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ABSTRACT

In recent years economists have attempted to estimate the private and social rates of return from investments in education. Another area that must be considered is the effect of education on the rate of technological change and on capital formation. Still another factor that must be taken into account is the organization of education and research and development (R&D). Because education contributes to economic growth by influencing the rate of diffusion of innovations and because American educational institutions influence the diffusion process directly as well as via their students, government and industry must cooperate to develop R&D efforts that focus on future demands and training programs for researchers and scientists. Among the types of studies that are particularly needed are the following: econometric productivity studies that include education; investigations of the educational level of inventors; examinations of the effect of educational levels on the nature and shape of learning curves; analyses of the relationship between the educational level and speed of response to innovations; and constructions of simple mathematical models relating educational levels, the rate of diffusion of new technology, and the rate of economic growth. (This analysis is one in a series on the relationship between education and productivity.) (MN)

EDUCATION, R AND D, AND PRODUCTIVITY GROWTH

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1. Introduction

In this paper, commissioned by the National Institute of Education, I have been asked to address the following questions: (1) Does education affect productivity growth apart from its effects on the quality of the labor force? (2) Does education have large and potentially measurable external economies not captured through wages and salaries? (3) What changes in the organization of R and D activities — including the ways in which R and D is linked to user organizations, universities, and the government — might increase the impact of R and D on productivity growth? (4) Are prospective supplies of research scientists, engineers, and technicians sufficient so that productivity growth will not be greatly hampered by personnel "shortages"? (5) To what degree is there cooperation and/or competition between private industry, universities, and government in the provision of R and D and the employment and training of researchers?

At the outset, it should be recognized that my treatment of these questions must be brief and selective. In the available space, I can only describe cursorily some of the relevant facts and models, summarize some of the salient work carried out to date, indicate some major methodological problems, and sketch out a half-dozen types of research that seem feasible and worthwhile. The purpose of this paper is to discuss the existing state of the art in this area and how it can be improved through future research, not to carry out such research. Sections 2-3 take up the measured returns from education and education's effects on the quality of labor input, as well as its external effects. Sections 4-6 discuss the interrelationships between education, R and D, and capital formation in the process of economic growth, as well as the importance of the organization of education and R and D. Sections 7-9 deal with education's effects on the diffusion of innovations; Sections 10-12 take up the supply of scientists and engineers; and Sections 13-14 deal with the cooperation and competition between various sectors of the economy with regard to R and D and the supply of manpower. Sections 15-20 suggest six types of research that, in my opinion, seem worthy of consideration. Section 21 provides some concluding remarks.

2. Rates of Return and External Effects of Education

In recent years, economists, following the lead of Theodore Schultz, Gary Becker, and others, have attempted to estimate the private and social rates of return from investments in education. Studies pertaining to the 1950s and early 1960s generally found that the private rate of return was relatively high. (For example, see Table 1.) But with regard to the market for college graduates, there seemed to be a notable change in the late 1960s. The large increase in college enrollments added to supply, while a leveling off of the upward trend in some professional and managerial jobs resulted in a less than proportional increase in demand. Richard Freeman has estimated that the private rate of return to B.A. training fell from 11.5 percent in 1969 to 8.5 percent in 1974. (See Table 2.)[1]

Of course, social rates of return can be quite different from private rates of return. Because students and their families pay only part of the social costs of education, the social rates of return may be below the private rates. (For example, see Tables 1 and 2.) The difference may be larger in countries where higher education is more heavily subsidized than in the United

Table 1 -- Private and Social Rates of Return from Investment in Schooling, White Males, U.S., 1959

Level of Education	Marginal private return	Marginal social return
Eighth-grade education	48.7%	19.8%
One to three years of high school	25.4	16.9
High school graduation	14.5	11.3
One to three years of college	12.1	8.3
College graduation	15.1	11.0

Source: Fred Hines, et al., "Social and Private Rates of Return to Investment in Schooling by Race-Sex Groups and Regions," Journal of Human Resources (Summer 1970).

Table 2 -- Social and Private Rates of Return from College Training, Males, 1959-74

Year	Social Rate of Return	Private Rate of Return
1959	10.5%	11.0%
1969	11.1	11.5
1972	9.5	10.5
1974	7.5	8.5

Source: Richard Freeman, "Overinvestment in College Training?," *Journal of Human Resources* (Summer 1975).

States. In the United Kingdom, Mark Blaug has estimated the private rate of return from higher education to be 14 percent, in contrast to the social rate of return of only about 6.5 percent.[2]

Such rate-of-return calculations have drawn criticism on a number of counts, one being that they do not take adequate account of the external effects of education. The education of one person, besides raising his or her own productivity, benefits others. Many have argued that a better educated citizenry should be more active in public affairs and better able to assume the responsibilities of citizenship. Better educated parents are likely to be better able to, and perhaps more inclined to, provide a stimulating environment for children in their pre-school years, as well as later. Moreover, as we shall indicate in much more detail in subsequent sections, education has an effect on the rate of technological change and on the rate of diffusion of innovations. These external effects may be very great. However, very little is known about their size, due largely to the enormous problems involved in measuring them.

3. Education's Effects on the Quality of Labor Input

Studies of the relationship between education and economic growth have tended to emphasize education's effects on the quality of labor input. Without question, these effects are very important. A person's education helps to determine what jobs he or she can perform and how well he or she can perform them. A continual increase in the educational level of the American labor force has improved the skills and versatility of labor and contributed to economic growth.

According to Edward Denison and others, this effect of education has been an important source of U.S. economic growth at least since 1910, and particularly since 1930.[3] Table 3 shows the changes during 1948-76 in the educational distribution of persons employed in the business sector. It is evident that there has been a very significant increase in years of school completed. For example, only about 12 percent of males had some college training in 1948; in 1976, this percentage was about 32.

As Denison and others have pointed out, various educational groups should be weighted by relative values, or marginal products, of the work their members do, not by the years their members spent in school. Table 4 shows the earnings differentials among various educational groups, based on census data for 1959 and 1969. When these data are adjusted for academic aptitude and socioeconomic status of parents, the weights obtained by Denison are shown in the last two columns of Table 4. One noteworthy point is that there seems to have been a reduction between 1959 and 1969 in the earnings differential between the most highly educated group and the least educated group.

Based on Denison's figures, 0.5 percentage points of the 2.4 percentage point annual increase in national income per person employed during 1948-73 were due to education's effects on the quality of labor input. During 1973-76, Denison's results are even more impressive: Although national income per person employed fell by 0.5 percent per year, education's effects of this sort increased national income per person employed by 0.9 percent per year. Among the principal reasons for the bigger contribution of education to the increase of national income per person employed in 1973-76 than in 1948-73 were that government absorbed a smaller share of the increase in the highly educated and that the average age of adult workers fell.

