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Contribution of R&D to Economic Growth in the United States

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Technological change is clearly an important factor in economic growth, both in the United States and in other countries, both now and in the past. In recent years—after neglecting the study of technological change for a long time—economists have shown a considerable interest in examining the relationship between research and development (R & D), on the one hand, and the rate of economic growth and productivity increase, on the other. In addition, there have been a number of discussions of whether we, as a nation, are underinvesting in certain kinds of R & D. In this article I describe briefly what we know—or think we know—about the relationship between R&D and economic growth and productivity increase. Also, some attention is devoted to the question of whether there may be an underinvestment in R & D. Finally, I try to indicate the trustworthiness and accuracy of existing findings, and suggest areas in which more research is needed.

At the outset, two important points should be noted. First, by focusing attention on the economic effects of R&D, I am not implying that only these effects of R&D are important. On the contrary, increased knowledge is clearly of great importance above and beyond its strictly economic benefits. Second, by looking at our nation's rate of economic growth and productivity increase, I am not assuming explicitly or implicitly that economic growth is, in some simple sense, what public policy should attempt to maximize. Clearly, the desirability of a particular growth rate depends on the way it is achieved, how the extra production is distributed, how growth is measured, and many other things.

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R & D and Economic Growth

The pioneering studies of the relationship between technological change and economic growth—by Solow (*1*), Abramowitz (*2*), and Fabricant (*3*)—occurred in the mid-1950's. In many respects, Solow's paper was most influential. Assuming that there were constant returns to scale, that capital and labor were paid their marginal products, and that technological change was neutral, Solow attempted to estimate the rate of technological change for the nonfarm American economy during the period from 1909 to 1949. His findings suggested that, for the period as a whole, the average rate of technological change was about 1.5 percent per year. More precisely, the output that could be derived from a fixed amount of inputs increased at about 1.5 percent per year.

Based on these findings, he concluded that about 90 percent of the increase in output per capita during this period was attributable to technological change, whereas only a minor proportion of the increase was due to increases in the amount of capital employed per worker. This conclusion received a great deal of attention—and caused some consternation among economists who had focused much more attention on the factors underlying the amount of capital employed per worker than on those underlying the rate of technological change. A flurry of papers followed Solow's, each modifying his techniques slightly or using a somewhat different data base.

After the first wave of papers in the mid-1950's, investigators began to feel increasingly uneasy about the basic methodology used in these studies. In essence, this methodology was the following. Economists, who view the total output of the economy as being due to various inputs of productive services into the productive process, began by specifying these inputs as labor and capital and by attempting to estimate the contribution of these inputs to the measured growth of output. Then, whatever portion of the measured growth of output that could not be explained by these inputs was attributed to technological change. The crudeness of this procedure is obvious. Since the effect of technological change is equated with whatever increase in output is unexplained by other inputs, the resulting measure of the effect of technological change does not isolate the effects of technological change alone. It also contains the effects of whatever inputs are excluded—which, depending on the study, may be economies of scale, improved allocation of resources, changes in product mix, increases in education, or improved health and nutrition of workers.

To remedy some of these limitations, a number of additional studies were carried out in the early 1960's, the most comprehensive and influential one being by Denison (*4*). Denison attempted to include many inputs—particularly changes in labor quality associated with increases in schooling—that had been omitted, largely or completely, in earlier studies. Since it was relatively comprehensive, his study resulted in a relatively low residual increase in output unexplained by the inputs included. Specifically, Denison concluded that the "advance of knowledge"—his term for the residual—was responsible for about 40 percent of the total increase in national income per person employed during 1929–1957.

Of course, technological change can stem from sources other than organized R & D, as evidenced by the findings of Jewkes *et al.* (*5*) concerning the importance of independent investors as a source of major inventions, and the findings by Hollander (*6*) and others concerning the importance of technological changes that depend in no significant way on formal R & D. Denison estimates that about one-fifth of the contribution to economic growth of "advance of knowledge" in 1929–1957 can be attributed to organized R & D. But this is the roughest kind of guess, and Denison himself would be the first to admit that this estimate is based largely on conjecture.

Fundamental Problems of Measurement

How firmly based is the current state of the art in this area? In other words, how reliable are the estimates of the contribution of R & D to economic growth in the United States? I have already indicated some of the difficulties present in these estimates. Unfortunately, there are a number of additional problems of a fundamental nature that must be understood as well. First, the measured rates of growth of output on which these estimates are based suffer from a very important defect, particularly for present purposes, because, to a large extent, they fail to give proper credit and weight to improvements in the quality of goods and services produced, and these improvements are an important result of R & D. For example, the growth rate would have been the same whether antibiotics were developed or not, or whether we devoted the resources used to reach the moon to public works. In general, only those changes in technology that reduce the costs of end products already in existence have an effect on measured economic growth. Unfortunately, the measured growth of national income fails to register or indicate the effects on consumer welfare of the increased spectrum of choice arising from the introduction of new products.

Second, the models on which these estimates are based may not take into account the full complexity of the relationships among the various inputs. In particular, as Nelson, Peck, and Kalachek (*7*) have pointed out, if the returns to some input are dependent on the rate of technological change, and if this is not recognized explicitly, some of technology's contribution to economic growth will be attributed incorrectly to other inputs. This may be the case with education, since the returns to education would probably have been less if technological change had occurred at a slower pace. It may also be the case with "the reallocation of resources," a factor sometimes used to explain part of the residual increase in output.

