Industrial Research in America: Challenge of a New Synthesis

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Industrial research has been a mighty contributor to the growth of the American economy over the past hundred years. Today the importance of such research is greater than ever. In fact, research as an integral part of technological innovation is the principal way in which industries can compete worldwide and offset rising energy, raw material, and labor costs, as well as cope with government regulation. In the United States, technological innovation has faltered over the past 10 years. The challenge now is to renew this prime source of the country's industrial strength through a synthesis utilizing the characteristic strengths of industry, academia, and government. There are fundamental forces setting this synthesis in motion, so the chances for achieving it appear promising. In the 1980's, the result may well be an explosive growth of industrial innovation. But the result is by no means assured. Required are long-range investment by industry and stable, realistic policies by governments to encourage such investment.

Summary. Industrial research in America faces a new era. Success will depend on a synthesis utilizing the strengths of industry, government, and academia to achieve industrial innovation. The origins of U.S. industrial research in the 19th century have led to its current traditions and philosophy. Vigorous, diverse, animated by both basic scientific knowledge and empirical techniques, it is today channeled by both societal needs and new technical possibilities. Many of its efforts involve fundamental research. Meeting future expectations will require even broader science, much of it from academia, as well as a license to function from governments and society.

The Antecedents

As recently as 1860, there were no industrial laboratories in the United States. Industrial research was scattered, pragmatic, and far below what today would be considered "critical mass." It followed the American tradition of individualism, self-reliance, and practical arts and skills, inherited from Franklin, Jefferson, and Jackson. Modern industrial research began with Thomas Edison's laboratory in West Orange, New Jersey, in the 1880's. Subsequently, over a period of 30 to 40 years, there was a proliferation of industrial research establishments. This movement was not exactly American pioneering. There were examples to be followed in the remarkable chemical and optical industries of Germany, but the driving force for such a profound development may have been happenings in the academic, scholarly community.

In the early 19th century, the true American scholar aspired to be the "omnipotent man." Later in the 19th century, academic specialization in the United States became the order of the day (*1*). By 1850, there were the beginnings of disciplinary departments in the universities, a trend which progressed rapidly and led to the specialized education that we see today. At the turn of the century, undergraduate education was liberal, concentrating on the unity of knowledge, while graduate education was pointed toward special disciplines in depth. Emerging from this system was an elite of experts, specialists who were the leaders of thinking in their fields. This fragmentation of American scholarship, particularly in science, has led to the rigid departmental lines we see today in many academic institutions and the high degree of specialization of their graduates. This specialization is fundamentally at odds with the aims of industrial research, namely the creation of new enterprise that is interdisciplinary in character. It is for this reason that industrial laboratories are still reluctant to establish classical disciplinary departments. Industrial research departments are interdisciplinary or are organized according to the functions of the business or its products. Many universities are reluctant to admit new interdisciplinary specialties as degree-granting departments since they may detract from the classical disciplines.

It is a plausible speculation that the creation of great interdisciplinary industrial research laboratories during the late 19th and early 20th centuries was a response to the increasing specialization of the scholarly community. In support of this idea, Arthur D. Little said in his 1913 presidential address before the American Chemical Society (*2*), "it must be admitted with regret that our own institutions of learning have, generally speaking, failed to seize or realize the great opportunity facing them. They have almost universally, neglected to provide adequate equipment for industrial research and . . . have rarely acquired that close touch with industry essential for familiarity and appreciation of its immediate and pressing needs." But whatever the reason may be, it is true today that academic and industrial research institutions are organized differently, reflecting their underlying raisons d'être.