Table 3 — Percentage Distribution of Persons Employed in the Business Sector, by Sex and Years of School Completed, 1948, 1964, and 1976

<table>
<tr><th rowspan="2">Years of school completed</th><th colspan="3">Males</th><th colspan="3">Females</th></tr>
<tr><th>1948</th><th>1964</th><th>1976</th><th>1948</th><th>1964</th><th>1976</th></tr>
<tr><td>None</td><td rowspan="2">8.76</td><td>0.67</td><td>0.32</td><td rowspan="2">4.37</td><td>0.34</td><td>0.26</td></tr>
<tr><td>Elementary, 1-4</td><td>3.56</td><td>1.65</td><td>1.67</td><td>0.72</td></tr>
<tr><td>Elementary, 5-7</td><td>14.64</td><td>8.90</td><td>4.65</td><td>9.88</td><td>5.93</td><td>2.75</td></tr>
<tr><td>Elementary, 8</td><td>21.04</td><td>14.13</td><td>6.36</td><td>18.15</td><td>11.72</td><td>4.92</td></tr>
<tr><td>High school, 1-3</td><td>20.17</td><td>19.78</td><td>15.68</td><td>18.77</td><td>19.58</td><td>15.97</td></tr>
<tr><td>High school, 4</td><td>23.10</td><td>32.50</td><td>38.80</td><td>37.33</td><td>46.02</td><td>49.88</td></tr>
<tr><td>College, 1-3</td><td>6.58</td><td>10.23</td><td>15.69</td><td>7.51</td><td>10.14</td><td>16.28</td></tr>
<tr><td>College, 4</td><td rowspan="2">5.71</td><td>6.25</td><td>10.00</td><td rowspan="2">3.98</td><td>3.42</td><td>6.42</td></tr>
<tr><td>College, 5 or more</td><td>3.97</td><td>6.85</td><td>1.20</td><td>2.80</td></tr>
<tr><td>Total</td><td>100.00</td><td>100.00</td><td>100.00</td><td>100.00</td><td>100.00</td><td>100.00</td></tr>
</table>

Source: Edward Denison, Accounting for Slower Economic Growth (Washington, D.C.: Brookings Institution, 1979).

Table 4 — Standardized Earnings and Weights, Nonresidential Business, 1959 and 1969

Years of school completed	Standardized earnings (Elementary, 8=100) 1959	1969	Weight (Elementary, 8=100) 1959	1969
None	71.6	82.1	75	87
Elementary, 1-4	86.5	89.7	89	93
Elementary, 5-7	95.5	95.6	97	97
Elementary, 8	100.0	100.0	100	100
High school, 1-3	112.6	112.6	111	111
High school, 4	127.3	125.6	124	122
College, 1-3	153.9	148.5	147	142
College, 4	201.3	195.6	189	184
College, 5 or more	264.2	243.2	219	207

Source: E. Denison, op. cit.

4. Education, R and D, and Technological Change

Besides having an important effect on the quality of labor input, education also contributes to economic growth via its effects on the rate of technological change. Clearly, a nation's rate of technological change depends on the size and quality of its educational system. In this regard, it is important to point out that science and technology are two quite different things that have drawn together only recently. Until the twentieth century, it was not true that technology was built on science. Even today, many technological advances rely on little in the way of science. However, in more and more areas of the economy (such as aircraft, electronics, and chemicals), technological change has come to depend on a strong scientific base. Merely to imitate or adapt what others have developed, a nation needs high-caliber scientists.

A nation's educational system influences its rate of technological change in at least three ways. First, and perhaps most obviously, it determines how many scientists and engineers are graduated, and how competent they are. Clearly, the rate of technological change depends on the quantity and quality of the available scientific and engineering talent. Second, the educational system influences the inventiveness and adaptability of the nation's work force. Despite the closer links between technology and science, workers and independent inventors remain important sources of inventions in many areas. Third, the educational system also influences the rate of technological change and innovation via the training of managers.

Industrial managers are a key agent in the innovative process. It is important to recognize that the proper management of innovation is much more than establishing and maintaining a research and development laboratory that produces a great deal of good technical output. The coupling of R and D with marketing and production is crucial. Many good ideas are not applied properly because the potential users do not really understand them, and many R and D projects are technically successful but commercially irrelevant because they were not designed with sufficient comprehension of market realities. The crucial coupling task is up to management.

5. Sorting Out the Effects on Economic Growth of Education, R and D, and Capital Formation

When one recognizes that education affects the rate of economic growth via its effects on the rate of technological change, as well as through its effects on the quality of labor input, it becomes much more difficult to measure the contribution of education to economic growth. The effects of education and R and D are mixed up in a variety of ways. For example, current investments in education reduce the cost of generating technological change in the future because they push the supply curves for scientists and engineers to the right. At the same time, a rapid rate of technological change is likely to increase the returns from greater education. Thus, some of the returns apparently due to education may reflect the rate of technological change.

To see why a rapid rate of technological change is likely to increase the returns from greater education, note that rapid technological change puts a premium on workers' being able to learn new techniques quickly. Highly educated workers frequently are required in the plant when processes are new because these processes have not been routinized and laid out for people who do not understand many aspects of them. Similarly, highly educated workers frequently are required in the sales force when products are new because only such workers are able to grasp quickly the nature and advantages of these products and to communicate them effectively to potential purchasers and users.

Before going any further, it should be recognized that there also are great difficulties in separating the effects on economic growth of education or R and D from those of investment in physical capital. To a considerable extent, new technology must be embodied in physical capital to be used. For example, a numerically controlled machine tool must be built to take advantage of certain advances in machine tool technology. At the same time, advances in technology tend to increase and sustain the returns from investing in physical capital. Without the technological advances that have occurred since his day, some of Ricardo's dire predictions concerning the returns from such investment might well have come true.

6. Importance of the Organization of Education and R and D

Still another factor that must be taken into account is the organization of education and R and D. The contribution of both education and R and D to economic growth depends on their organization and their relationship to industry and management. In the United States, much basic research is carried out in educational institutions. In contrast to industrial and government laboratories, the traditional responsibility of the universities has been to expand the frontiers of basic science, rather than to develop particular new products. Universities perform over half of the nation's basic research, and have the unique responsibility of providing the scientists and engineers of the future. These two functions -- basic research and graduate education -- are closely related; in many cases, the President's Science Advisory Committee's 1960 statement that "each is weakened without the other" is quite correct.

Turning to industrial R and D, the probability that an R and D project will be commercialized (given technical completion) is directly related to the degree to which R and D and marketing are integrated. In some firms, the R and D staff has not always worked very closely with the marketing staff, the result being that the R and D output has not been as well mated with market realities as it might have been. The R and D staff should be able and willing to respond to the marketing staff's needs, and the marketing staff should be involved in R and D project selection. Successful innovation depends on R and D being integrated with marketing. Detailed data indicate that firms that effect a closer integration between marketing and R and D tend to increase the probability of commercialization (given technical completion) significantly. Case studies of successful and unsuccessful innovation seem to point in the same direction.[4]

To illustrate, consider three chemical firms of roughly the same size and with very similar R and D expenditures. At about the same time, they all experienced reorganizations. In two firms, the result was a closer integration of R and D with marketing. Communication channels and networks linking them were improved, and marketing's input to R and D decision making increased substantially. On the other hand, in the third firm, the reorganization resulted in less integration of R and D with marketing. R and D tended to establish its own criteria and priorities regarding projects without paying nearly as much attention to marketing as before the reorganization. Based on data concerning more than 330 individual R and D projects that occurred from three to seven years before the reorganization to five to eight years after it, we could compare the probability of commercialization (given technical completion) before the reorganization with that after the reorganization in each firm. (See Mansfield (1981b).) This probability increased by about 20 percentage points in the two firms that effected a closer integration of R and D with marketing, and it fell by about 20 percentage points in the firm that permitted less integration of R and D with marketing.

