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On the Sources and Significance of Interindustry Differences in Technological Opportunities

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ABSTRACT

The set of technological opportunities in a given industry is one of the fundamental determinants of technical advance in that line of business. We examine the concept of technological opportunity and discuss three categories of sources of those opportunities: advances in scientific understanding and technique, technological advances originating in other industries and in other private and governmental institutions, and feedbacks from an industry's own technological advances. Data from the Yale Survey on Industrial Research and Development are used to measure the strength of various sources of technological opportunity and to discern interindustry differences in the importance of these sources. We find that interindustry differences in the strength and sources of technological opportunities contribute importantly to explanations of cross-industry variation in R&D intensity and technological advance.

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I. Introduction

Technological advance has been remarkably rapid in some industries and in some directions but very slow in others. Whether measured by patents, innovation counts, or total factor productivity, the rate of technological progress differs widely across industries. To be sure, none of these measures of technological advance is adequate to assess technological progress in those fields, like computers and pharmaceuticals, where much new technology is associated with the introduction of new products that allow things to be done that could not be done before. In particular, total factor productivity growth is a highly imperfect measure of the benefits from new technology in such fields. Nevertheless, the ranking of industries implied by these measures generally agrees with overall impressions we have about where technological advance has been rapid and where it has been slow. Industries like electronics and air travel top the list while footwear and housing construction are located toward the bottom.

Industries also differ in the amount of resources they devote to R&D, whether measured in absolute terms or relative to sales. Typically, firms in industries in which total factor productivity has grown rapidly are intensively engaged themselves in R&D or have upstream suppliers who are so engaged. But this positive correlation, which also appears between R&D intensity and other measures of technological advance, only pushes the question back a stage. Why is R&D intensity high in some industries and low in others?

Various explanations have been offered. One often described as the "Schumpeterian" view attributes differences in industry R&D intensity to differences in firm size and market structure. The evidence, however, provides only very weak support for this explanation. The most careful recent work confirms the simple descriptive characterization provided by Richard R. Nelson, Merton J. Peck, and Edward Kalachek (1967) twenty-five years ago. Namely, among firms in an industry that do formal R&D, there is no appreciable effect of scale on R&D intensity, although the probability of engaging in formal R&D does increase with size. Innovation (measured by patents or counts) per employee or per dollar of sales tends to be highest in small firms, but it increases once again for the very largest firms. These effects, however, are barely significant in large samples, and they explain only a small fraction of the cross industry variance. The literature on the effects of market structure is similarly ambiguous. Although traditional measures of market structure are sometimes statistically significant in explaining R&D intensity or innovation, the magnitude of the effects is not economically important. The regression results are also quite fragile; the effect of market structure tends to vanish when other industry characteristics are included as explanatory variables. For a review of recent empirical work in this area see Cohen and Levin (1989).

A second line of explanation of interindustry differences in R&D, associated most with the work of Jacob Schmookler (1966), emphasizes the role of market size and growth in demand in determining the level of innovative activity. Schmookler conceived of science as a generic pool of results that could be put to use by a wide range of industries. Although Schmookler understood that the pool itself would grow over time, he claimed that the firms most likely to exploit science at any particular point in time would be those in industries marked by intense and growing demand. Consequently, he expected that time series on market size would lead those on patents, and he found empirical support for this hypothesis in various capital goods industries. Historians of technology have offered a different view. William Parker (1972) and Nathan Rosenberg (1974) each described historical episodes during which the nature of technology itself, rather than the size or growth of the market, dictated the sequence of industries making practical use of a particular constellation of scientific ideas. And others, notably Vivian Walsh (1984), have shown that time series evidence confirming that market size leads patents does not necessarily demonstrate that demand drives technological advance. A major innovation, embodied in one or a few patents, can provide an enormous stimulus to demand, which in turn makes profitable a sequence of follow-on innovations that are associated with a large number of patents.

Over the past several years economists who begin at a variety of intellectual starting places have proposed another answer to the question of why R&D intensity is high in some industries and low in others. They argue that R&D intensity in an industry is largely determined by two key variables -- technological opportunity and the ability to appropriate returns from new developments. The former determines the productivity of R&D; the latter determines the fraction of the returns from R&D that the innovator is able to retain.[1]

There has been a considerable amount of recent work on interindustry differences in the ability to appropriate returns. Perhaps the most comprehensive data have been provided by the Yale survey, which we designed and executed several years ago. A report on our findings regarding interindustry differences in appropriability was published in the

1987 Brookings Papers on Economic Activity: Special Issue on Microeconomics. Our work, along with Edwin Mansfield's (1981,1985,1986) and earlier work of Christopher T. Taylor and Z. Aubrey Silberston (1973), confirms strongly that appropriability conditions differ markedly across industries.

The effects of appropriability conditions on R&D and innovative output are complicated. Given demand and opportunity, stronger appropriability enhances the private incentive to engage in R&D, but weaker appropriability lowers the cost of research (increases opportunity) for others. In short, there is a conflict between what have been called the incentive and the efficiency effects of appropriability. In models developed by Michael Spence (1984) and by Richard Levin and Peter Reiss (1984, 1988), a greater ability to appropriate the returns of R&D increases R&D spending unambiguously but also may reduce the rate of technical progress. In empirical work, Levin (1988) has shown that industries in which information flows among competitors via low-cost channels have higher rates of innovation than those in which high-cost channels are used.

A theme developed by Richard Nelson and Sidney Winter (1982), by Robert Merges and Nelson (1990), and by Levin (1982, 1988) is that the nature of technology may help to distinguish industries in which stronger appropriability is better for social welfare from those in which more appropriability is worse for society as a whole. When technology advances in discrete, independent steps, the greater incentive that innovators face if they can appropriate more returns from their work tends to be beneficial to society. In contrast, if technological improvements are cumulative so that each invention incorporates and builds on features that came before, the easier flow of information about technological developments that exists when firms cannot easily block others from developing and commercializing technology that builds on their own work redounds to society's benefit. Where the technology is of this building-block character, providing too much protection for innovators may inhibit technological progress.

Despite the evidence from economic history, from case studies, and from the econometric work of Scherer (1982) and others, that the supply side matters, there has been much less theoretical and empirical work on interindustry differences in technological opportunities. These differences may be very important, however, in explaining differences among industries in rates of technological progress. For example, in a model developed by Nelson (1988), technological opportunity alone determined the rate of technical advance. The profit-maximizing R&D intensity increased both as technological opportunity increased and as appropriability conditions strengthened. Given the level of technological opportunity, however, a higher level of appropriability -- and a consequently higher R&D intensity -- raised only the level of technology, not its rate of change. Recent econometric work by Nelson and Edward Wolff (1992) provides empirical support for these propositions.

The relative lack of attention to the role that technological opportunity plays in determining an industry's levels of R&D intensity and technological progress derives in part from the lack of precision in defining the concept and the lack of operational measures of its empirical referent. Technological opportunity certainly matters, but we need a better conceptualization and measurement of it. In this paper, we shall try to lend greater precision to the concept, to develop various operational measures of an industry's technological opportunity, and to examine interindustry differences in technological opportunity.

