, the key factor was almost invariably "perception of a demand." Studies have documented that scientific understanding and techniques often played a critical role in successful inventive efforts, but that the understandings and techniques drawn upon often tended to be relatively "old." A study funded by the Department of Defense, "Project Hindsight," explored the key scientific and technical breakthroughs that enabled the development of a number of important weapons for the military. The study found that almost invariably these breakthroughs came about as the result of research addressed to particular needs, rather than "basic research" done with little awareness of or concern about those problems.

The NSF responded by funding "Project Traces," which looked farther back in the history of various technological advances and found that many of them were in fact made possible only because of earlier "basic research." David Mowery and Nathan Rosenberg, in an article summarizing and criticizing this debate (1979), argued that it was pointless to focus on either "perception of demand" or "perception of a technological opportunity" as the only factor stimulating a particular technological effort. They pointed out that it made sense to invest only in cases where both a scientific opportunity and a practical demand were present.

In many technologies, the early findings continue to hold up—much of the science being drawn upon in the private sector is not new science. There are, however, some areas in which the connections between university research and commercial application are relatively close: pharmaceuticals, certain other chemical technologies, various fields of electronics, and more recently, biotechnology. In these fields, inventors seem to draw on science that is quite recent.

The nature of the interaction between application and the development of basic concepts was illuminated by a survey research project conducted about ten years ago. Industry executives in charge of R&D were asked about the importance of various bodies of basic and applied science for technical advance in their industry. They were also asked about the relevance of current research in these scientific areas. Most respondents rated the relevance of a "science" much higher than the relevance of "university research in that science." But evidence supports the interpretation that effective industry R&D in a specific field almost always requires that the scientists and engineers work-

ing in industry had to be trained in universities so that they are familiar with the basic scientific understandings and techniques. In many cases, however, new advances in science were not exploited in industrial R&D. If we separate the wetware (educational) and software (research) outputs of the university, for most businesses it was the output of wetware that mattered.

The responses regarding what fields of university research were most relevant to technical advance in industry were interesting. For the most part the industrial respondents tended to score most highly the relevance of university research in the engineering fields and in such scientific fields as materials science and computer science—fields in Pasteur's quadrant. Most of the respondents stated that university research in basic disciplines such as mathematics and physics was not particularly relevant to technical advance in their lines of business. But this does not mean that basic research in the fundamental disciplines is not relevant to technical advance. It suggests that the results of basic research in such fields as mathematics and physics influence technical change indirectly, by improving and stimulating research in the more applied scientific and engineering disciplines.

## **POLICY IMPLICATIONS**

There is no inherent danger in moving toward an environment where economic and commercial opportunities are given more explicit weight in determining broad areas of "national need" and where national security and health carry less weight. This change poses little risk, provided it does not reduce the fraction of research that is focused on fundamental concepts and does not shorten the time horizon over which payoffs are measured. The best way to avoid such a shift would be to preserve the institutional arrangements for supporting research that have worked so well. Universities have offered an extremely effective environment for exploring basic concepts and pursuing distant payoffs. A shift toward commercial and economic objectives should be accomplished by changing the emphasis in university research, not by pushing that research into the private sector. There must continue to be a place in the university for modern-day Pasteurs.

The returns from this attempt to adjust priorities will be larger if it is accompanied by two complementary developments. One is a change in orientation of

advanced training programs in the sciences and engineering. They should move toward training people for work in the private sector and away from the presumption that Ph.D.s, or at least good ones, get recycled into academia. It may be possible to go a long way toward this goal merely by changing the attitudes and expectations that permeate the graduate faculty. Changing attitudes and expectations will not be easy, but the alternative is to stand by while the number and quality of people getting advanced training in the sciences declines. In an era of rapidly unfolding technological opportunities, it would be perverse to cut back on advanced training in science.