Third, it is not clear how one can get from an estimate of the contribution to economic growth of technological change (or advance of knowledge, in Denison's terms) to an estimate of the contribution to economic growth of R & D. Clearly, there is no reason that these two estimates should be the same; on the contrary, one would expect the latter estimate to be smaller than the former. But the estimate that results from the models discussed above is the former estimate, not the latter—which is the one we want. As pointed out, Denison does make an attempt to derive the latter estimate from the former, and to do so, he is forced to make extremely rough assumptions. To a certain extent, numbers must simply be pulled out of the air.

Fourth, there are difficulties in measuring inputs, the measurement of aggregate capital being a particularly nettlesome problem. Since errors in the measurement of inputs will result in errors in the estimated contribution of these inputs to economic growth, these errors will also be transmitted to, and will affect, the residual unexplained increase in output, which is used to measure the contribution of technological change to economic growth. Also, it is difficult to adjust for quality changes in inputs, and there are problems in constructing proper price deflators. According to Jorgensen and Griliches (*8*), there are important errors of measurement and aggregation in the measures that are ordinarily used, and these errors inflate the residual.

Fifth, difficulties are caused by the fact that much of the nation's R & D is devoted to defense and space purposes. For example, some observers note the tremendous increase in expenditures on R & D in the postwar period and conclude that, because productivity has not risen much faster in this period than it did before the war, the effect of R & D on economic growth must be very small. What these observers forget is that the bulk of the nation's expenditures on R & D has been devoted to defense and space objectives and that the contribution of such expenditures to economic growth may have been limited. Moreover, they fail to realize that improvements in defense and space capability per dollar spent will not show up in measures of output because government output is valued at cost. (Also, they fail to recognize the fact that product improvements and new products often fail to register in output measures and that the effects of R & D often occur with a considerable lag.)

Based on this catalog of problems and limitations, it is clear that the current state of the art in this area is not strong enough to permit very accurate estimates of the contribution of R & D to the economic growth of the United States. At best, the available estimates are rough guidelines. In no sense is this a criticism of the economics profession or of the people working in this area. On the contrary, a great deal of progress has been made since the pioneering ventures into this area a little over a decade ago. Given the small number of people working in this area and the inherent difficulty of the problem, it is hard to see how much more could have been achieved.

R & D and Productivity Increase in Individual Industries

During the late 1950's, important work concerning the rate of productivity increase in various industries was going on at the National Bureau of Economic Research; this project culminated in Kendrick's book (*9*). As part of this work, Terleckyj (*10*) carried out a study of the relationship between an industry's rate of increase of total factor productivity during the period from 1919 to 1953 and various industry characteristics. According to his results, an industry's rate of growth of total factor productivity was related in a statistically significant way to its ratio of R & D expenditures to sales, its rate of change of output level, and the amplitude of its cyclical fluctuations. Specifically, the rate of growth of total factor productivity increased by about 0.5 percent for each tenfold increase in the ratio of

R & D expenditures to sales and by about 1 percent for every 3 percent increase in the industry's growth rate.

Subsequently, two other papers appeared on this topic, one pertaining to agriculture, one pertaining to manufacturing. The agricultural study, by Griliches (*11*), investigated the relationship in various years between output per farm in a given state and the amounts of land, labor, fertilizer, and machinery per farm, as well as average education and expenditures on research and extension in a given state. The results indicate that, holding other inputs constant, output was related in a statistically significant way to the amount spent on research and extension. Moreover, the regression coefficient of this variable remains remarkably stable when cross sections are deleted or added and when the specification of the model is changed somewhat.

The manufacturing study, by Mansfield (*12, 13*) was based on data regarding ten large chemical and petroleum firms and ten manufacturing industries in the postwar period. Both for firms and for industries, the measured rate of productivity change was related in a statistically significant way to the rate of growth of cumulated R & D expenditures made by the firm or industry. The specific form of the relationship depends somewhat on whether technological change is assumed to be disembodied (better methods and organization that improve the efficiency of both old capital and new) or capital embodied (innovations that must be embodied in new equipment if they are to be utilized). When technological change was disembodied, the average effect of a 1 percent increase in the rate of growth of cumulated R & D expenditures was a 0.1 percent increase in the rate of productivity increase. When technological change was capital embodied, it was a 0.7 percent increase in the rate of productivity increase.

In addition, Minasian (*14*) studied the relationship between value added, and labor, capital, and cumulated R&D expenditures in 17 firms in the chemical industry from 1948 to 1957 (*15*). In all but one of the specifications of the model tried by Minasian, a firm's cumulated R & D expenditures are related in a statistically significant way to the firm's value added, holding its labor and capital inputs constant. Moreover, his estimate of the regression coefficient for cumulated R & D expenditures is strikingly close to the result obtained by Mansfield. Thus, the findings of the two studies tend to reinforce one another.

Finally, Brown and Conrad (*16*) carried out a study of the relationship between R & D expenditures (as well as education and other variables) and productivity increase in a number of U.S. manufacturing industries in the postwar period. Their results, published in 1967, indicated that R & D expenditures had a statistically significant effect on the rate of productivity increase. Also, in their judgment, their findings indicate that a given percentage increase in R & D expenditures in durable goods industries produces a substantially larger percentage increase in productivity than does the same percentage increase in R & D expenditures in nondurable goods industries.