We begin, in Section II, with a theoretical examination of the concept of technological opportunity and a discussion of three general categories of sources of any particular industry's technological opportunities. Then in Section III, we shall describe how we sought, in the Yale survey, to measure the strength of these various sources of technological opportunity. Our results concerning how industries differ in the importance of these sources are described in Section IV, and in Section V, we explore the extent to which differences in the strength and sources of technological development across industries explain variation in R&D intensity and technological advance among those lines of business. A final section contains concluding remarks.

II. The Character and Determinants of Technological Opportunity

The proposition that technological opportunities are richer in some industries than in others is plausible enough, as are some rough and ready ideas about why. For example, successful basic research on gene cloning opened a wide range of opportunities to develop new pharmaceuticals, new seed varieties, and new medical test devices. Similarly, the discovery that certain ceramic materials display superconductivity at significantly higher temperatures than was earlier dreamed possible pointed to industrial research opportunities that did not exist, or at least had not been seen, before. If low-cost superconductivity is achieved, a wide range of new possibilities will be opened for research and development that aims to achieve faster computers, more efficient electricity transmission, and high-speed trains.

Despite the importance of the concept of technological opportunities, it is not apparent how to formalize or to measure them. Opportunities for technological development are varied and multi-faceted. Nevertheless, in the context of seeking to explain interindustry differences in R&D intensity by differences in technological opportunities and in the ability to appropriate returns, several related formalizations are suggested. Technological opportunities, which comprise the set of possibilities for technological advance, may be measured in terms of the distribution of values of improved production-function or product-attribute parameters that may be attained through R&D, or, alternatively, as the distribution of returns to R&D, given demand conditions, the current level of technology, and the appropriability regime. In the search model of R&D activity, which analogizes R&D to drawing balls from an urn, technological opportunity describes the distribution of values of the balls in the urn. When technological opportunity is "high," the distribution of draws has a higher mean than or stochastically dominates the distribution of draws when opportunity is "low." In the other standard model of R&D that analogizes R&D to physical investment and the stock of knowledge to the stock of physical capital, technological opportunity corresponds to the function that maps the flow of R&D into increases in the stock of knowledge. In these contexts, appropriability refers to the fraction of the returns produced by R&D that the firm making the investment can reap for itself. It is the ratio of the private to the social returns at the margin.

These characterizations of technological opportunity suggest that R&D at the level of the firm or industry is subject to diminishing returns. As resources are devoted to R&D and projects are completed, technological opportunities are depleted and the pool of opportunities can be exhausted. The two best known models of R&D activity -- the search model and the R&D capital model -- display diminishing returns. But, in fact, the pool of opportunities is constantly being replenished. It is precisely the sources of new technological opportunity -- the additions to the pool -- and their relative importance in different industries that we seek to measure.

A striking characteristic of industries that are commonly thought to be rich in technological opportunities is that high R&D intensities and high rates of technical advance tend to be sustained over time. They do not fall off as one would expect if the most productive opportunities were being exhausted and no new ones were being added. For example, although there certainly are fluctuations, technical advance in industries like semiconductors and synthetic materials continues at a high rate. Perhaps the key characteristic that distinguishes industries with high technological opportunities from those in which such possibilities are limited is that those opportunities are being augmented, or renewed, at a higher rate in the former than in the latter. Thus, a high R&D intensity can be sustained in the semiconductor industry because even though firms are exploiting prevailing opportunities at a rapid rate, new ones are being created with comparable speed. In contrast, in the industries producing lumber and wood products only a low R&D intensity can be sustained. A higher rate would deplete technological opportunities more quickly than new ones are being created. The resulting decline in marginal returns would cause a reduction in the R&D intensity that firms find profitable.[2]

We distinguish three different sources of new contributions to an industry's pool of technological opportunities; contributions from each source serve to offset the diminishing returns to which a fixed pool would give rise. First, advances in scientific understanding and technique expand the pool of technological opportunities. Second, technological advances in other industries, both inside and outside the vertical chain of production, and in other institutions in the economy, can enrich technological opportunities within a given industry. Finally, there are positive feedbacks from an industry's technological advances in one period that open up new technological opportunities for the next. We will consider the character of these different sources of technological opportunity in turn.

A. The Advance of Scientific Understanding

The most powerful and, over the long run, almost certainly the most important source of new technological opportunities has been the advance of scientific knowledge. The last decades of the nineteenth century were marked both by a significant and sustained increase in the rates of technological advance in a wide variety of sectors and by the coming of age of formal science as a body of knowledge. Since that time formal science has significantly illuminated the opportunities for technological advance and provided the basis for the other important forces that offset diminishing returns to technological opportunity, which we have identified.

It is widely believed that most significant technological breakthroughs can be traced directly to advances in basic general scientific understanding that occurred just prior to the breakthrough. For some technological advances this description is accurate. Modern radio can be traced to Maxwell's work in fundamental physics done several decades earlier, and the atomic bomb followed the research of physicists in the thirties who were seeking a better understanding of the fundamental nature of matter. Many current developments in biotechnology can also be traced quite directly to recent advances in basic science. But perusal of, for example, the numerous case studies compiled by Jewkes, Sawers, and Stillerman (1958) suggests that direct and simple linkages from science to technology are the exception, not the rule. The connections between scientific advance and technical advance are generally complex and subtle; the lags are long and the feedbacks intricate.

A number of studies have documented that, for the most part, scientists and engineers engaged in industrial R&D employ science as a set of tools and stock of knowledge to be tapped in problem-solving (see, e.g., Gibbons and Johnston, 1974). Used this way, old science may be as useful as more recent developments, and the relation between technological advance and the current scientific frontier may be remote. The evidence is overwhelming that most applied R&D efforts start with a need or an objective and then reach back to science to enable the goal to be achieved. In general, the science employed will be in the mind of the researcher or otherwise easily accessible, as through consultation with other workers. Some industrial R&D scientists will be more up to date than others, and as scholars like Thomas Allen (1977) have shown, these often serve as "inside consultants." It is rare that the stimulus for an applied R&D effort comes from an appreciation of new basic scientific findings, and the search for relevant science carries no presumption in favor of recent science.

Considering just this connection between basic science and technological advance, can it be argued that scientific advance generates offsets to diminishing returns to R&D? We believe it can, although the postulated relation is not as straightforward as that implied by the view that new basic science directly yields new technology. From the more complex perspective, as science advances over time, the pool of potentially useful knowledge and techniques is enhanced, old understandings are sharpened or revised, and new ones are added. More generally, the problem-solving power that can be tapped by industrial scientists increases. Thus, some old problems that could not be addressed adequately before become solvable. Furthermore, newly minted graduate scientists and engineers come to their industrial jobs with up-to-date knowledge and technique, thereby making these new resources more readily available in industrial R&D. From this perspective, the education of a new generation of industrial scientists might be seen as the major contribution of universities, the locus of most basic scientific activity, to technical advance.