If university research and graduate training are to be oriented more toward the needs of industry, it is also important that mechanisms for interaction between university and industry scientists and engineers be widened and strengthened. Universities and companies might strive for a significant increase in the extent to which industry scientists spend periods of time in academia and academic scientists in industry. These exchanges might even be supported by government funds. Rather than giving money directly to firms to do research on specific topics, the government might also explicitly subsidize the training of students who will go to work in the private sector. By taking these steps, the government could subsidize the inputs that go into private-sector research instead of contracting with firms for specific research outputs. This would let market demands and market perceptions of opportunity continue to be the primary forces that allocate resources between specific research projects in the private sector. It would avoid the pork-barrel politics that can arise when the government writes checks to business firms.

As the arguments from the previous section make clear, it is generally not good practice to establish "property rights" on the output from scientific research. This is true whether that research is directed at practical problems facing the military, health professionals, or business firms. There are important efficiency advantages in a system where the government subsidizes the production of fundamental concepts and insights and gives them away for free. The Bayh-Dole Act of 1980 marked a major retreat from the principle that knowledge subsidized by the government should circulate freely, and the continuing argument about issues such as whether "gene fragments" ought to be patentable clearly reflects strong pressures to move even further in this direction. Even as we

strengthen property rights on the applications end of the software spectrum, we should not establish private property rights on bodies of knowledge and techniques that have wide and nonrivalrous applications, particularly when many of these applications are in further research and development. A renewed attention to the needs of industry need not be associated with a major change in our intellectual property rights regime. There is no reason to treat science as being "private" rather than "public" knowledge.

World War II produced a new set of principles about the role of the federal government in support of science. The arguments presented in Vannevar Bush's report captured some of these principles. The major support that the defense department and the National Institutes of Health provided for mission-oriented ba-

sic research reflected others. This new understanding encompassed the traditional principle that private funds should be the main support for commercial applications of science. To this was added a new set of principles about science: Government funds should be used to finance the search for new fundamental concepts and insights.

These principles are as relevant today as they were then. We should adjust the details of science and technology policy in response to changing circumstances. But we should not change our principles.

To order reprints, call 1-800-352-2210;  
outside the United States, call 717-632-3535

## FOR FURTHER READING

MURRAY ABRAMOVITZ, "Resource and Output Trends in the United States since 1870," *A.E.R. Papers and Proceedings* 46 (1956): 5-23.

———, "Catching Up, Forging Ahead, and Falling Behind," *Journal of Economic History* 46 (1968): 385-406.

K.J. ARROW, "Economic Welfare and the Allocation of Resources for Invention," in *Rate and Direction of Inventive Activity*, Princeton, NJ: NBER and Princeton University Press, 1962, 609-25.

M.N. BAILY and A.K. CHAKRABARTI, *Innovation and the Productivity Crisis*, Washington, DC: The Brookings Institution, 1988.

R. BARRO and X. SALA I MARTIN, "Economic Growth across States and Regions," *Brookings Papers on Economic Activity* (1991), 107-58.

R. CORNES and T. SANDLER, *The Theory of Externalities, Public Goods, and Club Goods*, Cambridge, England: Cambridge University Press, 1986.

M. GIBBONS AND R. JOHNSTON, "The Roles of Science in Technological Innovation," *Research Policy* 3 (1974).

Z. GRILICHES, "Research Costs and Social Returns: Hybrid Corn and Related Innovations," *Journal of Political Economy* 66 (1958): 419-31.

———, "The Search for R&D Spillovers," *Scandinavian Journal of Economics* 94 (1992): S29-47.

———, "Productivity, R&D, and the Data Constraint," *American Economic Review* 84 (1994): 1-23.

D.W. JORGENSON, F. GOLLOP, and B. FRAUMENI, *Productivity and U.S. Economic Growth*, Cambridge, MA: Harvard University Press, 1987.

LILY E. KAY, *The Molecular Visions of Life*, Oxford: Oxford University Press, 1993.

DJ. KEVLES, *The Physicists*, New York: Vantage Books, 1979.

A.K. KLEVORICK, R.C. LEVIN, R.R. NELSON, and S.G. WINTER, (forthcoming), *Research Policy*.