Edison's laboratory in West Orange was the first true industrial laboratory, and led to what we know today as the General Electric Laboratories and later to the RCA Laboratories. Alexander Graham Bell's legacy from about the same era is the Bell Telephone Laboratories. Indeed, by 1913, Arthur D. Little (*2*), in his presidential address before the American Chemical Society, could point to numerous industrial laboratories (though not all were labeled as such) including Eastman Kodak, E. I. du Pont, U.S. Steel, and Westinghouse—a total of 50 in all. In 1931, Maurice Holland (*3*) referred to "1600 industrial research laboratories," and he further said, "Every [leading] company . . . operates a research laboratory as an integral part of the company organization." It would be notable indeed if this galaxy of laboratories could be attributed to specialization within American academic institutions, a movement thought to be inimical to what today we call technological innovation, which involves the use of research results in producing marketable products

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or services. As research is the creation of knowledge, innovation is its use and involves many disciplines including nontechnical ones.

Beginning in the time of Edison (*4*), a schism developed between the inventors and the scientists. Edison was a public hero, and subsequent industrial research tended to follow his model. It was characterized by Little (*2*) as follows. "The Edison method is a synonym for specialized, intense research which knows no rest until everything has been tried." This paradigm of doing what worked, catalyzed by inventive insight and keen observation, carried the day. After the telephone, the light bulb, the phonograph, and a thousand other diverse inventions came the automobile, inexpensive aluminum (the Hall process), artificial abrasives (Carborundum), artificial graphite, the Wilson process for calcium carbide and industrial uses of acetylene, the Frasch process for sulfur removal from refined oil, and many others. The public and many professional people were impressed. Support for the Edisonian technique was forthcoming from Little (*2*), who said, "Most of us believe that the doctrine science for science's sake is as meaningless and mischievous as that of art for art's sake, or literature for literature's sake. These things were made for man, not for themselves, nor was man made for them." Henry Rowland, in his famous "Plea for pure science" (*5*), stated the case for the opposition: "To have the applications of a science, the science itself must exist. Should we stop its progress, and attend only to its applications, we shall soon degenerate into a people like the Chinese, who have made no progress for generations, because they have been satisfied with the applications of science, and have never sought for reasons in what they have done."

Yet, even in that era, there were those who began to see that these views could be reconciled within the concept of industrial research with a purpose. The most obvious reconciliation is merely acceptance that the motivation of the researcher (understanding) and that of the sponsor (utility) can be different. The beginning of this view was registered by the leaders of the time. J. J. Carty, of the American Telephone & Telegraph Co., in his 1916 presidential address to the American Institute of Electrical Engineers (*6*), spends substantial time detailing the difference between "pure" and "applied" scientific research. He says clearly that the difference is not one of content or method, but lies "in the motive." He then rejects the idea that pure research can be sustained in industry (despite obverse suggestions by other, unspecified people), presumably because "contributions of pure science as a whole become of incalculable value to *all* the industries." Indeed, the value of pure science was well recognized by J. Franklin Crowell in his 1909 paper "Science and investment" (*7*), in which he relates scientific principles and research to corporate success.

Such enlightened views did not, however, change the basically empirical nature of U.S. industrial research in the large. During the pre-World War I era, much of the pure science input for industry came from Europe. The war changed that. It set U.S. industry out on its own and, according to Carty (*6*), stimulated "a growing appreciation of the importance of industrial scientific research, not only as an aid to military defense but as an essential part of every industry in time of peace. . . . [Yet] the manufacturers of our country as a whole have not yet learned of the benefits of industrial scientific research and how to avail themselves of it." Over the decades of the 1920's and 1930's, the universities and colleges remained isolated from industry as far as research was concerned, with some important exceptions such as the highly productive association with the aircraft industry of Theodore von Karman of the California Institute of Technology, and with the petroleum industry of Warren K. Lewis of the Massachusetts Institute of Technology.

World War II marked the beginning of the modern U.S. research complex incorporating academic, industrial, and governmental elements. The needs of wartime defense and the scientific response, producing electronics, computers, and nuclear energy, had at least as great an influence on the public mind as did Edison's developments in his time. Again there followed a "golden age" for research. "Where are the universities to obtain the money necessary for carrying out the grand scheme of scientific research?" was Carty's question in 1916. "From public spirited men and women who desire to dispose of their wealth . . . and . . . from the industries themselves," he answered. But a new answer came from the academics who had participated in the war enterprise—the federal government.