A substantial percentage of a firm's R and D results may lie fallow because other parts of the firm do not make proper use of them. According to estimates made by executives of 18 of the firms studied in Mansfield et al. (1977), the percentage of R and D projects that were economic successes would have increased by about one-half if the marketing and production people had done a proper job in exploiting them. (And it is important to note that the non-R and D executives seemed to agree on this point with the R and D executives.) If this figure is anywhere close to the truth, it suggests that faulty interfaces between R and D and the rest of the firm result in a very substantial decrease in the productivity of industrial R and D.[5]

7. Education and the Diffusion of Innovations

Education contributes to economic growth by influencing the rate of diffusion of innovations, as well as the rate of technological change. The rate of diffusion of innovations is, of course, of great importance, since no matter how splendid a new technique or product may be, its effect on economic growth will be nil unless it gains acceptance. According to the available data, it frequently takes a decade or more before one-half of the major firms in an industry begin using an important innovation. And in many cases, it takes longer. The rate of diffusion varies widely. For example, it took about fifteen years for half of the major pig-iron producers to use the byproduct coke oven, but only about three years for half of the major coal producers to use the continuous mining machine. (See Mansfield /1968/.)

There is considerable evidence that better educated managers tend to be quicker to adopt new technology than poorer educated managers. In agriculture, Everett Rogers (1962) reports that a number of studies have found that education was related to how rapidly a farmer began using a new technique.

This would be expected, since better educated farmers are likely to be better informed and better able to judge the benefits and costs of innovations than less well educated farmers.

In the tool and die industry, Mansfield (1971) found that whether or not a firm adopted numerically controlled machine tools before 1968 was related to the education of the firm's president. Better-educated entrepreneurs were in a better position to understand the issues regarding numerical control, to have the flexibility of mind to use it, and to be in contact with technical and university centers and the relevant literature. Most of the users (for which we have data) were college graduates, but most of the nonusers finished high school or less. The difference was statistically significant.

Another variable that might be expected to influence whether or not a tool and die firm adopted numerically controlled machine tools is the age of the firm's president. Younger entrepreneurs may be more likely to make the break with the past, their emotional attachment to old skills and old technology being weaker and their willingness to take risks probably being greater than their older rivals. The data are consistent with this hypothesis, the median age of the users being about 48 and the median age of the nonusers being about 55. However, age and education are themselves correlated, and when a multiple regression is run (age and education being independent variables, the dependent variable being a dummy variable showing whether or not a firm used numerical control before 1968), the effect of education is statistically significant, but the effect of age is not.

In a subsequent study in Mansfield et al. (1977), it was determined that education had a significant effect on how rapidly a tool and die firm began using numerically controlled machine tools, when several other variables are held constant. The relevant regression equation is:

$$(1) \qquad X_i = 0.129 + \underset{(1.257)}{0.032Y_i} - \underset{(1.497)}{0.123n_i} + \underset{(3.608)}{0.014H_i} - \underset{(2.201)}{0.027A_i} + \underset{(3.135)}{0.212E_i} ,$$

where X_i equals one if the i^{th} firm used numerically controlled machine tools by the beginning of 1970 and zero otherwise; H_i is the firm's size, measured by the number (in thousands) of employees; n_i is the number of people in the firm who had to approve a decision to adopt numerically controlled machine tools; Y_i is the number of years that the managers of firm i had known of numerically controlled machine tools (as of 1970); and A_i is the age (in 1960) and E_i is the education (in years beyond the eighth grade) of the managers involved in the decision. The coefficients of E_i, H_i, and A_i are all significant at the 5 percent level, the coefficient of n_i is significant at the 10 percent level, and the coefficient of Y_i is significant at the 15 percent level. (The t-statistics are shown in parentheses.)[6]

Data are also available for industries other than tools and dies. Based on information concerning 104 firms in ten industries (aircraft engines, airframes, printing presses, coal-mining machinery, digital computers, large steam turbines, machine tools, farm machinery, tools and dies, and industrial instruments), an increase of 10 percent in the years of schooling of the company's president, other things equal, is associated with a 0.02 increase in the probability of use of numerically controlled machine tools by 1970.

8. Education and Diffusion: A Simple Model

About 15 years ago, Richard Nelson and Edmund Phelps (1966) published a model relating education to the diffusion process. Although this model is "as simple a one as we can invent," according to the authors, it is worth some consideration. It is assumed that

$$(2) \qquad Q(t) = F[K(t), A(t) L(t)] ,$$

where Q is output, K is capital, L is labor, and t is time. A(t) is the index of technology in practice. $T(t)$ is the level of technology that would prevail if technological diffusion were completely instantaneous. Supposing that the latter technology level advances at a constant rate λ,

$$(3) \qquad T(t) = T_0 e^{\lambda t} .$$

Assuming that the time lag (w) between the creation of a new technique and its adoption is inversely related to some index of educational attainment, h,

$$(4) \qquad A(t) = T(t - w(h)),$$

where $w'(h) < 0$.

One interesting implication of this model is that, all other things equal, the return to education is directly related to λ, the rate of advance of the theoretical level of technology. Specifically,

$$(5) \qquad \frac{\partial Q(t)}{\partial h} = -\lambda w'(h) \times \text{Wage Bill}$$

Consequently, the marginal productivity of education is an increasing function of λ, given the wage bill, and is positive only if $\lambda > 0$.[7]

9. Educational Institutions and the Diffusion Process

American educational institutions have influenced the diffusion process directly, as well as via their students. Particularly in the agricultural sector, universities have played an active role in the dissemination of new technology. The federal extension staff serves as partners with state governments, through their land-grant universities and county governments, to form the Cooperative Extension Service. These levels of government share in financing and conducting educational programs to help the public learn about and apply new technology developed at the land-grant universities, the Department of Agriculture, and elsewhere. The state land-grant universities have a staff of specialists, plus area and county agents working with individuals and groups, to help them apply new technology.

In 1965, the State Technical Services Act was passed by Congress. It authorized for industry a program somewhat analogous to the agricultural extension service -- universities and technical schools throughout the country distributing technological information to local firms and serving as economic planning centers for their areas. The program, under the direction of the Department of Commerce (which proposed a similar plan in its earlier Civilian Industrial Technology program), was expected to include about 30 states in its first year. The major purpose of this industrial extension service was to increase the rate of diffusion of new technology. Some firms, particularly small ones, are slow to adopt new techniques because they are unable to comprehend and evaluate technical information. The industrial extension service provided demonstrations, short courses, and conferences, as well as referral to specialized consultants and experts. In this way, it hoped to narrow the gap between average and best practice.