This description of the connection between science and technology suggests that advances in science enhance problem-solving capabilities in applied R&D in an unsystematic, even serendipitous, way. Scholars who have stressed the autonomous development of science would support this view of the interaction. But in fact many contemporary sciences and related engineering disciplines are relatively closely harnessed to efforts to solve problems in applied technology.

Thus, we perceive a second kind of connection between scientific and technological advance that involves the scientific and engineering disciplines in which research is deliberately focused on facilitating technical progress of various kinds. Work in fields like metallurgy, materials science, computer science, electrical engineering, and pathology -- all of which are strongly represented in academia as well as in industry -- directly facilitates technological advance and enhances the problem-solving capacity of those who endeavor to make such progress. Because the applied sciences and engineering disciplines respond to problems generated by practical experience, developments in these fields tend to provide important, direct offsets to the depletion of the pool of technological possibilities in the industries toward which their efforts are directed.

Sociologists of science have pointed to theoretical physics as canonical and have argued that the great advances in that field have been driven by scientific curiosity and the natural unfolding of discovery rather than by any particular interest in applications. Thermodynamics, which was expressly oriented to trying to understand steam-engine physics, has been regarded as an exception within physics. If, however, the sociologists of science had focused instead on chemistry, or on biology following Pasteur, the view of what drives modern science might have been much different. Thermodynamics might not have been regarded as the exception to the rule but as the norm.

In view of these two different roles that science plays in shaping technological opportunities -- one as a stock of knowledge and the other as a flow of often directly relevant knowledge -- several different questions arise. In our research we tried to address the following:

- Do industries differ in the directness of their linkages to science?
- Do they draw upon different fields of science?
- Which industrial technologies are strongly linked to advances in science?
- Advances in which fields of science most powerfully affect technological opportunities?

We believe a strong case can be made that university research usually is important when new research findings directly influence industrial innovation. Thus our way of seeking answers to the last two questions was to ask the following:

- Which industries draw most on scientific research undertaken in universities?
- Which fields of university research most strongly influence technical advance in industry?

B. Technological Advances Originating Outside the Industry

Technological opportunities in one industry can be enriched by technological advances that are achieved in others. For example, the use of new ceramic materials in aircraft engines permitted construction of engines that operated at higher temperatures and pressures than older materials could withstand. Technological opportunities in the design of aircraft engines were thus made possible by the development of new materials in another industry. The history of technology is replete with such examples.

The creation of new general purpose components -- for example, power sources or electronic components -- quite often opens new technological opportunities in a variety of industries that use that kind of component. Thus, the light internal combustion engine made possible both a viable automobile design and machine-powered flight, although the work on engines was motivated far more by the former than the latter objective. Similarly, the invention of the transistor opened up vast technological opportunities in the design of radios, televisions, calculators, and computers despite the fact that its inventor worked for a company that produced only telephonic equipment.

Advances in production process technology and equipment, which are often the result of work done by upstream suppliers, also can expand a downstream industry's opportunities to improve product attributes and designs. For example, Watt's steam engine would not have been possible without the earlier advances that occurred in the machinery used to bore metal. The latter permitted the fashioning of the more accurate and uniform cavities required for the steam engine. Similarly, the adoption of honeycomb structures in aircraft design was dependent upon the development of numerically-controlled machine tools that could produce such structures.

Improvements in the instruments used for measuring, testing, and manipulating materials in the laboratory also affect the set of results industrial R&D can attain. This is a point that Derek Price (1984) and Nathan Rosenberg (1992), among others, have stressed. Instruments initially designed for purely scientific purposes, such as devices to measure nuclear magnetic resonance or to charge, accelerate, and direct ions, have had substantial impact on the technological opportunities available, respectively, in medical diagnostics and in semiconductor manufacturing (Rosenberg, 1992).

In addition to the industries that supply materials, equipment, and research instruments, another source of technological opportunities for firms in a given line of business is the set of users of the industry's products. Based on their experience with the current product, the industry's customers may contribute ideas about improving the product or process. In other situations, technological advances in the customer industries may stimulate new developments in the product they buy. Eric von Hippel (1976, 1977) has documented the importance of user feedback for product design by firms producing scientific instruments and semiconductor process equipment.

Other external sources, outside the vertical chain of production, also contribute to the technological opportunities in some industries. These potential sources include government laboratories, universities, professional and technical societies, and independent inventors.

The contributions that external sources make to technical advances in an industry almost surely increase the industry's technological progress. Whether they raise or lower the productivity of R&D in the industry is more uncertain. It is an open question whether, in any particular case, R&D done beyond the boundaries of an industry and R&D done within the industry are complements or substitutes. The relation between the two efforts depends on the kind of work considered. Thus, R&D that is done on a production process by an upstream supplier might well be both a substitute for process R&D in the line of business itself and a complement to product R&D undertaken by that industry. Although one would expect technical change in an industry to be positively related to the R&D done by its upstream suppliers as well as to the R&D efforts of firms in the industry itself, whether a strong upstream program would stimulate or diminish industry R&D is uncertain.

We are interested in the contributions that technological advances outside an industry -- whether they originate in another industry or in another private or public establishment -- make to different industries. Which external sources are most important to different industries? For which industries are the technological advances of supplier firms very important, and in which is the progress of downstream firms significant? How do industries differ in terms of the contributions made to them by university research and by government laboratories?

C. Feedbacks from Technology

In many simple models of R&D, activities undertaken today simply create better technologies, and this in itself diminishes the stock of untapped technological opportunities. But in a number of industries today's research also generates new starting points and new knowledge, which enrich technical opportunities for tomorrow. Furthermore, what a firm learns from its own R&D may be augmented by feedback from other firms that make or use the new product or process.

Nathan Rosenberg (1969) identified a type of feedback from technology that he called "compulsive sequences." He described the innovative efforts in an industry at a given time as being concentrated on a limited number of distinct, identifiable problems. When one of these "bottlenecks" is overcome, it generates new technical problems that must be solved if the full benefits of the initial breakthrough are to be gained. Rosenberg cited the history of technology in the machine tool industry as an example, while other scholars have identified similar bottleneck/breakthrough sequences in textile manufacturing, coal and steam technology, and petroleum refining.

Other feedbacks involve the creation of new knowledge or opportunities as a result of prior advances. For example, the successful development of a new aircraft engine that operates at higher pressures and temperatures than prevailing engines could endure will confirm engineers' judgments that it was possible to design such an engine. Given that achievement, the engineering staff can begin to think about how to create an engine that will perform at still higher operating temperatures and pressures. The present success may have been made possible at least partly by new discoveries, for example, that ceramics could be used on parts that previously had been made of metal. Success in using ceramics on these parts naturally suggests that it might be possible to extend the range of application still further. That predisposition might be reinforced by the enhanced understanding of ceramics and the improved skills in shaping them that were gained in the course of the prior R&D effort. Finally, the airlines that purchased the engines might report that greater use of ceramics reduced required maintenance, and this might further stimulate engine manufacturers to try to replace metal by ceramics in other parts.