Government responded, slowly at first but then at an increasing rate, through the Defense Department (particularly the Office of Naval Research), the Atomic Energy Commission, the National Science Foundation (NSF), and the National Institutes of Health. Thus philanthropic and industrial funding of university research was overwhelmed by government. The great research universities prospered. Most significant was the emergence of new industries in clusters around these research foci—the Route 128 complex near Cambridge, Massachusetts, the peninsula near San Francisco (now known as Silicon Valley), and more recently the North Carolina Research Triangle—and in less concentrated form in many other areas. As long as the businesses of these industries were compatible technologically with federal requirements, they could draw their intellectual sustenance from the nearby universities and the graduates they produced. Some of these and other industries developed the knack of securing continuing financial support from the government and have built vital organizations on this base. A significant factor has been speculative research funding by government as a part of existing development and production contracts, allowing firms to begin research on new technologies that can lead to new contracts.

These activities, however, left out important segments of industry (*8*). There was a false start on establishing fundamental research progams by many companies in the 1950's and 1960's as a result of the "science is wonderful" syndrome. But a chasm remained between academic specialization and the so-called basic civilian industries including engineering as a practice. This situation lies behind today's lamentations about lack of technological innovation in these basic industries, and government attempts to stimulate research by direct funding. But there is serious doubt the aerospace-electronics pattern of federally inspired innovation can produce similar results in other industries. There is no direct connection between the source of federal funds and an outlet for research results to commercial, useful ends. Thus industrial research must itself evolve to meet the demands of the coming decades.

Some Qualities of Industrial Research

The nature of industrial research is rooted in the nature of industry itself. Industry in the United States must be self-supporting and self-sustaining if it is to be successful. Thus profits are essential to pay for the investment residing in the business and to provide for the future through reinvestment. Part of reinvestment is for research and development, another part for capital installations, and in natural resource companies some is for exploration. Achieving adequate profits is usually a struggle. Competition, foreign and domestic, is on the rise; consumer preferences and markets are more volatile than ever; governments are assuming an adversary or even punitive stance. This atmosphere breeds an industrial culture pointed toward survival. Activities in corporations, large and small, are oriented by this goal. Although survival is essential, the goals of the corporation go much further. It is worth quoting Crowell (*7*) again: "The corporation will survive only . . . by being a better producer of wealth out of natural resources and by being a better distributor of wealth, once created. . . . The corporation [exists] on the at least implied promise of bringing . . . better returns for [the use of resources] than [the people] can win working alone." This statement, written in 1909, still capsules the corporate responsibility.

With this backdrop, it is not surprising that industrial research is aimed at those fields which are thought to underlie the business of the firm. Even in very large corporations, this statement is true. In fact, most of them take pride in what might be called "integrity of purpose" in their research operations. This is not to say that the work may not be fundamental and uncover new knowledge. In many instances, that is the outcome. But either prospectively or retrospectively, both researcher and management assess the potential impact of the results along business and technological as well as scientific lines. Retrospective assessment is quite common for fundamental research, since it is well accepted that its most significant results are not likely to be predictable. In such an environment, quality is the essential, and much care is taken in hiring and evaluating research people and providing for their continuous education and training.

It is significant that researchers can be far removed intellectually from the marketplace and the business operations of the firm. One research director remarked to his corporation's board that the primary loyalty of the best research people is to their disciplines, not to the corporation, and deviations from this norm were certain to produce second-rate research (*9*). This is a strong statement, but one well accepted by much of corporate management in large firms today.

Another telling statement (attributed to David Slepian of Bell Laboratories and the University of Hawaii) is that industrial research is "random in the small, but ordered in the large." This principle says that individual researchers have great freedom, but that integrity of purpose is sustained by a subtle cultural climate generated by the researchers themselves and their surroundings. One cannot go to work every day for, say, 10 years at Bell Laboratories without absorbing the culture of the communications business as practiced by AT&T. The same is true for other firms. Yet researchers have been able to maintain the creativity that gives rise to unfettered ideas which can revolutionize the company's business.