After a relatively short life, this program was discontinued by the government. Unfortunately, the industrial extension service faced problems that were absent in the case of the agricultural extension service. Whereas the latter could deal with a relatively homogeneous group of clients, the former could not; whereas it was possible in earlier days for an agricultural extension agent to be familiar with most relevant aspects of agricultural technology, it is impossible now for anyone to be familiar with most aspects of industrial technology; whereas individual farmers seldom view each other as competitors, in manufacturing, one firm's gain in productivity and sales may be partly at the expense of another. In addition, it is more difficult in the case of the industrial extension service to delineate the set of appropriate clients. The firms that were most eager to use the service and those that were easiest to persuade to adopt new techniques were not necessarily those for whom the service could do the most good.

10. Scientific and Engineering Employment Since World War II

In any discussion of education and R and D, it is essential that attention be devoted to the adequacy of existing and prospective supplies of engineers and scientists. This is a question that has arisen continually over the past 30 years. Since World War II, there have been three quite distinct periods with regard to the employment of engineers and scientists. The first period, from about 1950 to 1963, was marked by rapid growth of jobs for engineers and scientists. As shown in Table 5, the employment of engineers and scientists grew by over 6 percent per year, which was far in excess of the rate of growth of total nonfarm employment. In part, this rapid increase was due to increases in defense activities and in the space program. During this period, there were many complaints of a shortage of engineers and scientists.

The second period, from about 1963 to 1970, saw the employment of engineers and scientists grow at about the same rate as total nonfarm employment. The employment of scientists grew more rapidly than the employment of engineers, because there was a relatively rapid increase in college enrollments and research programs. The relatively slow rate of increase of engineering employment reflected cutbacks in defense programs and space exploration, among other things.

The third period, from about 1970 to 1976, was marked by a very slow growth of scientific and engineering employment. Whereas total nonfarm employment grew by 1.9 percent per year, the employment of engineers and

Table 5 -- Average Annual Percentage Change in Scientific, Engineering, and Total Nonfarm Employment, 1950-63, 1963-70, and 1970-76

Type of Employment	1950-63	1963-70 (percentages)	1970-76
Scientists[a]	7.0	4.8	4.1
Engineers	6.5	2.5	0.4
Scientists and engineers	6.6	3.2	1.5
Nonfarm wage and salary workers	1.7	3.3	1.9

Source: National Science Foundation, Science Indicators, 1978 (Washington, D.C.: Government Printing Office, 1979).

[a]Excludes psychologists, social scientists, and computer specialists, for which comparable data are not available.

scientists grew by 1.5 percent per year. (Indeed, between 1970 and 1972, there was a 20,000 decline in engineering employment.) In considerable part, this was due to a slower growth (or curtailment) of college enrollment, R and D expenditures, and defense activities -- particularly in aircraft and related products.

Unemployment rates for scientists and engineers have tended to be very low. During the 1960s, the unemployment rate for these workers was below one percent. But in 1971, due partly to the cutbacks in defense spending and some R and D programs, the unemployment rate for scientists and engineers rose to about 3 percent. By 1973, it fell below one percent once again. However, in 1975, the unemployment rate for engineers increased to 2.6 percent, due to the recession.

Most engineers and scientists are employed by industry. Over one million were employed in the industrial sector in the mid-1970s, as compared with about 300,000 in universities and colleges, and about 200,000 in the federal government. Table 6 shows the allocation of industry's labor force among various work activities. About 37 percent of the scientists and 26 percent of the engineers are involved in R and D or R and D management. However, this does not mean that the others do not play an important role in the process by which technology is developed and applied. The interface between R and D and the rest of the firm is of fundamental importance in determining the rate of innovation, as Mansfield et al. (1971, 1977), Freeman (1974), and others have indicated. Production engineers, sales engineers, and other non-R and D engineers and scientists play a significant part in the innovation process.

Given the slowdown in the demand for engineers, it is not surprising that the percentage of bachelor's (and first professional) degrees awarded in engineering declined continually and significantly between 1960 and 1975.

Table 6 -- Percentage Distribution of Industry's Scientific and Engineering Labor Force, by Primary Work Activity, 1974

Primary Work Activity	Scientists	Engineers (percentages)	Scientists and Engineers
R & D and R & D management	37	26	29
Management of non-R & D activities	15	20	19
Production and inspection	13	17	16
Design	1	18	14
Computer applications	19	2	6
Other activities	15	17	16
Total	100	100	100

Source: National Science Foundation, Science Indicators, 1976 (Washington, D.C.: Government Printing Office, 1977).

In 1960, engineering degrees were 10 percent of the total; in 1975, they were 4 percent of the total. The percentage of bachelor's (and first professional) degrees in the physical and environmental sciences fell from 4 percent in 1960 to 2 percent in 1975. (In contrast, the percentage in the social sciences increased from 8 percent in 1960 to 14 percent in 1975.) Turning from undergraduates to graduate students, enrollments for advanced degrees in science and engineering decreased from 38 percent of all advanced degree enrollment in 1960 to 25 percent in 1975. By late 1981, there were many warnings from leading engineering schools of a shortage of doctoral engineers in particular. According to Paul Gray, president of Massachusetts Institute of Technology, there was a need for more young people to prepare for faculty careers in engineering and some areas of applied science.[8]

11. Projected Supply and Utilization of Scientists and Engineers

Government agencies — in particular, the Bureau of Labor Statistics and the National Science Foundation — have made projections of the supply and utilization of scientists and engineers in the 1980s. In its 1979 Annual Report, the National Science Board reviewed these projections. The Bureau of Labor Statistics is quoted as saying that there will be an ample supply of scientists through the mid-1980s. For engineers, demand and supply were estimated to be roughly in balance, and engineering graduates were expected to encounter good employment opportunities through the mid-1980s.

Turning to individual fields of science, there seemed to be considerable variation in the outlook.[9] In geology, there appeared to be favorable employment opportunities, due in part to increasing exploration for oil and other minerals. If recent trends continue, a shortage of geophysicists seemed quite possible. Favorable opportunities were projected for chemists and physicists in the nonacademic sector. About three-fourths of chemists' total employment was expected to be in industry. In physics, the generally favorable prospects reflected an anticipated cutback in the supply of physicists, not an appreciable increase in the demand for them. In astronomy and mathematics, the situation seemed likely to be less rosy. The number of degrees granted in astronomy was expected to continue to exceed job openings. Mathematicians were expected to face keen competition for jobs.

In the social and life sciences, there was also appreciable variation among fields. Economists with advanced degrees were expected to have favorable job opportunities in nonacademic work. Life scientists with advanced degrees also were expected to have good opportunities. But those with training in anthropology and sociology seemed likely to encounter keen competition for jobs. For psychologists with advanced degrees, job opportunities appeared greatest for people specializing in applied areas such as industrial psychology and clinical counseling.

Both the National Science Foundation and the Bureau of Labor Statistics made projections of the supply and utilization of doctoral scientists and engineers in the mid-1980s. Depending on the model used, the number of students expected to receive science and engineering doctorates (corrected for international migration) was 185,000 (the Bureau of Labor Statistics' projection for 1976-85) to 210,000 (the National Science Foundation's projection for 1977-87). Based on these projections and estimates of attrition, the labor force of doctoral scientists and engineers was expected to be about 415,000 in the mid-1980s. Of these people, about 345,000 were expected to be engaged in scientific and engineering activities.