If the feedback mechanisms described above are sufficiently well-defined, technological development may tend to proceed along what Nelson and Winter (1977) call "natural trajectories." In some situations, they argue, technological advance proceeds fairly steadily in a relatively clear direction and does not lurch myopically from one bottleneck to the next. Certain engineering heuristics develop in these industries, and these are used and strengthened to solve a particular problem -- for example, increasing yield for a given production process or increasing the range of output over which economies of scale are achieved or improving the performance characteristics of the product. Devendra Sahal (1981) also has described these phenomena.

In our view and that of other scholars of technical advance, these kinds of feedback from current technological advances provide a partial offset to diminishing returns to R&D. The logic of such feedbacks suggests, however, that while they can partially offset the tendency of R&D to deplete prevailing opportunities, in the long run they cannot totally offset that tendency. It does not seem plausible, for example, that progress along natural trajectories alone could permanently forestall the exhaustion of opportunities for technological advance. Thus, despite evidence that these feedbacks from technological advance in one period to further development in the next have been quite important in some industries in which both R&D intensity and technological advance have been sustained at high rates, the underlying logic of these mechanisms makes it highly unlikely that they alone could have permitted such impressive progress.

We shall present evidence from the Yale survey that sheds light on the importance of various natural trajectories in different industries. To the extent that R&D managers accurately assess the importance of these trajectories in their lines of business, the responses to our questionnaire will reflect the extent to which diminishing returns to R&D are offset in different industries by positive feedbacks of the sort we are describing here.

III. The Yale Survey on Industrial Research and Development

Our results about the sources and significance of interindustry differences in technological opportunities derive from the survey of industrial research and development we undertook in 1983-84. The questionnaire itself, our survey methods, and the limitations of our survey are discussed in detail in our 1987 article. Here we present only the basic information about the survey needed to assess and understand the results we provide on technological opportunity.

The survey was directed at high-level R&D managers who were knowledgeable about both the relevant technology and market conditions in their lines of business. We followed the Federal Trade Commission's definitions of lines of business, which in manufacturing principally correspond to four-digit SIC industries although some are defined as groups of four-digit (or even three-digit) industries. We received responses from 650 managers representing 130 lines of business. For 75 lines of business we had more than two respondents, for 45 of those industries we had five or more responses, and for 18 we had ten or more completed questionnaires. The sample was reasonably representative of firms engaged in R&D with one notable exception. Specifically, we excluded firms that did not have publicly traded securities. As a consequence, the representation of small firms in our sample was limited and nearly all start-up ventures, which are important sources of innovation, were excluded.

We treated the R&D managers who completed the survey as informed observers of their respective lines of business, not as representatives of a particular firm. The respondents were asked to report typical experiences or central tendencies for their lines of business. This increased our ability to understand interindustry differences, but it also resulted in heterogeneity in the responses for a given line of business. The intraindustry heterogeneity was magnified by the inherently subjective semantic scales we used in the survey. Most questions asked respondents to locate answers on a seven-point Likert scale. For example, managers were asked to evaluate on a seven-point scale, running from "Not relevant" to "Very relevant," the relevance of chemistry to technological progress in the line of business over the preceding 10-15 years. Since there is no objective anchor for such evaluative rankings, and since we were in no position to suggest one, different R&D managers may have used the scale differently even though they perceived the same environment.

IV. Interindustry Differences in Technological Opportunities

In this section, we present our survey results on interindustry differences in the three sources of technological opportunity described in Section II. We begin with the contributions of scientific advance to technological progress in different lines of business.

A. The Advance of Scientific Understanding

Science, we have suggested, enhances efforts to advance industrial technology in two ways. First, it provides an expanding pool of theory, data, technique, and general problem-solving capability that is employed in industrial R&D. The science drawn from the pool is not necessarily new. Second, scientific developments sometimes directly open new technological possibilities -- proposing new solutions to old problems, pointing to promising new avenues to pursue, and occasionally even providing prototypes for elaboration and refinement. We have proposed that, where this direct contribution arises, the science involved is often an applied science or an engineering discipline, although nuclear physics (in military applications) and molecular biology (in contemporary biomedical applications) are notable instances where recent advances in basic science have had an almost direct impact on technology.

To explore interindustry differences in the strength of science in the first role, we asked each of the R&D managers responding to our survey questionnaire to indicate the relevance of various fields of basic science and applied science to technological progress in his or her line of business over the preceding 10-15 years. The basic scientific fields were biology, chemistry, geology, mathematics, and physics. The fields of applied science were agricultural science, applied math and operations research, computer science, materials science, medical science, and metallurgy. We asked our respondents to score relevance on a seven-point semantic scale on which a score of one indicated "not relevant" and a score of seven indicated "very relevant."

Consider first the overall pattern of responses across the fields of basic and applied science. Table 1 reports for each field of science the number of industries in which the mean relevance score was five or higher and the number of industries in which it was six or higher. This is a simple but robust method of summarizing the responses.[3] The table also indicates selected industries in which the particular science was highly relevant to technological progress.

Every field of basic and applied science received a score of six or higher from at least a few of the 130 lines of business in our sample. Among those fields that were regarded as highly relevant (earning a mean relevance score of six or more) to only a few industries were biology, geology, mathematics, applied mathematics, agricultural science, and medical science. On the other hand, several disciplines were relevant to a large number of industries. Thus, chemistry, materials science, metallurgy, and computer science each received mean scores of six or higher from over thirty industries. The widespread relevance of the first three of these fields undoubtedly reflects the longstanding importance of the composition and properties of materials in most industrial technologies, and the relevance of the newer field of computer science surely reflects the nearly universal scope of potential applications for computers in product design and process control.

The lists of particular sciences that the various industries identified as important for their technological progress contain few surprises; neither do the lists of industries in which each science is most relevant. Thus medical science and biology are rated as important by the industries that one intuitively believes are closely connected with them -- drugs and medical/surgical instruments for medical science; drugs, pesticides, animal feeds for biology. The industries related to agriculture almost always rate agricultural science as important, and they also often give high marks to biology and chemistry. The industries that are generally deemed to employ chemical-based technologies--drugs, organic chemicals, plastics, petroleum refining, pulp and paper -- all judged chemistry to be important. Finally, materials science, computer science, and sometimes physics were rated as important by industries like semiconductors, computers, and communications equipment.

It is not at all surprising to find the "high tech" sectors -- semiconductors, aerospace (guided missiles, aircraft engines, ball bearings), drugs, and agricultural chemicals -- heavily represented in the list in Table 1 of industries in which the different sciences were highly relevant to technological progress. The influence of mathematics, operations research, and computer science on motor vehicles and machine tools reflects the contribution of these mathematically based disciplines to computerized automation. Some industrial applications of science are also quite clearly linked to health and safety issues. Note, for example, that asbestos appears among the list of industries making the most of contributions from medical science. Tobacco, coffee, and confectionery products (which includes sweeteners) were also among those to which medical science was highly relevant.