Evaluation of Productivity Studies

How reliable are these estimates of the relationship between R & D and productivity increase in individual industries? Clearly, one advantage of these studies is that the effect of R & D is not derived indirectly as a residual. Instead, an industry's—or a firm's or area's—R & D expenditures are introduced as an explicit input in the productive process. Thus, it is possible to obtain explicit relationships between R & D and productivity increase; it is no longer necessary to attribute to technology or R&D whatever cannot be explained by other factors. This is a real advantage.

But a number of important problems remain. First, too little is known about the characteristics of the activities that firms call "research and development." This lack of information has been a hindrance to progress in this area, since, without a reasonable amount of information on this score, it is difficult to interpret or evaluate models relating R & D expenditures to other economic variables. Clearly, if the figures on "research and development" contain routine technical services and other such activities, the estimates based on these figures will be affected. It is difficult to tell how important this problem is, but, for some purposes, I would guess it to be a serious problem.

Second, even if one were sure that R & D figures were reliable, there would still be the possibility of spurious correlation. Firms and industries that spend relatively large amounts on R & D may tend to have managements that are relatively progressive and forward looking. To what extent is the observed relationship between R & D and productivity increase due to this factor rather than to R & D? Obviously, this is difficult to answer because the quality of management is very difficult to measure. Nonetheless, most investigators seem to feel that only a small part of the observed relationship is due to spurious correlation of this sort.

Third, a large percentage of the R & D carried out by many industries is directed at productivity increase in *other* industries. Consequently, relationships between R & D in an industry or firm and productivity increase in the *same* industry or firm catch only part of the effects of R & D. Unfortunately, too little effort has been directed at introducing interindustry or interfirm flows of technology into the sorts of models that underlie these relationships. Also, the estimates that are obtained depend on the extent of the lag between the time that R & D is carried out and the time that the effects of R & D show up in productivity indexes. Clearly, this lag is often substantial. Unfortunately, the models on which these estimates are based often make very crude assumptions concerning the length of the lag.

Fourth, there is a host of technical problems. To what extent is technological change disembodied, and to what extent is it capital embodied? If R & D is treated as investment in new knowledge—as it is in most of these studies—what depreciation rate should be used? Also, there is the perennial problem of how R & D expenditures should be deflated, as well as the problem of the form of the production function that should be used in particular cases. The answer one gives to these questions can have a significant effect on the estimates one obtains (*17*). However, none of these problems is entirely resolved, although some work has been devoted to the deflation problem and to the form of the production function.

Fifth, studies of the relationship between R & D and productivity increase in individual industries suffer, of course, from a number of the same problems that beset studies of the contribution of R & D to economic growth. Some of these problems are inadequacies of the output measures used, poor specification of the relationship among inputs, and difficulties in measuring inputs.

Based on this discussion of the problems in the existing estimates of the relationship between R & D and productivity increase in individual industries, it is clear that the current state of the art in this area is not strong enough to permit definitive estimation of these relationships. Nonetheless, although the results are subject to considerable error, they establish certain broad conclusions. In particular, existing econometric studies do provide reasonably persuasive evidence that R & D has a significant effect on the rate of productivity increase in the industries and time periods that have been studied.

Externalities, Riskiness, and Investment in R & D

At this point, I turn to the question of whether or not, from a purely economic point of view, the United States is underinvesting in R & D. Certain propositions bearing on this question are widely accepted by economists and should be set forth at the beginning of this discussion. The first proposition is that, because the results of research are often of little direct value to the sponsoring firm but of great value to other firms, there is good reason to believe that, left to its own devices, the market would allocate too few resources to R & D—and that the shortfall would be particularly great at the more basic end of the R & D spectrum. The reason for this is fairly obvious: the market operates on the principle that the benefits go to the person bearing the costs, and vice versa. If a firm or individual takes an action that contributes to society's welfare, but it cannot appropriate the full gain, then it obviously is less likely to take this action than would be socially desirable.

The second proposition is that, because R & D is risky for the individual firm, there is good reason to believe that the market, left to its own devices, would allocate too few resources to R & D. Of course, the risk to the individual investor in R & D is greater than the risk to society, since the results of the R & D may be useful to someone else, not to himself, and he may be unable to obtain from the user the full value of the information. Because the economic system has limited and imperfect ways of shifting risks, there would be an underinvestment in R & D. For this reason, too, one would expect the underinvestment to be greatest at the more basic end of the R & D spectrum (*18*).

These defects of the market mechanism in allocating resources to R & D have long been recognized. For example, Pigou set some of them forth quite clearly in the 1920's (*19*). Moreover, they have been recognized in the realm of practical affairs and of social organization, as well as in the realm of social science. Our society, taking account of these defects of the market mechanism, does not depend exclusively on the market for an investment in R & D. On the contrary, a very large proportion of the nation's expenditures on R & D stems from government agencies, private foundations, and universities, all of which supplement the R & D supported through the market mechanism. Thus, the relevant question is not whether the market mechanism requires supplementing, but whether the type and extent of supplementary support provided at present is too large or too small, and whether it is allocated properly.

Salient Characteristics of the Nation's Investment in R & D

Before discussing the above question, several important characteristics of the nation's investment in R & D must be noted. First, as is well known, the nation's investment in R & D is focused very strongly on defense and space technology. During the early 1960's, over 55 percent of the nation's R & D expenditures were for these purposes. With the passage of time, this percentage has decreased, but even in 1970, about 43 percent of the nation's investment in R & D was for these purposes (*20*). The relevance to economic growth of much of this huge investment in defense and space R & D has been questioned by many economists.