What will happen to the remaining 70,000 doctoral scientists and engineers? Clearly, there is a very small chance that they will be unemployed. Instead, they were expected to move into other fields. Among mathematicians and social scientists, the situation looked particularly bleak. In mathematics, it was expected that 21-30 percent of mathematics Ph.D.s will be working outside science and engineering. In social science, the proportion was expected to be 19-27 percent.

Finally, it is worth pointing out that the existing evidence seems to indicate an underinvestment in civilian technology in the United States, from an economic point of view. Because firms frequently cannot appropriate many of the social benefits arising from their innovations (due to imitation), and for other reasons, the social returns from innovative activity seem to exceed the private returns. (See Mansfield et al. (1977).) Thus, it would be hazardous to assume that the earnings of R and D scientists and engineers measure at all accurately the value to society of their efforts. Further, their earnings in some periods seem to have differed from what would arise under competitive conditions, which also makes this assumption questionable. (See Arrow and Capron (1959).)

12. Accuracy of Firms' Forecasts of Engineering Employment

In government, universities, and business, policy makers must make decisions that depend, explicitly or implicitly, on forecasts of the number of scientists and engineers employed in various sectors of the economy at various points in time. For example, in evaluating the adequacy of existing engineering manpower, public policy makers must try to forecast how many engineers will be employed in the private sector. The National Science Foundation, the Bureau of Labor Statistics, and other groups have made forecasts of this sort for decades. While such forecasts sometimes are based on a collection of forecasts made by firms of their own engineering employment, very little is known concerning the accuracy of firms' forecasts of this kind.

In this section, we present information concerning the accuracy of such forecasts and suggest a simple model that may be useful in improving their accuracy. Very detailed data were obtained from a well-known engineering association which has collected such forecasts from firms for many years. For 54 firms in the aerospace, electronics, chemical, and petroleum industries, comparisons were made of each firm's forecasted engineering employment with its actual engineering employment during 1957 to 1976. Since data were obtained concerning a number of forecasts of each firm, the accuracy of 218 such forecasts could be evaluated.[10]

Our findings indicate substantial interindustry variation in forecasting accuracy. In the aerospace industry, the forecasting errors for individual firms have been large, as can be seen in Table 7. For example, even when firms forecasted only six months ahead, the mean percentage error was about 10 percent. In the electronics, chemical, and petroleum industries, the forecasting errors for individual firms have been much less, although the mean percentage error for two-year forecasts in the electronics industry was about 12 percent. The relatively large forecasting errors in the aerospace industry (and to a lesser extent, the electronics industry) seem to be due to its heavy dependence on government defense and space programs which were volatile and hard to predict.

While the forecasting errors for individual firms are substantial, they tend to be smaller when we consider the total engineering employment for all firms in the sample. On the average, the six-month forecasts were in error by about 2 percent, the two-year forecasts were in error by 1 percent, and the five-year forecasts were in error by about 3 percent. The fact that there was so little bias in the forecasts is encouraging since, for many purposes, the principal aim is to forecast total engineering employment in some sector of the economy, not the engineering employment of a particular firm.

Models are sometimes constructed in which it is hypothesized that firms at each point in time have a desired employment level for a particular

Table 7 -- Mean Percentage Error in a Firm's Forecast of Its Engineering Employment, 54 Firms, 1957-76

Industry	Forecasting Interval[a] (Years)			
	0.5	2	5	10
		(percentages)		
Aerospace	10.3	15.9	41.2	88.7
Electronics	4.6	12.4	15.4	26.5
Chemicals	3.2	5.7	17.3	22.0
Petroleum	2.8	5.5	13.1	9.4

[a]The forecasting interval is the length of time between the date when the forecast is made and the date to which it applies.

Table 8 -- Estimated Regression Coefficients,[a] Equation (7)

Industry	Independent Variables			$\bar{R}^2$
	ϕ_0	$D_i(t)$	$I_i(t)$	
Chemical	.32 (0.95)	-4.61 (5.8)	0.74 (2.15)	0.78
Petroleum	-1.21 (1.2)	-6.55 (3.1)	2.33 (2.35)	0.51

[a]The t-statistic is shown in parentheses below each regression coefficient.

kind of labor, and that they set their actual employment level for this kind of labor so as to move part way toward this desired employment level. Thus, in the case of engineers, firms are continually adjusting their employment toward the level that they would regard as optimal if changes in employment levels could be made instantaneously and if the inefficiencies involved in too rapid a change in engineering employment could be avoided. If $E_i(t)$ is the i^{th} firm's engineering employment at time t, and if $\tilde{E}_i(t+1)$ is its optimal or desired employment one year hence, then $E_i(t+1)$ can be represented as

$$(6) \quad E_i(t+1) = E_i(t) + \theta_i(t) \left[\tilde{E}_i(t+1) - E_i(t)\right].$$

In other words, $\theta_i(t)$ is the proportion of the way that the i^{th} firm's engineering employment moves toward the desired level between time t and time t+1.

Assuming that one can estimate $\theta_i(t)$, equation (6) can be used to forecast $E_i(t+1)$, since data can be obtained at time t regarding $E_i(t)$ and $\tilde{E}_i(t+1)$. The engineering association collected data concerning $\tilde{E}_i(t+1)$ for various times between 1957 and 1968, so we were able to obtain direct estimates of $\theta_i(t)$ for seven major chemical firms and six major petroleum firms during this period. These were all of the firms for which appropriate data were available.[11] The mean value of $\theta_i(t)$ is very similar for the two industries: it is 0.73 in chemicals and 0.72 in petroleum. These results are quite similar to those of Freeman, although his estimates of the rate of adjustment are based on quite different kinds of data.

To explain differences among time periods and firms in the value of $\theta_i(t)$, it seems reasonable to hypothesize that

$$(7) \quad \theta_i(t) = \phi_0 + \phi_1 D_i(t) + \phi_2 I_i(t) + u_i(t),$$

where $D_i(t)$ is the desired proportional increase in engineering employment between time t and time t+1, $I_i(t)$ is the ratio of the i^{th} firm's profits in time t to those in time t-1, and $u_i(t)$ is a random error term.[12] A priori, we would expect ϕ_1 to be negative since, if attaining its desired employment level means that the firm must increase its employment by a relatively large percentage, this firm will move a relatively small proportion of the way toward this desired level because of the costs of rapid change in employment levels. Similarly, we would expect ϕ_2 to be positive because relatively large increases in profits will influence firms' expectations and make them bolder in moving toward desired employment levels.

To determine the goodness of fit of the hypothesized model in equation (7), we obtained least-squares estimates of ϕ_0, ϕ_1, and ϕ_2, as shown in Table 8. The results show that each of the regression coefficients has the expected sign and is statistically significant. This model explains over three-quarters of the variation in $\theta_i(t)$ in chemicals and about one-half of such variation in petroleum. Using the least-squares estimates of ϕ_0, ϕ_1, and ϕ_2, one can estimate $\theta_i(t)$ for each firm on the basis of its values of $D_i(t)$ and $I_i(t)$. Inserting this estimate of $\theta_i(t)$ into equation (6), one can forecast $E_i(t+1)$. Based on the data for these firms, the resulting forecasts are appreciably better than those of the firms themselves. This result seems encouraging. Although much more work needs to be done, it appears that better forecasts may result from the application of this simple sort of model.