Because there are substantial differences among industries regarding the fields of science that R&D managers view as most relevant, it is not apparent how to construct the "best" measure of the proximity of an industry to science. We have constructed two measures. One is the mean relevance score of the science that was rated as most relevant by respondents in an industry. The second measure for each line of business is the sum across all the fields of science of the mean relevance scores that respondents in the industry assigned to the various sciences.

Table 2 presents the rank ordering on these two measures of the closeness to science of the industries from which we received ten or more responses; the lines of business closest to science appear at the top. There is a positive correlation between our two measures. By either criterion, drugs and semiconductors appear very close to science, while motors, generators, and industrial controls, and motor vehicles parts and accessories are relatively distant from science. There are, however, some interesting differences between the two rank orderings. In particular, the chemistry-based industries rank lower when proximity is based on the sum of the relevance scores than when it is judged using the highest relevance score. This suggests that the scientific links to these industries, though strong, are concentrated. In contrast, semiconductors and related devices tend to draw strongly on a number of fields of science -- chemistry as well as physics and four of the six applied sciences we included. Consequently, the semiconductor industry ranks especially high when proximity to science is measured by summing the scores over all fields of science.

Our probes of interindustry differences in the importance of new scientific developments to technical advance were less direct. We had some doubts about the ability of our respondents to distinguish sharply between the general relevance of a scientific field and the relevance of recent developments in that field, and we were also concerned about our ability to draw a distinction for them within the constraints on explanatory length imposed by the written questionnaire. Further, we are strongly inclined to the view that when new science is important, universities are often important (indeed, often dominant) sources of that new science. Thus we use the relevance ratings that industries gave to university-based research in a field as a proxy for the relevance of new basic and applied science as well as a direct indicator of lines of business in which university research is relevant.

Table 3 presents the same information concerning the relevance of university research in a field of science to industrial technology as Table 1 did for science in general. It reports for each field of science in our questionnaire the number of industries that gave university research in that field a mean relevance score of five or higher and the number that gave it a mean score of six or seven. Table 3 also indicates selected industries for which the particular field of university science was highly relevant to technological progress.

The data suggest systematic differences between the role of science as a pool of knowledge (as measured by the general relevance of science) and the role of new discoveries (as proxied by the relevance of university research). Overall, university-based research in a field is reported as much less important to recent technological advance than is the overall body of science in that field. For example, 43 industries (1/3 of the sample) gave chemistry as a field a mean score of 6 or more, but only 3 give university-based chemistry research such a high score. A total of 74 industries (more than 1/2 of the sample) rated the relevance of chemistry as a field at 5 or higher, but only in 19 lines of business did university research in chemistry receive that high a mean score. Similarly, in physics, computer science, materials science, and metallurgy, the generic relevance of the field to industrial technology is perceived to be much greater than the specific relevance of university research.

In general, the discrepancy between the measured relevance of generic science (a pool of knowledge) and that of university science (new results) is greater for basic than applied science. This is not surprising because research in the applied sciences and engineering disciplines is guided to a large extent by perceptions of practical problems, and new findings often feed directly into their solutions. In contrast, to the extent that new research in basic science is relevant to industrial technology, it is likely to be as an addition to the broad knowledge base rather than as directly useful results. As Table 3 shows, the university research in applied sciences and engineering fields tends to have greater relevance to industry than does university research in basic sciences. Computer science, materials science, metallurgy, and the engineering disciplines have high relevance scores in the largest number of industries.

This by no means implies that new findings in fundamental physics, for example, are not relevant to industrial innovation. The history of technology reveals convincingly that they often are. Rather, we read our findings as indicating that advances in fundamental scientific knowledge have their influence on industrial R&D largely through two routes. One, which we have mentioned, is through influencing the general understandings and techniques that industrial scientists and engineers, particularly those whose training is recent, bring to their jobs. The other is through their incorporation in the applied sciences and engineering disciplines and their influence on research in those fields.

Table 3 suggests that biology is an exception to the rule that university research in a basic science is judged less relevant to industrial innovation than the broad stock of knowledge in that field. R&D managers in 14 industries gave biology as a field a score of 5 or more; respondents in 12 lines of business rated university research in biology that high. Thus, almost all the industries that value the contribution of the biological sciences generically -- small as that number is -- also value university-based contributions in that field. This reflects the fact that a very substantial fraction of agricultural and medical research is conducted in universities. Furthermore, insofar as the importance of new scientific developments and the importance of university research are highly correlated, those industries with technologies based in the biological sciences seem to be fed by new scientific developments to an unusually great degree.

These findings are consistent with the results reported by Francis Narin and Dominic Olivastro (1992), who find that U.S. patent documents for drugs and medicines cite recent scientific publications with four times the frequency of patents in the next highest product field (chemicals, excluding drugs and medicines). Patents covering scientific and professional instruments and electronic devices are the next most inclined to cite recent scientific publications, a general pattern that would seem consistent with the industries identified in Table 3 as closely linked to university science.

Our findings are also consistent with the answers our respondents gave when asked to rate the importance of the contribution of various outside sources to technological progress in their lines of business, a topic we will take up in detail next. For purposes of the current discussion, we list in Table 4 the industries from which we had three or more responses that gave university research (without specification of a field) a mean score of four or higher. Most of these industries operate in the agricultural or health fields and draw on university research in the basic and applied biological sciences. The system of publicly supported university research in these fields was expressly intended to stimulate and support change in agriculture and associated industries and in medicine. The list includes, as well, engineering and scientific instruments and semiconductors, industries that draw on university research in computer science, materials science, and electrical and mechanical engineering. Public funding of that research was also undertaken with the goal of contributing to technological progress in the specific industrial areas that have benefitted.

Finally, the survey results display some patterns one might expect to find among the contributions of the various sciences. The relevance scores given by individual respondents (or measured as the mean responses within an industry) for both agricultural science and medical science are highly correlated with that of biology, though less highly correlated with one another. The relevance scores of operations research, computer science, materials science, and metallurgy are highly correlated with the relevance of physics and mathematics. Chemistry is highly correlated with biology, and physics with mathematics. The relevance of physics to technology in a line of business is negatively correlated with that of biology.

B. Technological Advances Originating Outside the Industry

The responses to our survey provide insights into the contributions that different outside sources have made to technological progress in different lines of business. We asked survey respondents to assess, on our semantic 7-point scale (1 = no contribution, 7 = very important source of contribution), the importance of 10 sources. They fall naturally into two groups: (a) sources within the industrial chain -- firms within the line of business, material suppliers, suppliers of equipment used in manufacturing, suppliers of equipment used in research, and users of the products of the line of business; and

(b) sources outside the industrial structure -- university research, government research labs, other government agencies, professional or technical societies, and independent inventors.