Numerous groups within the government—an early example being the White House Panel on Civilian Technology—have been interested in the extent of the benefits to civilian technology —the "spillover" or "fallout"—from military and space R & D. Obviously, the extent of this spillover has implications regarding the extent to which the investment in defense and space R & D has relevance for economic growth. It is perfectly clear that the value of the spillover that has occurred in the past has been substantial—the computer, numerical control, integrated circuits, atomic energy, and many other significant advances having stemmed at least partly from military R & D. However, it is also clear that the contribution of a dollar of military and space R & D to economic growth is considerably less than the contribution of a dollar of civilian R & D. Moreover, in the opinion of some observers, the spillover per dollar of military-space R & D is unlikely to be as great as it was in the past, because the capabilities that are being developed and the environment that is being explored are less closely connected with civilian pursuits than they were in the past.

Second, just as the government's expenditures on R & D are concentrated largely in a few agencies (the Department of Defense, the National Aeronautics and Space Administration, and the Atomic Energy Commission) with defense and space missions, so industry's expenditures on R & D are concentrated in a few industries. In 1969, 82 percent of all industrial R & D expenditures took place in only five industries—aerospace, electrical equipment and communication, chemicals (including drugs), machinery, and motor vehicles. Of course, this concentration is due in part to the fact that these industries perform a great deal of R & D for the federal government. But if one looks only at company-financed R & D, the concentration is nearly the same, with these five industries accounting in 1969 for 75 percent of all company-financed R & D expenditures. Moreover, this concentration seems to be increasing (*21*).

Industry's R & D expenditures are also concentrated largely on products, not processes. For example, according to a survey of business firms carried out in the early 1960's, about 47 percent of the firms reported that their main purpose was to develop new products, and about 40 percent reported that it was to improve existing products: only 13 percent reported that it was to develop new processes (*22*). However, lest there be any misunderstanding, it should be recognized that one industry's products may be part of another industry's processes. Thus, when a machinery producer improves its products or when a chemical producer improves its products, the result may be an improvement in the processes of industries that buy and use the machinery or chemicals.

Third, this nation's investment in R & D is focused very strongly on development, not research. The distinction between research and development, although hazy and indistinct in some cases, is important. Research is aimed primarily at the search for new knowledge, whereas development is aimed at the reduction of research findings to practice. In 1970, according to estimates made by the National Science Foundation, about two-thirds of the nation's investment in R & D went for development, only about one-third for research (*20*, p. 7). Much of the development work carried out by industry and government is aimed at very specific objectives and involves large expenditures on prototypes and pilot plants. It is important to avoid the (unfortunately common) mistake of confusing this activity with research.

Moreover, it is important to recognize that much of the R & D carried out by industry is aimed at fairly modest advances in the state of the art. Studies carried out by Hamberg (*23*), Jewkes *et al.* (*5*), and others seem to indicate that the really major inventions seldom stem from industrial laboratories of major firms, which are primarily contributors of minor "improvement" inventions. Also, surveys indicate that firms emphasize relatively short payout periods for R & D, this emphasis being another indication that most R & D carried out by the responding firms is aimed at improvements or minor changes in existing products (*22*). In addition, detailed studies of the characteristics of the R & D portfolio of a number of industrial laboratories by Mansfield (*13*, *24*), Meadows (*25*) and others provide direct evidence that the bulk of the work involves rather small technical risks.

Recent Judgments on the Adequacy of the Nation's Investment in R & D

Is the type and extent of R & D support that society presently uses to supplement the market mechanism adequate from an economic point of view, and is this support allocated properly? In recent years, there have been several discussions of this question, each carried out by people who have devoted considerable time and energy to this task. I will summarize their views and then discuss the evidence underlying their conclusions.

In 1963, the Organisation for Economic Co-operation and Development (OECD) published a report by Freeman, Poignant, and Svennilson which concluded, "It seems therefore inherently improbable that the scale on which governments supplement civil R & D in sectors other than atomic energy is anything like sufficient to attain the optimum" (*26*). In their view, "in spite of all the factors which concur to increase the level of R & D activity, there are serious reasons for believing that this level is in many cases inadequate for sustained and rapid economic growth" (*26*, p. 35). In 1964, the U.S. Council for Economic Advisors sounded a similar note when they stated that "in a number of industries the amount of organized private research undertaken is insignificant, and the technology of many of these low-research industries has notably failed to keep pace with advances elsewhere in the economy" (*27*).

In 1966, the President's Commission on Technology, Automation, and Economic Progress concluded that too little was being spent by the government on R & D in the fields of urban transportation, pollution control, and housing. For example, on housing the commission stated: "As it has in agriculture, the Federal Government should actively stimulate research in housing and community development through research grants and through its own building activities. It should also support basic research to establish performance criteria (e.g., moisture resistance, insulation, lighting, etc.) for housing and housing components" (*28*).

In 1967, Nelson, Peck, and Kalachek, summarizing a 2-year study of this question, concluded that there were several important areas where there existed a significant degree of market failure which was not remedied adequately by government programs. They suggested that a national institute of technology be established to provide grants for R & D aimed at placing the technology of various industries on a stronger scientific base and to test the feasibility and desirability of advanced designs. In their view, work of this sort, which falls between basic research and product development, is in need of additional support. In cases where a broad-scale systems view is needed but is prevented by the smallness of firms and fragmentation of markets, the institute would support work through the middle and later stages of development (*7*, p. 177).