However, the license allowed within this system has its ups and downs as the corporate climate changes. An interesting statement indicating a tightening situation appeared recently in the *New York Times* (*10*), attributed to Irving S. Shapiro of Du Pont. He said, "It's nice to . . . let them [scientists] do what they want to do. In recent years, we've had to manage research from a business perspective." This attitude was prompted by a Du Pont "profit plunge" in the mid-1970's. During such times particularly, some fine industrial contributions have been "bootlegged," at least in their early stages. At other times and in other large corporations, research programs and individual activities have been less constrained. But in most cases, there is considerable leeway in the system to evaluate new ideas and follow where they lead.

In small firms, the instinct for survival is even stronger than in larger firms. Research is almost always closely integrated with other activities including development, engineering, manufacturing, marketing, and financing. The total needs of the business are controlling since the margin for survival is tight. It is not unusual for small firms to spend as much as their total profits on R & D. Their R & D has integrity of purpose with a vengeance.

Medium-sized firms often find themselves in a peculiar position. They are not large enough to fund much fundamental research and are too large for easy integration of R & D with other business activities. The larger the firm the more likely it is to have a centralized research laboratory, established to gain synergism of multidisciplinary interactions and to share major pieces of capital equipment. In smaller firms, R & D is carried out closer to the marketplace in the operating divisions. The middle-sized firms often use both techniques, with longer range research centralized and short-term development dispersed.

Centralized research laboratories tend to become enclaves. Difficulties of coupling research activities to the other corporate functions are well known. There is almost always a struggle between those who believe that the research laboratory should serve the interests of the marketing and production elements and those who believe that new technology should determine marketing goals. This struggle is often seen as an opposition of long- and short-range outlooks. When all is said about this matter, it is a management problem, not a technical one. It is management's responsibility to see that promising long-range research is allowed, particularly among the most imaginative and creative researchers, and to encourage an awareness of the larger business environment.

The goal orientation or purposefulness of industrial research almost rules out basic research according to the motivational definition adopted by NSF. This is one reason why fewer and fewer industries will admit to doing basic research. However, as noted earlier, the motivations of the researcher and the sponsor may be different. Further, work of a very fundamental nature is often done in industry, coupled to the purposes of the firm. Several Nobel Prizes and numerous National Medals of Science have been awarded for industrial research. Indeed, there is substantial agreement that an increasing share of the nation's seminal research is going on in industry.

Quantitative Features of Industrial Research

Perhaps the most perplexing question facing modern research administrators is "How much is enough?" Most industrial research enterprises are not limited by ideas; there are usually more possibilities than can be funded or staffed, so that priorities and choices must be addressed. Various analytical and numerical techniques have been used to formalize the setting of priorities. To the extent that these encourage serious technical evaluation, they serve the purpose well. But too often, such techniques tend to decrease the margins for scientific judgment. Before priorities and choices, there are the matters of the size and shape of industrial research today.

Industrial R & D is by far the largest segment of the technical enterprise in the United States. Of the 610,000 scientists and engineers engaged in R & D in 1979, more than three-fifths were employed by industry. In dollar terms, industry performs about 72 percent of the total, the remainder being performed by government institutions (15 percent) and nonprofit organizations including academic institutions (13 percent). The total R & D funding in the United States for

1980 is estimated to be \$57.3 billion. Of this, about 48 percent comes from the federal government, another 48 percent from industry, and the remainder from other private sources (*11*).

However, there are profound differences beyond size between R & D in industry and elsewhere. Industry is strongly oriented toward applied R & D, which accounts for 97 percent of total industrial activity. Thus basic research remains a minor factor financially. However, this startlingly small figure may be misleading. The widely accepted and official NSF definition of basic research hinges on the motivation for the work (*12*, p. 69). By ignoring the character of the work, NSF may have ruled a great deal of fundamental research out of the basic category.