The survey results for extraindustry sources of technological knowledge are reported in Table 5, which is similar to the tables we used to report results on the contributions of the different sciences. We indicate the number of lines of business that gave the external source a mean importance score of 5 or higher, the number giving it a score of 6 or 7, and selected industries in which that external source was viewed as making a large contribution to knowledge.

Many industries valued highly the contribution made to their technological progress by firms located somewhere else in the vertical chain of production. Nearly half the industries valued contributions from suppliers of materials at 5 or more, and nearly half ranked suppliers of production equipment that high. Material suppliers were especially important sources of technology in food and forest products industries and in electronics industries. Equipment suppliers made valuable contributions to technology in food, forest, and metals products industries. These findings are consistent with those of Pavitt's study (1984). Suppliers of research equipment played a much less important role in enriching technological opportunities than did other upstream sources, but they were important in food products, drugs, soaps, and semiconductors.

The contributions that users or customers made to technological advance were rated at 5 or more by about one-quarter of the respondents. The contributions from customer industries were seen as most important in the machinery, electrical equipment, and surgical and medical instruments sectors. This is consistent with the work of Eric von Hippel (1976,1977), who found that user industries played an important role in advancing the technology of the semiconductor-process-equipment and scientific instruments industries.

The contributions to technological progress in a line of business that were made by sources outside the vertical chain of production generally were seen as less important than the contributions of upstream and downstream firms in the chain. Government research labs and other government agencies seem to have played a quite minor role in generating technological progress in most of the lines of business on which our sample firms reported. More than one-third of the industries indicated that government labs made no contribution to the industry's technology while more than one-half of the lines of business gave the same assessment for other government agencies. There were, however, six lines of business in which government labs were viewed as making an important contribution (with a mean score of 5 or higher). These included fertilizers, logging and sawmills, and optical instruments. Similarly, there were five industries, including automobile components and optical instruments, that indicated that other government agencies made an important contribution to technological progress.

Our earlier discussion touched on the role of university research in generating technological progress. We noted that, for the most part, industries draw on science as a pool of knowledge and make little use of the most up-to-date university research findings. Indeed in twenty-three of the lines of business, our respondents estimated that university research made no contribution at all to technological progress in the industry. In some lines of business, however, as we noted earlier, university research is important. In our sample, respondents from fifteen lines of business gave university research a relevance score of four or higher; these are listed in Table 4. As we stressed earlier, the fields of university research feeding into these industries tended to be the applied sciences and engineering disciplines, rather than the more fundamental sciences. Furthermore, the industries listed in Table 4 have been deliberately targeted by government agencies that have funded university research in these fields to support technical progress in these industries.

Professional and technical societies were seen as contributing importantly to technical advance in only a few industries. Indeed, 19 lines of business reported that such organizations made no contribution at all. It is interesting and surprising that among these was synthetic fibers since one might have expected chemical and textile societies to have played more of a role in achieving progress in synthetics. On the other hand, professional and technical societies were rated as important contributors to technological advances in 12 industries, which included two forestry-related industries -- logging and sawmills and paper industries machinery.

Finally, independent inventors played an important role in 9 lines of business, for all of which we had only 1 or 2 responses. For the most part these are industries in which the firms are small and where formal R&D programs are limited. Nearly a quarter of the lines of business in our survey, 32 industries, indicated that independent inventors made no contribution to technological progress in those industries.

Despite the importance of extraindustry sources of technological knowledge, especially those sources with vertical linkages, in nearly all the lines of business within our sample, firms within the industry were viewed as playing a very important role in generating technological progress. The mean response on the 7-point scale was 5.92. The mean was 5 or higher for 116 of the 130 lines of business -- nearly 90% of the industries -- and 6 or higher for 72 of the lines of business. Not surprisingly, there was a statistically significant simple correlation of .32 between an industry's R&D intensity and the reported contribution of firms within the line of business.

C. Natural Trajectories

To measure the extent to which technological opportunities feed back on themselves and are enhanced by the presence of natural trajectories, we asked respondents to rate the extent to which certain technological activities were engaged in consistently and repeatedly in their lines of business. Table 6 lists a group of technological activities oriented toward production processes and then a group concerned with product characteristics, together with the number of lines of business in which each activity was rated as important. We also indicate selected industries in which the trajectory was important.

The results show that what Nelson and Winter call natural trajectories are indeed pervasive in manufacturing technology. With a couple of exceptions, each of the natural trajectories was viewed as important by at least thirty percent of the lines of business in our survey. Nearly two-thirds of the industries rated the importance of mechanization at 5 or higher and similarly for process-yield improvement. Over two-thirds gave that high a rating to improving the product's performance characteristics, and more than two-thirds rated designing products for specific market segments at that level. The importance of changes in the scale of production and changes in product dimensions was less pervasive. The former was relevant, however, to certain materials processing industries, and changes in product dimensions were important to semiconductors and computers.

The presence of natural trajectories was highly intercorrelated. On the process side, mechanization or automation, improvement in process yield, and improving the properties of input materials tended to occur together. Similarly, with regard to technological activities concerned with product characteristics, the reported importance of improvements in the performance characteristics of the product, designing products for specific market segments, and customization of the product tended to be highly correlated. The importance attached to movement toward a standardized or dominant product design, however, was negatively correlated with the importance a line of business attached to these other natural trajectories on the product side.

V. Patterns of Technological Opportunity and Industrial R&D Performance

In this section, we address two further questions about interindustry differences in technological opportunity. First, to what extent do industries differ in their overall patterns of technological opportunity? Second, how closely related to the presence of technological opportunity are an industry's innovative effort and its innovative output?

In Table 7 we portray some intersectoral differences in the pattern of technological opportunities. To avoid losing the forest for the trees, we aggregated our data to the level at which the NSF collects R&D data, which is roughly 25 2-digit and groups of 3-digit industries. We focus on six industrial sectors: electronic components; aircraft and missiles; drugs; stone, clay, and glass; metal products; and nonelectrical machinery. For each of these sectors, we list the mean score the respondents in the sector gave to major sources of technological opportunity.

The data in Table 7 reveal some interesting patterns. We can readily distinguish industries that are rich in technological opportunity from those that are not. The electronic components sector gave every single source a higher score on our seven-point scale than did the three sectors with the least abundant opportunities: stone, clay, and glass; metal products; and non-electrical machinery (excluding office and computing equipment). This is almost, but not quite, the case as well for comparisons between the ratings given by the aircraft and missiles sector and those given by the low opportunity sectors.

Within the low opportunity sectors there are some interesting differences. Two of them -- the stone, clay, and glass industries, and metal products -- have relatively strong connections with at least one science. In contrast, no science is viewed as highly relevant to progress in non-electrical machinery. External sources make only a limited contribution to technology in stone, clay, and glass and in the non-electrical machinery sector. On the other hand, firms in the metal-products sector report that their equipment suppliers are important contributors to technological advance in their industry.