At about the same time, Capron, formerly assistant director of the Bureau of the Budget, stated: "My own view on this is that we can say nothing with much confidence on theoretical grounds about the social adequacy of our total R & D effort—though my hunch is that as a nation we are underinvesting in R & D over all. However, I think we can say with assurance that the existence of noncompetitive elements and sectors of the economy produces a misallocation of resources within the R&D total" (*29*). Specifically, it is Capron's view that too large a fraction of the total R & D effort is spent in oligopolistic industries and on relatively modest improvements, too little being spent in more competitive industries and on more far-reaching work.

Nature of the Evidence

I have summarized briefly the conclusions of a number of economists who have been concerned with the question of whether or not the R & D support that society presently gives to supplement the market mechanism is adequate in total and allocated properly. They generally seem to be of the opinion that the nation's investment in R & D may be too small, but this opinion is often characterized as little more than a hunch. They are much more confident, it appears, that, whether or not the total investment in R & D is too small, the investment is not properly allocated, there being too little R & D devoted to (i) more ambitious attempts to place the technology of various industries on a stronger scientific base (Nelson, Peck, and Kalachek), (ii) urban transportation, pollution control, and housing (Automation Commission), and (iii) more competitive and fragmented industries (Capron). Or, more precisely, this is what they believed at the time they expressed their views in print.

What sorts of evidence are these conclusions based on? First, some of these studies rely largely on judgment combined with economic theory. For example, Nelson, Peck, and Kalachek, who lean heavily on this kind of support, believe that (*7*, pp. 172–173):

> While the present state of knowledge is not strong enough to permit derivation of quantitative rates of return, or optimal allocations of resources, it is strong enough to suggest that for certain kinds of activities there are serious market imperfections. . . . When there are significant external economies, unsupplemented private initiative is unlikely to support work to the extent that is socially optimal. Where government policies already exist

which provide added incentive or reduce private costs, or which supplement effort directly, it is difficult to say whether the latent tendency toward underallocation of private effort has been compensated. However, where policies do not exist, where incentive modifications appear minor relative to the gap between private and social returns, or where direct supplements appear small relative to the scope of socially desirable work (clearly a matter of judgment), a presumption exists that further allocation of resources would yield a higher than average rate of return, and that government policies to achieve such an expansion are in the public interest.

Second, these studies rely on the results of several econometric investigations which indicate that, for the industries and fields under investigation, the marginal rate of return from an investment in R&D has been very high. One of the first studies of this kind was Griliches' study of the returns from agricultural R&D (*30*). He found that the rate of return from the investment in agricultural research between 1937 and 1951 in the United States was between 35 and 170 percent. For two very successful projects—hybrid corn and hybrid sorghum—the rate of return on the investment was several hundred percent (but these two projects are obviously far from representative). Subsequently Griliches (*11*) estimated that the gross social rate of return to research (and extension) expenditures was about 300 percent—a figure that he regarded as being quite consistent with his estimate of 35 to 170 percent net social rate of return to agricultural research, based on different data and a different approach (*31*).

For manufacturing, Mansfield (*12*) and Minasian (*14*) estimated the marginal rate of return from R&D in the chemical and petroleum industries. Mansfield's results indicated that the marginal rate of return was about 40 percent or more in the petroleum industry, and about 30 percent in the chemical industry, if technological change were capital embodied (but much less if it were disembodied). Minasian's results indicated about a 50 percent marginal rate of return on investment in R&D in the chemical industry. In addition, Mansfield provided some evidence that the marginal rate of return seemed relatively high (15 percent or more) in the food, apparel, and furniture industries.

Finally, based on computations for the economy as a whole, Denison (*4*) concluded that the rate of return from R&D was about the same as the rate of return from investment in capital goods. His estimate of the returns from R&D was lower than the estimates of other investigators, perhaps because he assumed no lag between R&D expenditures and their contribution to economic growth. The calculated rate of return on R&D could be much higher if R&D's contribution occurred only with a lag (*32*). In his 1969 presidential address to the American Economic Association, Fellner (*33*) estimated the average social rate of return from technological-progress activities and concluded that it is "substantially in excess" of 13 or 18 percent, depending on the cost base, and that this is much higher than the marginal rate of return from physical investment at a more or less given level of knowledge.

Evaluation of the Evidence

How conclusive is the evidence described above? First, consider the judgmental approach adopted by Nelson, Peck, and Kalachek, among others. Clearly, this approach, although sensible and frequently used in all fields, is limited by the large subjective component that inevitably must enter the calculations. It is very difficult to estimate the extent of the external economies arising from particular types of R&D, or to determine whether incentive modifications are small relative to the gap between private and social returns, or to tell whether supplementary R&D provided by government and nonprofit institutions is small relative to the scope of socially desirable work. The weight one places on this evidence must depend on the confidence one puts in the judgment and objectivity of the investigators (*34*).

Second, consider the econometric approach adopted by Griliches, Mansfield, and others. This approach is more objective in many respects. Certainly the assumptions underlying the estimates are specified clearly, and one can see how sensitive the results are to changes in these assumptions. But this does not mean that the results can be accepted uncritically. On the contrary, since most of these estimates depend on, and are derived from, the studies of R&D and productivity growth in individual industries, they are subject to many of the limitations of these studies. The seriousness of these limitations has been stressed earlier, and should be stressed again (*35*). In addition, practically all of these econometric studies were carried out several years ago, and the estimates generally pertain to the late 1950's or early 1960's. It is by no means clear that the results would be different today, but, of course, one cannot rule out that possibility. In addition, some of these studies try to measure the social returns from R&D, while others measure only the private returns to R&D (and perhaps part of the social returns not included in the private returns).