13. Competition and Cooperation of R and D and Education

As we have seen in the previous three sections, the educational establishment produces manpower that is of great importance in R and D. But this is not the only way in which R and D and education relate to one another with regard to manpower; in addition, R and D often competes with higher education for manpower. The size and allocation of government and industrial R and D expenditures, as well as various policies of government and industry, influence the allocation of scientific and engineering effort between teaching, on the one hand, and applied research and development, on the other.

Fritz Machlup and others have pointed out that applied programs compete with teaching for scarce scientific and engineering talent, and that increases in these applied programs can be dangerous if, by curtailing the supply of teachers, they reduce excessively the rate of increase of the supply of scientists and engineers. Studies have been made of the distribution of scientists and engineers between teaching and other work, and simple models have been used to derive "optimal" allocation rules.[13] Unfortunately, as their authors are aware, these studies suffer from the fact that applied work and teaching may require somewhat different sorts of talents, that the available data completely overlook the crucial differences in quality among scientists and engineers, and that the models oversimplify the relationships between teaching and R and D. Nonetheless, the basic point -- that applied research and development compete with basic research and teaching for scarce talent -- is worth making. Moreover, in recent years, this point has been brought home to many universities, which have found it difficult to compete with industry for new Ph.D.s. According to one recent statement, starting salaries in industry are about double those in the universities in some fields. (See Bromley (1981).)

There has also been considerable interest in the effects of federal research grants to universities on the quality of undergraduate education. During the 1960s, the House Subcommittee on Research and Technical Programs claimed that federal research programs "have harmed scientific higher education by excessively diverting scientific manpower from teaching, and by overemphasizing research to the detriment of teaching...." (It claimed too that an important imbalance had developed between the natural sciences, on the one hand, and the social sciences and humanities, on the other.) Because it is so difficult to measure the quality of undergraduate education, it was difficult to know how seriously to take these criticisms. Although the subcommittee seemed to think that the adverse effects of government research programs were borne out by the published testimony of university professors and administrators, a close examination of this testimony showed that a great many of the respondents did not agree with this conclusion. The subcommittee report seemed to oversimplify the situation. Undergraduate education has been faced with many problems, but it is not clear that government research grants and contracts have, on balance, done more harm than good.

14. Competition and Cooperation of Federally Financed and Industry Financed R and D

Just as there has been considerable controversy over the effects of increased government and industrial R and D programs on higher education, so there has been considerable controversy over the effects of federally supported R and D on privately financed R and D. Some economists argue that increases in government R and D funding are likely to reduce the R and D expenditures of the private sector because (among other reasons) firms may receive government support for some projects they would otherwise finance themselves. Other economists say that government R and D is complementary to private R and D, and that increases in the former stimulate increases in the latter. It is universally recognized that this question is of great importance both for policy and analysis, but little is known concerning it.

To shed light on the effects of federal support on privately financed R and D in the important area of energy, we recently chose a sample of 25 major firms in the chemical, oil, electrical equipment, and primary metals industries.[14] Together they carry out over 40 percent of all R and D in these industries. To estimate the extent to which these firms obtained government funding for energy R and D projects that they would have carried out in any event with their own funds, we obtained detailed data on this score from each of the firms. Moreover, even more detailed data were obtained concerning a sample of 41 individual federally funded energy R and D projects. These projects account for over 1 percent of all federally supported energy R and D performed by industry.

The following are some of the conclusions stemming from this study. First, it appears that these firms would have financed only a relatively small proportion of the energy R and D that they performed with government support. Based on our sample of firms, they would have financed only about 3 percent if the government did not do so. Based on our sample of individual projects, they would have financed about 20 percent if the government did not do so. It would be very useful if similar estimates of this sort could be obtained for various kinds of R and D outside the field of energy.

Second, if a 10 percent increase were to have occurred in federal funding for their energy R and D in 1979, the response (for all 25 firms taken as a whole) would have been that, for each dollar increase in federal support, they would have increased their own support of energy R and D by about 6 cents per year for the first two years after the increase in federal funds. In the third year after the increase, there would be no effect at all. This finding is based on careful estimates by senior R and D officials of each firm. It is worth noting that there are substantial differences among firms in their response. Note too that the results are quite consistent with those obtained by Levin and Reiss (1981) and Terleckyj and Levy (1981) in their econometric studies of the aggregate relationship between federally funded R and D expenditures and privately funded R and D expenditures.

Third, if a 10 percent cut were to have occurred in federal funding for their energy R and D in 1979, the response (for all 25 firms taken as a whole) would have been that, for each dollar cut in federal support, they would have reduced their own support of energy R and D by about 25 cents in each of the two years following the tax cut. In the third year after the federal cut, there would have been about a 19 cent cut in their own spending. Taken at face value, it appears that a 10 percent cut in federally funded energy R and D would have a bigger effect on privately funded energy R and D than would a 10 percent increase. But until more and better data are obtained on this score, we feel that this difference should be viewed with considerable caution.

Fourth, in modeling the effects of federally funded R and D on the economy, our results indicate that it may be more realistic to view such R and D as a factor that facilitates and expands the profitability of privately funded R and D, rather than focus solely (as most econometric studies have done) on the direct effects of federally funded R and D on the productivity of the firms and industries performing the R and D. Based on our sample of federally funded projects, it appears that such projects typically make only about half as large a direct contribution to the firm's performance and productivity as would be achieved if the firm spent an equivalent amount of money on whatever R and D it chose. But in about one-third of the cases, the federally financed R and D projects suggested some further R and D into which the firm invested its own funds. (The likelihood of such a spinoff is enhanced if the firm helped to formulate the ideas on which the project was based.) If federally funded R and D is viewed in this way, econometricians may have more success in measuring its effects on productivity in the private sector.

15. Inclusion of Education in Econometric Productivity Studies

Based on our discussion in previous sections, it is clear that education affects productivity growth apart from its effects on the quality of labor input. Education, as pointed out in Section 2, results in external effects of various kinds. In particular, education affects productivity growth via its effects on the rate of technological change and the rate of diffusion of innovations, as indicated in Sections 4 to 8. In this connection, the adequacy of the supply of scientists and engineers, taken up in Sections 10 to 13, is of obvious importance.

Having reached this conclusion, and having discussed relevant issues concerning the organization of R and D activities and the degree of cooperation or competition between private industry, universities, and government in the provision of R and D and the employment and training of researchers, we must turn now to a discussion of how education's effects on productivity growth (apart from its effects on the quality of labor input) may best be analyzed and, at some future time, measured. In Sections 15 to 20, I shall suggest six kinds of studies that, in my opinion, seem important and worthwhile. At the outset, it should be recognized that they are unlikely to provide more than a fraction of the information that policy makers would like to have on this score. But they seem to me to be sensible places to start.