There are also interesting differences among the high opportunity sectors. Drugs and electronic components both have extremely strong links to science, but with the exception of chemistry, they are tied to entirely different sciences. The aircraft and missiles sector is much less strongly influenced by advances in the basic sciences. Upstream suppliers are very important in electronics, somewhat less so in aircraft, and not at all important in drugs. On the other hand, reflecting the strong science connections, university research and government laboratories are far more important in the drug industry than in the others. Finally, while the electronics sector has a variety of very strong natural trajectories, several of these activities -- improving process yield and change in product dimensions -- are much less important in aircraft and missiles. In contrast, improving process yield and improving product performance are the only important natural trajectories in pharmaceuticals; all the other feedback mechanisms are much weaker in the drugs sector than in the other two high opportunity sectors.

Turning to the second question we address in this section, Table 8 reports the correlation at the line of business level between three measures of technological performance and the reported relevance of each source of technological opportunity. The first measure of technological performance we use is industry R&D intensity, as measured by the Federal Trade Commission data on industry-level R&D spending as a percentage of sales. Note that R&D intensity, of course, measures an input to production of technical advance, not performance itself. As Nelson observed long ago, richer technological opportunity should unambiguously improve innovative output, but it will not necessarily increase innovative inputs.[4]

The other two measures of technological performance are drawn from responses to our survey. We asked our respondents to assess, on a 1-7 scale (with 1 = very slow, 7 = very rapid), the rate of process innovation and the rate of product innovation in their lines of business since 1970. We use the mean responses for each line of business as measures, respectively, of process innovation and of product innovation in that industry. Since reliable total factor productivity measures are not available at our level of disaggregation, to check the reasonableness of our survey-based measures we aggregated our data to the NSF level. Our measure of product innovation correlates .59 with total factor productivity while the correlation of our process innovation measure with the standard productivity measure is .52. R&D intensity is also highly correlated with our measures of innovation.

The results in Table 8 indicate that R&D intensity in an industry is strongly correlated with the strength of that industry's connections with several of the fields of science. That intensity is also positively correlated with the contributions made by university research and government laboratories, which suggests that the latter two kinds of R&D stimulate and complement industrial R&D. These are similar to the findings in Nelson and Wolff (1992). Strong contributions from upstream suppliers, on the other hand, were not positively correlated with industry R&D intensity, and there are some indications that the work of equipment suppliers and industry R&D are partly substitutes. Two of the product-oriented natural trajectories were positively associated with industry R&D intensity, but no process trajectory was positively correlated with this measure.

Turning to our measures of rates of product and process innovation in an industry, the connections with the applied sciences tend to be more strongly associated with rapid innovation than are the ties with the basic sciences. As we noted earlier, the effects of the latter may well operate through the strengthening of the former. The contributions of university research and of government labs are positively correlated with the reported rates of both product and process innovation.

In contrast to their negligible, even negative, correlation with R&D intensity, the contributions of upstream and downstream industries are positively correlated with product and process innovation. And the strength of natural trajectories is also much more closely correlated with our innovation measures than with R&D intensity in an industry.

Not surprisingly, natural trajectories directed to processes tend to be correlated more strongly with the rate of process innovation than with the speed of product innovation, and the reverse is true for product-oriented trajectories. Because the standardization of products tends to occur late in an industrial life cycle (Abernathy and Utterback, 1978), when process improvement is the focus of R&D, it is not surprising that our standardization measure is the single product trajectory that is more strongly correlated with the rate of process innovation. Also, the availability of improved materials from upstream sources correlates significantly with both process and product advance, while the contribution of equipment suppliers affects only process innovation.

The correlations reported in Table 8 are, of course, all simple correlations. The signs of these partial correlations are preserved, however, in the multivariate regressions that are estimated in articles by Cohen, Levin, and Mowery (1987), by Levin, Cohen, and Mowery (1985), by Levin and Reiss (1988), and by Nelson and Wolff (1992), all of which use data drawn from our survey.

V. Concluding Remarks

The survey-based measures of technological opportunity that we have described have performed quite well in studies explaining interindustry variation in innovation rates and R&D intensity. Nevertheless, these measures seem only to scratch the surface of the puzzle of what makes technological advance more rapid in some industries than in others. A deeper understanding of how science, external innovation, and internal feedbacks affect the rate of technical advance will undoubtedly require an accumulation of detailed case studies. To be useful, however, these studies must maintain an analytical focus on the distinctions among opportunity, appropriability, and demand conditions that we now have good reason to believe are properly regarded as the fundamental determinants of technical advance.

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Table 1

The Relevance of Science to Industrial Technology

Science	Number of industries with scores: ≥ 5	≥ 6	Selected industries in which the relevance of science to technological progress was large:
Biology	14	8	Drugs, pesticides, meat products, animal feed
Chemistry	74	43	Pesticides, fertilizers, glass, plastics
Geology	4	3	Fertilizers, pottery, nonferrous metals
Mathematics	30	9	Optical instruments, machine tools, motor vehicles
Physics	44	18	Semiconductors, computers, guided missiles
Agricultural science	16	9	Pesticides, animal feed, fertilizers, food products
Applied math/operations research	32	6	Guided missiles, aluminum smelting, motor vehicles
Computer science	79	35	Guided missiles, semiconductors, motor vehicles
Materials science	99	46	Primary metals, ball bearings, aircraft engines
Medical science	8	5	Asbestos, drugs, surgical/medical instruments
Metallurgy	60	35	Primary metals, aircraft engines, ball bearings

Table 2

Proximity of Lines of Business to Science

Ranked by Highest Relevance Score Given to a Science	Ranked by Sum of Relevance Scores across All Sciences
Drugs	Semiconductors and Related Devices
Semiconductors and Related Devices	Measuring and Control Devices
Plastics Materials and Resins	Pulp, Paper, and Paperboard Mills
Surgical and Medical Instruments	Drugs
Petroleum Refining	Petroleum Refining
Plastic Products	Aircraft and Parts
Steelworks, Rolling and Finishing Mills	Electronic Computing Equipment
Electronic Computing Equipment	Surgical and Medical Instruments
Industrial Organic Chemicals	Steelworks, Rolling and Finishing Mills
Aircraft and Parts	Industrial Inorganic Chemicals
Communications Equipment	Plastic Products
Pulp, Paper, and Paperboard Mills	Communications Equipment
Perfumes, Cosmetics, and Toilet Preparations	Pumps and Pumping Equipment
Industrial Inorganic Chemicals	Plastics Materials and Resins
Measuring and Controlling Devices	Industrial Organic Chemicals
Pumps and Pumping Equipment	Perfumes, Cosmetics and Toilet Preparations
Motor Vehicle Parts and Accessories	Motors, Generators, and Industrial Controls
Motors, Generators, and Industrial Controls	Motor Vehicle Parts and Accessories