Yet, having taken pains to point out the limitations of the individual bits of evidence that have been amassed, we must not lose sight of an impressive fact: no matter which of the available studies one looks at [other than Denison's (*36*)], the conclusions seem to point in the same direction. In the case of those using the judgmental approach, there is considerable agreement that we may be underinvesting in particular types of R&D in the civilian sector of the economy. In the case of the econometric studies, every study of which I am aware indicates that the rate of return from additional R&D in the civilian sector is very high.

Needed Research concerning R&D

I have indicated that, although considerable progress has been made in the last decade in furthering understanding of the relations between R&D and economic growth and productivity increase, existing knowledge is too weak to permit very confident or definitive statements concerning these relations. Although existing knowledge may be of some use in formulating public policy in this area, it is limited by many serious problems and can only be regarded as tentative. Given that this is the case, what steps might be taken to further knowledge in this area? In addressing myself to this question, I will first describe the needed research concerning R&D, then the needed research concerning the process of technological change, and finally the needed research concerning economic growth and productivity increase. Needless to say, I shall have to be selective, and my choice of topics will probably be influenced by my own biases.

With regard to R&D, there are at least six important areas that are in need of considerable additional research.

1) Much more information is needed concerning exactly what is included

as R & D in various industries. It is perfectly clear that without such information it will be impossible to interpret relations—or lack of relations—between measured R & D and other economic variables with any real confidence. What proportion of R & D, as measured by the customary figures, is routine service work? What proportion is aimed at fairly certain, and modest, design improvements? My co-workers and I have made detailed studies of the characteristics of the R & D portfolios of a sample of firms in the chemical, petroleum, and electrical equipment industries (*37*). But this work is only a beginning. Work is also needed to provide better price indexes for R & D in particular industries, so that it will be possible to compare more accurately expenditure data at various times. Some work has been done on this score too (*38*), but much more needs to be done. In addition, attempts should be made to develop measures of inventive effort that include the work of independent inventors and that are comparable for both large and small firms.

2) Given more detailed breakdowns of R & D in various industries, it is important to disaggregate R & D in the models used to relate R & D to economic growth and productivity increase. On the basis of existing work, it is perfectly clear that R & D expenditures include outlays on activities of quite different sorts, which would be expected to have quite different effects on productivity. Although it was reasonable to use total R & D expenditures in earlier studies, an attempt should now be made to go beyond this crude beginning. After all, some of the most interesting questions in this area relate to the returns from various kinds of R&D—R&D directed at small product improvements, R&D directed at more major inventions, and so on. Unless we disaggregate R & D, such questions cannot be answered.

3) We need more information about the expected profitability and risk attached to the R & D portfolios of particular laboratories and firms, as well as more data concerning the decision-making process with regard to project selection and the allocation of R & D funds in various laboratories and firms. Such information would allow a determination of the extent to which firms are risk-averters and a study of the social implications of the decision rules employed, explicitly or implicitly, by the firms. My co-workers and I have made a number of such studies (*37, 39*), but they pertain to only a small sample of laboratories. Since studies of this sort must utilize detailed data that can only be derived from intensive work with individual firms, progress in this area depends on researchers' being willing to immerse themselves in the operation of individual laboratories.

4) We need more information concerning economies of scale in particular types of R & D. There are numerous reasons for thinking that there are economies of scale in R&D up to some point—"lumpiness" of capital equipment used in R & D, advantages from specialization of labor, reduction of risks due to the law of large numbers, and so forth. However, we know very little—industry by industry—about the extent of these economies of scale for particular kinds of work or about the size of R & D establishment beyond which further increases in size bring little or nothing in the way of further efficiency for the type of work in question. Freeman (*40*) has shed some light on this subject in the electronics industry, but it is still largely unexplored. This is very unfortunate, since the returns derived from a certain expenditure on R & D—and the socially optimal organization of R & D—will depend on these economies of scale.

5) We need more information concerning the conditions and mechanisms leading to the application of basic science and its translation into new products and processes. According to recent studies (*41*), the United States has been more adept than Western Europe at the application and translation of the findings of basic science into economically significant innovations. What are the reasons for this superiority, if indeed it exists? What is the mechanism in various areas leading to the translation of new basic science into technology? These are important questions, and ones about which little is known—although the TRACES study (*42*) provides some relevant and significant information. To appreciate the importance of these questions, it should be noted that the country that does the basic scientific work in a particular area may not be the one that reaps the greatest economic benefits from the technological innovations in that particular area. The extent of the economic benefits from fundamental research depends on the facility and efficiency with which the results of fundamental research are applied. Fortunately, according to the OECD studies, the United States seems to have been relatively adept at the application of fundamental research, the consequence being that the economic returns from basic research have probably been relatively high in the United States. But why has this been the case, and can we be sure it will continue to be the case in the future?