To begin with, it may be possible to obtain some useful information by extending econometric studies of R and D and productivity to include education. In the typical studies that have been carried out in this area, it is assumed that:

$$Q = A\, e^{\phi t} R^{\alpha} K^{\beta} L^{1-\beta}, \tag{8}$$

where Q is the value-added of the industry or firm under consideration, R is the industry's or firm's R and D capital (defined as the sum of its depreciated past R and D expenditures), K is its physical capital stock, and L is its labor input. Frequently, too, it is recognized that the R and D expenditures of industries or firms supplying equipment or other inputs to this industry or firm should be included in this production function as well. (See Mansfield [1980a, 1980b, 1981a, 1968].)

According to our previous discussion, higher levels of education (among managers and workers, as well as engineers or scientists) may affect the productivity of R and D. Thus, education might be included as an additional variable in this equation, or some sort of interaction term between R and D and education might be introduced. A limited amount of investigation along this line has already been begun. For example, Brown and Conrad (1967) carried out a study that proceeded in this direction, based on the CES production function. Also see Griliches (1964).

In addition, educational levels are likely to be relevant to the speed and extent of technology transfer from sources outside the industry or firm. Thus, ϕ, which is a measure of the rate of technological change resulting from factors other than the industry's or firm's own R and D, may be a function of the educational level. This, of course, is quite consistent with the evidence concerning the diffusion of innovations presented in Section 7.

There is no reason why education could not be included in some such way in econometric production functions of this sort. As noted above, Brown and Conrad conducted a study about fifteen years ago that included education. At the same time, however, the difficulties should not be minimized or glossed over. For one thing, when we talk about educational level, are we talking about the educational level of the managers, the workers, the R and D personnel, or some combination or subset thereof? In small firms, it can be fairly easy to designate the people who are most directly involved in the relevant decision making process or in utilizing the relevant new technology. But in large, far-flung organizations, it can be extremely difficult to decide whose educational level should be included in such a model.

Also, it is difficult to measure how much education a person has. Years of schooling obviously are not a satisfactory measure for many purposes; e.g., a year at one school may represent far more education than a year at another school. Also, education is far from homogeneous. It is possible to spend a year at school studying Greek, physical education, or civil engineering, and it seems doubtful that each should be given the same weight in such a production function.

For these and many other reasons, a study of this type would call for considerable ingenuity. There are substantial problems in carrying it out. But work during the past decade concerning the economics of R and D has demonstrated that models of this sort, while crude, can be quite useful. Adding education to such models may be very difficult, but nonetheless worthwhile.

16. The Educational Level of Inventors

Another kind of study that might be useful is an investigation of the educational levels of inventors. Of course, it cannot be assumed that an inventor requires the educational level he achieved in order to function as an inventor. Perhaps he could have done just as well (or better) with less formal education. But information concerning the educational level of inventors would help to indicate the maximum formal education required to do various kinds of inventing. For example, if one were to find that the bulk of the inventors in a particular field had less than four years of college, it would appear that graduate degrees were not required, in the past at least, to do such work. Of course, it is always possible that inventors in this field would have been more effective or more prolific if they had had more schooling, but one would think that, if more schooling had been very important to such work, potential and actual inventors would have found it worthwhile to get additional schooling, and if they did not do so, they would have found it difficult to compete as inventors with people who had the extra schooling.

Almost 25 years ago, Jacob Schmookler (1957) published a small-scale survey of inventors in which he found that about half of them were not college graduates. He concluded that the common impression that invention was the province of a highly trained technological elite was over-drawn. It would be interesting to obtain such information for more recent years and for larger samples of inventors. Given the changes in the educational distribution of the population at large during the past 25 years, one would expect the situation now to be quite different from that described by Schmookler. But it would be useful to know whether the change has been greater or less than would be expected for this reason alone.

In addition, it would be interesting to break down the results by technological field or industry, since it seems much less likely that a person with a limited formal education could be a successful inventor in some fields than in others. Obviously, a person lacking considerable training in chemistry would be very unlikely to invent a new polymer, and someone untrained in medicine or science would be unlikely to invent a major new drug. But in other areas, ingenuity and practical experience may be much more important than formal scientific and engineering training.

There may be a tendency for formal education to be less important in areas where independent inventors are a major force. However, this tendency may not be as strong as might appear at first sight. Many independent inventors have very extensive formal training. For example, Edwin Armstrong, who played a central role in the use of frequency modulation in radio, was Professor of Electrical Engineering at Columbia University.

A study of this type would not provide a direct estimate of the effects of education on the rate of productivity increase. In this respect, it is unlike the study suggested in the previous section, which, if successful, might provide information of this sort. Nonetheless, it seems to me that a study of this sort would be worthwhile.

17. Effect of Education on Learning Curves

A third type of study that might be carried out is concerned with the effect of educational levels on the nature and shape of learning curves. At least four decades ago, aeronautical engineers noted that the number of labor-hours expended in the production of an airframe decreases as the total number of airframes previously produced goes up. Specifically, the amount of labor required to produce the N^{th} airframe of a particular type seemed to be approximately proportional to $N^{-1/3}$. This relationship, or "learning curve," has become basic to the production and cost planning of the Air Force. (See Asher [1956].) In addition, a variety of other studies carried out in the 1950s and early 1960s showed that learning curves of this sort were to be found in a wide range of industries other than aircraft production. For example, Hirsch (1956) found the same type of learning curve in the production of other kinds of machines, but the rate of learning is not the same as in aircraft. Lundberg (1961) referred to a very similar phenomenon as the "Horndal effect." He found that the Horndal iron works in Sweden had no new investment for a period of 15 years, but experienced an increase in output per manhour of close to 2 percent per year on the average.

Kenneth Arrow (1962) brought the learning curve into the mainstream of economic discussion. He emphasized two fundamental propositions. (1) "Learning is the product of experience. Learning can only take place through the attempt to solve a problem and therefore only takes place during activity." (2) "/ L/earning associated with repetition of essentially the same problem is subject to sharply diminishing returns. There is an equilibrium response pattern for any given stimulus, towards which the behavior of the learner tends with repetition. To have steadily increasing performance, then, implies that the stimulus situations must themselves be steadily evolving rather than merely repeating."

There is widespread agreement that learning by doing is an important source of productivity growth in many industries. Indeed, learning by doing can be important in the R and D process, as well as in manufacturing. (See Mansfield et al. /1977/.) Yet the underlying factors responsible for the rate at which learning occurs are not well understood. Clearly, the learning curve is different in some organizations than in others, but little is known about the reasons.

An econometric study might be conducted to determine whether (and if so, how) the learning curve depends on the educational levels of the members of the organization. One might suspect the existence of such a relationship, at least in some industries. But so far as I know, no evidence of this sort has been presented. If there is such a relationship, it might be used to help estimate the effects of education on productivity growth emanating from learning by doing. Of course, learning by doing is not dependent only on formal, deliberate training or education. Moreover, for some kinds of simple repetitive tasks, formal education may have no effect (or even a negative effect) on the rate of learning. But for a variety of important tasks and industries, the learning curve might be expected to depend on the level of education.