Table 3

The Relevance of University Science to Industrial Technology

Science	Number of industries with scores: ≥ 5	≥ 6	Selected industries in which the relevance of university science was large:
Biology	12	3	Animal feed, drugs, processed fruits/vegetables
Chemistry	19	3	Animal feed, meat products, drugs
Geology	0	0	None
Mathematics	5	1	Optical instruments
Physics	4	2	Optical instruments, electron tubes
Agricultural science	17	7	Pesticides, animal feed, fertilizers, food prods.
Applied math/operations research	16	2	Meat products, logging/sawmills
Computer science	34	10	Optical instruments, logging/sawmills, paper machinery
Materials science	29	8	Synthetic rubber, nonferrous metals
Medical science	7	3	Surgical/medical instruments, drugs, coffee
Metallurgy	21	6	Nonferrous metals, fabricated metal products
Chemical engineering	19	6	Canned foods, fertilizers, malt beverages
Electrical engineering	22	2	Semiconductors, scientific instruments
Mechanical engineering	28	9	Hand tools, specialized industrial machinery

Table 4

Industries Giving University Research a Relevance Score
of Four or Greater

Fluid Milk
Dairy Products Except Milk
Canned Specialties
Logging and Sawmills
Semiconductors and Related Devices
Pulp, Paper, and Paperboard Mills
Farm Machinery and Equipment
Grain Mill Products
Pesticides and Agricultural Chemicals
Processes Fruits and Vegetables
Engineering and Scientific Instruments
Millwork, Veneer and Plywood
Synthetic Rubber
Drugs
Animal Feed

Table 5

Extraindustry Sources of Technological Knowledge

Source	Number of industries with scores: ≥ 5	≥ 6	Selected industries in which external contribution to knowledge was large:
Material suppliers	55	16	Food products, lumber/wood products, radio/TV sets
Production equipment suppliers	63	21	Food products, lumber/wood products, metal working
Research equipment suppliers	20	4	Food products, drugs, soap/detergents, semiconductors
Users	30	6	Machinery, electrical equipment, surgical/medical instruments
University research	9	3	Animal feed, drugs
Government laboratories	6	2	Fertilizers, logging/sawmills, optical instruments
Other government agencies	5	2	Auto components, optical instruments
Professional/technical societies	12	3	Paper industries machinery, logging/sawmills
Independent inventors	9	5	Hand tools, metal doors/frames, etc.

Table 6

Natural Trajectories of Technological Advance

Technological Activity	Number of industries with scores: ≥ 5	≥ 6	Selected industries in which the indicated technological activity was important:
Changes in scale of production	43	13	Aluminum smelting, wet corn milling
Mechanization/automation	75	29	Radio/TV sets, meats, logging, motor vehicles
Improving process yield	83	41	Semiconductors, radio/TV sets, roasted coffee
Improving input materials	53	18	Radio/TV sets, ball bearings, transformers
From batch to continuous process	40	14	Meats, dairy prods., processed fruits/vegetables
Changes in product dimensions	23	5	Semiconductors, computers
Improving physical properties of the product	66	26	Motor vehicles, synthetic rubber, plastic materials
Improving performance characteristics of product	96	47	Vehicles, synthetic fibers, computers, semiconductors
Moving toward standardization	28	6	Wet corn milling, refrigeration/heating equipment
Designing for market segments	92	24	Paints, screw machinery products, cosmetics, radio/TV
Tailoring product for individual customers	62	24	Screw machinery products, mining machinery, turbines

Table 7

Patterns of Technological Opportunity by Sector

Source of Opportunity	Electronic Components	Aircraft & Missiles	Drugs	Stone, Clay & Glass	Metal Products	Non-Electrical Machinery
	High Opportunity Sectors			*Low Opportunity Sectors*		
Basic and Applied Sciences						
Biology	1.8	1.2	6.8	1.4	1.3	1.4
Chemistry	6.0	3.8	6.6	5.8	4.6	3.5
Physics	6.5	5.6	3.3	4.2	4.6	4.5
Computer science	6.2	6.3	5.1	4.4	4.7	3.8
Materials science	6.6	6.4	3.1	5.7	6.0	4.9
External Contributions						
Material suppliers	5.1	5.1	3.2	3.9	4.7	4.3
Equipment suppliers	5.8	5.1	3.7	4.4	5.1	4.5
Users	4.9	4.9	4.2	3.5	4.4	4.6
University research	4.0	3.1	5.4	2.7	2.7	2.8
Government laboratories	3.6	4.1	4.8	2.1	2.3	2.5
Natural Trajectories						
Mechanization/Automation	5.1	5.1	4.0	5.1	5.0	4.9
Improving process yield	6.4	5.0	5.5	5.1	4.8	4.5
Improving input materials	5.4	5.4	4.5	4.6	4.7	4.4
Changes in product dimensions	6.1	3.7	3.4	3.3	3.6	3.7
Improving product performance	6.5	6.2	5.1	5.2	5.1	5.8
Designing for market segments	5.3	5.7	3.3	4.4	4.4	5.1

Table 8

Correlation of Opportunity and Performance Measures

Source of Opportunity	R&D/sales	Process innovation	Product innovation
	Significance level of Pearson correlation with:		
Basic and Applied Sciences			
Biology	++	0	0
Chemistry	0	+	0
Physics	++	++	++
Computer science	++	++	++
Materials science	0	++	++
External Contributions			
Material suppliers	0	++	++
Equipment suppliers	-	++	0
Users	+	++	++
University research	++	++	++
Government laboratories	++	++	++
Natural Trajectories			
Scale changes	0	++	+
Mechanization/automation	-	++	+
Improving process yield	0	++	+
Improving input materials	0	++	++
Batch to continuous processes	0	++	0
Changes in product dimensions	++	++	++
Improving physical properties	0	++	++
Improving product performance	++	++	++
Moving toward standardization	0	++	0
Designing for market segments	0	0	++
Tailoring for individual buyers	-	0	++

++ = Correlation positive and significant at .01 level.
\+ = Correlation positive and significant at .05 level.
\- = Correlation negative and significant at .05 level.

NOTES

1. Strictly speaking, the technological opportunities facing a single agent or firm are not independent of appropriability conditions. For example, one firm's feasible advances in technology may be blocked by the property rights of another. Thus, it is important to distinguish between private and social technological opportunities.

2. The ranking of industries by R&D intensity is remarkably stable over relatively short historical periods, such as a decade. In the United States the rank correlation between 1978 and 1988 industry R&D intensities (measured at the 2-1/2 digit level by the National Science Foundation) is 0.956.

3. When the right-hand tail of the cross-industry distribution of mean responses (reported in Table 1) is large, the left-hand tail is almost always small, and vice versa. Moreover, the overall mean and median relevance scores for each field of science tend to be higher the larger is the right-hand tail of the cross-industry distribution.

4. Increased technological opportunity may raise the average product of R&D without raising its marginal product. Thus, greater technological opportunity can improve technological performance without calling forth an increase in R&D investment.