6) We need more information concerning the coupling of industrial R & D with marketing and production. Industrial R & D can have little economic impact unless it is applied. And the difficulties in bridging the gap between R & D, on the one hand, and marketing and production, on the other hand, are greater than is usually recognized. Systematic, in-depth studies of the problems in this area—and the ways in which industry has attempted to solve these problems—would be of considerable use. It is high time to begin to build this aspect of the R & D process into models relating R & D expenditures to productivity increase and economic growth. Also, it should be recognized that a large part of the riskiness of industrial R & D is due to commercial, not technical, uncertainty. For example, recent studies indicate that the probability of a firm's solving the technical problems involved in the typical R & D project is much greater than its turning out to be economically justified in having gone to the trouble and expense of solving them (*37, 43*). If this is indeed the case, it raises questions concerning the extent to which there is proper coordination between the R & D people, on the one hand, and the marketing and production people, on the other. Detailed and intensive studies should be carried out to shed light on this question, which has received limited—and often superficial—treatment in the past.

Needed Research concerning the Process of Technological Change

In addition, considerable research is needed to promote fuller understanding of the process of technological change.

1) We need to know much more concerning the role of R & D in the entire process of technological innovation. Until a few years ago, there was a tendency to equate R & D with innovation, the consequence being that the non-R & D activities associated with innovation were neglected. It now seems that the non-R & D aspects of innovation—tooling and construction of plant,

manufacturing start-up, marketing start-up, and so on—frequently account for as large a proportion of the total costs of a successful product innovation as does R & D (*37, 44*). We must recognize the importance of these non-R & D prerequisites to innovation in models of technological change. Also, it is important to learn more about the areas in which—and conditions under which—little or no formal R & D is required for innovation. Studies by Myers and Marquis (*45*), as well as others, show quite clearly that many innovations require little in the way of formal R & D. We need to know more about the origin, type, significance, and frequency of such innovations in a variety of industries.

2) Studies are needed of the conditions that promote or thwart the rapid conversion of an invention into an innovation, given that market and technical factors make such a conversion socially desirable. According to recent OECD studies (*46*), American firms are much more adept at achieving such a conversion than are Western European firms. In the United States, there is some evidence (*47*), albeit crude, that firms are achieving such a conversion more rapidly than they did in the past. But existing information tells us far too little. To what extent does an industry's market structure determine the average rate of conversion? To what extent do problems of interindustry and interfirm coordination lessen the average rate of conversion? Does the use of various management techniques that are currently in vogue have a perceptible or demonstrable effect? What are the characteristics of the managers and managements that seem to perform best in this regard?

3) We need to know much more about the sources of invention and innovation in various industries. With regard to invention, what has been the relative importance of independent inventors, small firms, large firms, universities, and so on, as sources of significant inventions in particular industries? The studies by Jewkes, Sawers, and Stillerman (*5*), Hamberg (*23*), Enos (*48*), and others are valuable, but there is a need for much more empirical work of this sort. Moreover, with regard to innovation, what has been the relative importance of firms of various kinds—large, small, conglomerate, single product, and so on—in particular industries? My co-workers and I have tried to provide data (*13, 37*) for a handful of industries—petroleum, steel, coal, ethical drugs. Attempts should be made to identify the firms that pioneered in the introduction of important new processes and products in other industries. Such information is needed if we are to obtain a better understanding of the factors and conditions conducive to invention and innovation and the relative efficiency and creativity of various kinds of organizations.

4) Studies are needed of the effects of market structure on an industry's rate of technological change. What is the effect of market structure on the amount spent by an industry on R & D and other innovative activities, the sort of R & D and other innovative activities carried out, the productivity of the industry's R & D, the quickness of the firms to innovate, and the rate of acceptance of new techniques and products (both those arising within and those arising outside the industry)? To what extent are giant firms in various industries required to ensure a rapid rate of technological change? These are extremely important questions. For some time, I—and a number of other economists—have been trying to gain a better understanding of them, but we are far from having trustworthy answers to these questions (*49*).

5) We need to know much more about the factors influencing the rate of diffusion of innovations. Mansfield and Griliches have formulated models of the diffusion process and obtained detailed data concerning the diffusion of a number of important innovations in manufacturing and agriculture (*13, 50*). These models have been used by Mansfield (*51*) and others for technological forecasting. However, existing data pertain to only a handful of industries, and much more work of theoretical and econometric sorts is needed. We also need to know much more about the mechanism and costs of transferring technology from organization to organization and from country to country. Although a 1966 conference (*52*) sponsored jointly by NSF and the National Planning Association helped to clarify some aspects of this topic, a great deal of work remains to be done. Theoretical work—such as that done by Arrow (*53*)—and detailed empirical work—such as Hall and Johnson's study (*54*) of the transfer of the production of the F-104 to Japan—is needed.

6) It seems to me that much more information and work is needed to measure more accurately the "spillover" to civilian technology from military and space R & D. I realize that an enormous amount of verbiage and papers of dubious distinction have been produced on this topic, but, as far as I know, the amount of penetrating, quantitative, objective analysis has been surprisingly limited (*55*). In view of the great importance of this question, more should be done. In addition, attempts should be made to study and evaluate various approaches designed to increase such "spillover." For example, NASA has adopted a number of approaches in its work with Midwest Research Institute, the Aerospace Research Applications Center at Indiana University, the University of Maryland, and other places. It would be extremely valuable to find out what the experience of these groups can teach us about the relative cost and effectiveness of various approaches.

Needed Research on Economic Growth and Productivity Increase

Considerable research is needed to promote a fuller understanding of the process of economic growth and productivity increase.