18. Education's Role in the Diffusion Process

A fourth type of study that should be carried out is concerned with the relationship between educational level and speed (and nature) of response to innovations. As we saw in Section 7, agricultural studies indicate that better educated managers tend to be relatively quick to adopt new technology. Moreover, studies of the diffusion of numerically controlled machine tools indicate the same thing in manufacturing. But aside from these rather limited investigations (described in Section 7), very little is known about education's role in the diffusion process.

Studies of this type should address at least four kinds of questions. First, practically nothing is known about the sort of education that is best correlated with a manager's speed of response. Do people majoring in science and technology adopt new technology faster than others with equivalent years of schooling? Do MBA's adopt new technology faster than M.A.'s in English? Second, in small firms, it may be possible to identify the people involved, and to see the mixture of educational levels and types they represent. Are some mixtures more conducive than others to rapid utilization of new technology? Third, in large firms, is it possible to single out and identify a small number of people that were responsible for the decision, and relate their educations to the firm's speed of response? Or are some of these decisions the product of so many people and committees that such an analysis would not be possible or meaningful? Fourth, are better educated managers more likely than others to adopt unsuccessful new technology, as well as successful new technology? In other words, are better educated managers better able than others to discriminate between successful and unsuccessful new technology, or are they more inclined to adopt new technology even if it is not superior to the old?

In my opinion, existing studies of this sort only scratch the surface. For example, increased education of a particular sort is likely to have more of an effect on the speed of response to some sorts of innovation than to others, but the very limited amount of information that has been derived to date cannot tell us anything about this or a host of other questions. More empirical studies of education's role in the diffusion process are both feasible and badly needed.

19. Simple Models of Education, Diffusion, and Growth

A fifth type of study that should be carried out is concerned with the construction of simple mathematical models relating educational levels, the rate of diffusion of new technology, and the rate of economic growth. This type of study should complement the work suggested in the previous section in at least two ways. (1) The empirical work in the previous section should help to suggest the form and nature of some of the relationships in these models. (2) The models described in this section should help to indicate some of the empirical work's implications regarding the magnitude of education's effects on productivity (apart from its effects on the quality of labor input).

As pointed out in Section 8, Nelson and Phelps began work on models of this sort about 15 years ago. Unfortunately, they have not extended the very simple models they constructed then. And so far as I know, neither has anyone else. Although this can be interpreted as an indication that the relatively primitive models they constructed were a dead end, I suspect that this is not the case.

My guess is that interesting models could be constructed to analyze education's effects on productivity growth via the rate of diffusion of innovations. As Nelson and Phelps point out, their own work is far from satisfactory or complete. But I see no reason why others could not build on these beginning steps. Indeed, I would think that such work, which would be relatively inexpensive, would be a very valuable complement to the empirical work described in the previous section.

20. The Supply of Scientists and Engineers

A sixth type of study that should be carried out is concerned with the supply of scientists and engineers. There is already considerable work going on in this area. Both the Bureau of Labor Statistics and the National Science Foundation are responsible for comprehensive projections of the supply and utilization of doctoral scientists and engineers. The National Science Foundation uses econometric models to help estimate the number of science-and-engineering-related positions that may be available by field for Ph.D.s. For the two largest categories of employment for Ph.D. scientists and engineers -- academic and industrial R and D -- demand equations are estimated, using standard sorts of regression analysis. Among the variables included in these equations are the level of R and D spending and the number of baccalaureates awarded in science and engineering (an index of teaching loads).

Although models of this sort have been subject to criticism, it seems to me that work of this sort is of importance. In addition, I think that studies of the demand for engineers and scientists by individual firms and of the accuracy of firms' forecasts are worthwhile, as indicated in Section 12 above. Public policy in this area has suffered because the markets for scientists and engineers -- and the process by which people choose and enter various fields -- have not been well understood.

Besides looking at the supply of scientists and engineers, it is also important that we understand more about the supply of technicians and other sorts of R and D support personnel. My own results indicate that the wages of support personnel rose more rapidly than the wages of scientists and engineers during 1969-78 in the eight major industries for which we have collected data.[15] What factors accounted for this difference? Can we construct models to help forecast the rate of price increase for various R and D inputs (such as scientists and engineers, support personnel, materials and supplies, and the services of R and D plant and equipment)?

In sum, many interesting questions of both analytical and policy importance exist in this area, and further efforts to help answer them would be very worthwhile.

21. Conclusions

Based on the previous discussion, it seems clear that education affects productivity growth apart from its effects on the quality of the labor force. Education certainly has external economies not captured through wages and salaries. Basic research and graduate education are complementary in many ways, and thus often take place together. With regard to applied R and D, it is very important that R and D be properly coupled with potential users (marketing and production groups in the case of industrial R and D). In efforts to tell whether existing and prospective supplies of scientists and engineers are ample, the Bureau of Labor Statistics and the National Science Foundation attempt to forecast the demand for, and utilization of, various kinds of technical personnel. Increases in applied R and D can be dangerous if, by curtailing the supply of teachers, they reduce excessively the future quantity and quality of scientists and engineers. Based on recent research, it appears that privately financed and federally financed R and D are mildly complementary.

In the previous six sections of this paper, I have sketched out a number of types of studies that might be carried out. In my opinion, all are worthwhile, if staffed with good people. But it should not be assumed that these studies will result in a precise or complete estimate of the effects of education on the rate of technological change and on productivity growth. Because the effects of education are so widely scattered, the extent and nature of education are so hard to characterize, and the rate of technological change is very difficult to measure, it seems realistic to expect that studies of this sort would provide only a small fraction of what economists and policy makers would like to know. The problems are inherently so difficult that it would be foolhardy to believe that a few studies of this sort would be more than a beginning. Nonetheless, such a beginning would be very useful.

Footnotes

[1]See Freeman (1975) and Welch (1979).

[2]See Blaug (1965).

[3]See Denison (1966, 1979).

[4]See Mansfield et al. (1977) and Freeman (1974).

[5]*Ibid*

[6]In equation (1), the sample consisted of 15 firms. Obviously, more data are needed.

[7]To derive the result in equation (5), note that

$$Q(t) = F[K(t), T_0 e^{\lambda[t-w(h)]} L(t)],$$

according to Nelson and Phelps.

[8]See "Engineering Education at the Crossroads: An Interview with MIT President Paul E. Gray," *Policy Choices*, Fall 1981.

[9]The forecasts summarized below come from National Science Foundation (1979), and reflect the situation at that time. Also, see Cain, Freeman, and Hansen (1973).

[10]See Brach and Mansfield (forthcoming) and Mansfield et al. (forthcoming).

[11]This model assumes that $\tilde{E}_i(t+1) > E_i(t)$, which was typically the case in the relevant period. Of course, if this is not the case, a different model should be used.

[12]More specifically, $D_i(t)$ equals $[\tilde{E}_i(t+1) - E_i(t)] \div E_i(t)$. For the chemical firms, $I_i(t)$ is the i^{th} firm's net income in year t+1 divided by its net income in year t. See the references in note 10.

[13]See Machlup (1962) and Intrilligator and Smith (1966).

[14]See Mansfield and Switzer (1981).

[15]See Mansfield, Romeo, and Switzer (1981).

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