1) We need to improve the measures of output on which the productivity statistics depend. As noted previously, existing measures of output do not record the effects of the introduction of new or improved products. This is a very important limitation. Some very competent observers, for example, the Price Statistics Review Committee, have recommended that the government experiment with price series that allow, even roughly, for product improvement. More might be done along this line. Also, measures such as gross national product do not recognize the social costs—pollution, accidents, and so on—arising from technological changes. To the extent that these costs are borne by government, not industry, they are counted as end products of a positive sort. Economists are becoming increasingly aware of this problem, but more should be done.

2) Better information of other kinds is needed as input to studies of the rate of productivity increase and technological change. For one thing, the price indexes used to deflate construction expenditures are questionable; indeed, they seem to be cost, not price, indexes (*56*). There are problems in adjusting capital inputs for the extent of

capacity utilization (and better estimates of the elasticity of substitution are needed). Obviously, errors from these sources can result in errors in the estimated rates of growth of capital and labor, which in turn can result in errors in productivity estimates. Turning to a different, but related topic, we need studies of the rate of technological change in various sectors of the economy that make greater use of engineering data and experience. For various reasons, economists, with some notable exceptions, have tended to avoid using engineering estimates. Here is a place where interdisciplinary work is badly needed. Also, it is extremely important that we develop better measures of the rate of productivity increase—and of the determinants of the rate of productivity increase—in the service sector of the economy.

3) We need a better understanding of the complex interrelationships among R & D, education, management, and capital formation in the process of economic growth. For example, consider the relationship between R&D and education. In most economic models, the contribution of education is perfectly straightforward: more educated workers are able to produce more than are less educated workers. As far as it goes, no one can take issue with this hypothesis. Nonetheless, the hypothesis may result in a misspecification of these models because it oversimplifies the relationship between education and economic growth (*7*). In part, the effect of education on economic growth depends on the rate of technological change, since an important effect of more education is to make managers and workers more adaptable to change and quicker to adopt innovations. Moreover, an investment in education of certain kinds is likely to increase the rate of technological change. For these and other reasons, the relations among these variables are richer and more complex than they are pictured in most contemporary economic models. We must learn more about the nature of these relationships and formulate models accordingly.

4) (A point that is related to the previous one), we should learn more about the extent to which technological change in various industries has been capital embodied or disembodied. That is, attempts should be made to estimate the extent to which new techniques and products in various industries in recent years have required new plant and equipment, the extent to which they could be "grafted" onto old plant and equipment and the cost of doing so, and the extent to which they can be accommodated or used without altering existing plant and equipment (*57*). Also, much more should be known about the process of "learning by doing" (*58*). These questions are important because the effects of capital formation on economic growth—and the extent to which utilization of new technology requires capital formation—depend on them.

5) In models designed to relate R&D to productivity increase in particular sectors of the economy, a better account should be taken of interindustry—and in some cases, interfirm—flows of technology. Specifically, we must take more realistic account of the fact that R & D in one firm or industrial sector often increases productivity in another firm or industrial sector. Some progress has been made in incorporating this fact into economic models, the study by Brown and Conrad (*16*) being a beginning. But much more must be done. Unless we learn how to do this more effectively, our estimates of the effects of R & D cannot help but be very crude.

6) We need to extend many kinds of studies of productivity increase to a larger number of countries. In many areas, we lack reliable data for countries other than the United States. For example, according to a recent OECD study (*46*), the rate of economic growth in the member countries is closely correlated with their performance in the diffusion of technological innovations. Yet very little is known about the diffusion process in countries other than the United States. A study is now under way to compare the rate of diffusion of selected innovations in various countries, but this study is only a beginning (*59*). Although there are many pitfalls in international comparisons, they obviously can be helpful, if carried out carefully, in disclosing the factors influencing diffusion rates.

In passing, it may be worthwhile to mention a few of the common pitfalls in international comparisons. For present purposes, perhaps the most important thing to note is that one cannot conclude that the returns from R&D in the United States are small because some countries that have invested a fair amount in R & D have relatively low growth rates, and some countries that have invested little in R&D have relatively high growth rates. Many factors other than R & D affect economic growth and should be taken into account in any such comparisons (*60*). Moreover, the fact that some countries spend much more than others on defense and space R & D should be taken into account—together with the fact that many important effects of R & D on true economic growth are not reflected in measured growth rates. Further, some countries that have not invested heavily in R & D have nonetheless achieved high rates of technological change by importing technology and by imitating and catching up with the technological leaders. Obviously, the technological leaders cannot achieve high rates of technological change in this way. Furthermore, some countries that have invested relatively large amounts in R&D have not been as efficient in converting the results of their R & D into innovation as the United States has. Thus, the returns from R&D in these countries may be a poor guide to returns in the United States.

Conclusions

Technological change has certainly contributed in a very important way to economic growth in the United States. Although existing studies have not been able to estimate this contribution with great accuracy, they have certainly indicated that this contribution has been large. Moreover, although econometric studies of the relationship between R & D and productivity increase have been subject to many limitations, they provide reasonably persuasive evidence that R&D has an important effect on productivity increase in the industries and time periods that have been studied. Turning to the adequacy of the nation's investment in R&D, there is too little evidence to support a very confident judgment as to whether or not we are underinvesting in certain types of R&D. However, practically all of the studies addressed to this question seem to conclude, with varying degrees of confidence, that we may be underinvesting in particular types of R&D in the civilian sector of the economy, and the estimated marginal rates of return from certain types of civilian R & D seem very high. Additional research is badly needed to determine more adequately the relationship of R & D to economic growth. I have indicated a number of specific areas where work is needed.

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