The false start on industrial basic research in the 1960's was based on the belief that unconstrained research would inevitably produce revolutionary innovations. Such results were not generally forthcoming in the time interval (less than 10 years) before the business management mentality overtook them. As a result, many industrial basic research laboratories were disestablished and the corresponding expectations rejected. Those negative attitudes about basic research not tied somehow to corporate objectives persist and undoubtedly affect industrial basic research statistics. The degree of this influence is in dispute. According to recent figures, industry in 1976 performed only 16 percent of all U.S. basic research, whereas in 1956 the number was 38 percent (*13*). It is not clear how much of this decrease can be attributed to a change in nomenclature, but some substantial piece undoubtedly can. One suspects that a much larger fraction of new knowledge than is indicated by the numbers is gained through industrial research, regardless of its motivations.

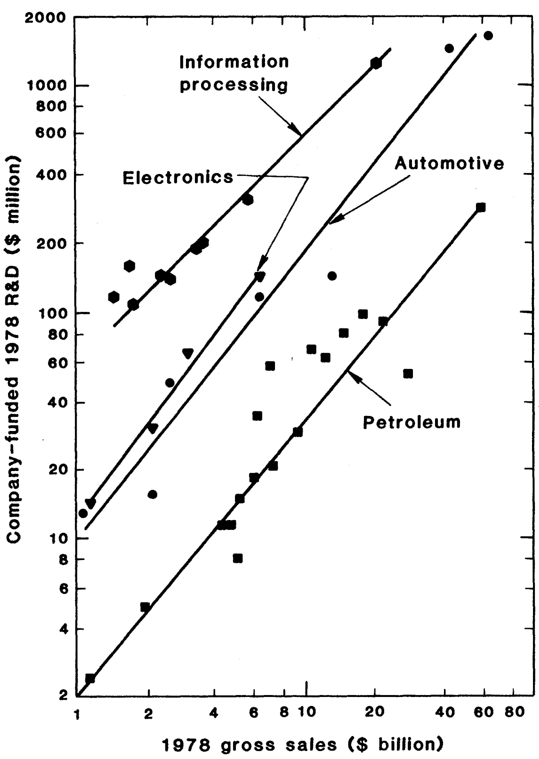
Table 1. Support of R & D by 400 top companies. Companies are divided into groups ranked by size of R & D expenditures. Expenditure per R & D professional is shown as a ratio to the average. Data are from (*12*).

Companies ranked by size of R & D expenditures	Expenditure per R & D professional as ratio to average
Companies 1 to 4	1.41
Companies 5 to 8	1.19
Companies 9 to 20	1.05
Companies 21 to 40	0.95
Companies 41 to 100	0.87
Companies 101 to 200	0.74
Companies 201 to 400	0.66
Companies 1 to 400	1.000

The above recitation of statistics presents a highly aggregated view of industrial research. Perhaps the greatest strength of such research, however, lies in its diversity, not its size. Each company structures its own research program according to its needs and means, yielding a highly varied set of activities. Some idea of this diversity can be gained by examining industry groupings. Research and development spending as related to the size of firms measured by gross sales is indicated in Fig. 1 (*14*). It is clear that some industries are much more research-intensive than others, depending on the nature of their markets and businesses. Within each industry group, the fraction of gross sales allocated to R & D goes up as company size increases above \$1 billion in sales. Perhaps the most intensive are small high-technology firms, but data are not available for this group.

It is also true that the larger the R & D program, the more support is provided each researcher. The data on this are shown in Table 1 (*12*, p. 36). Greater support of professionals should lead to more effective use of this scarce resource.

The research mix also shows marked diversity. As indicated in Fig. 2, some industries are more inclined toward both basic and applied research than others (*12*, p. 69). The chemical industry apparently works heavily in research in contrast to development, as does the petroleum industry. The aerospace industry is much more inclined toward development, as is the electronic components industry. Government-funded research at universities and in federal laboratories relevant to these industries is substantial, and may in part displace indus-



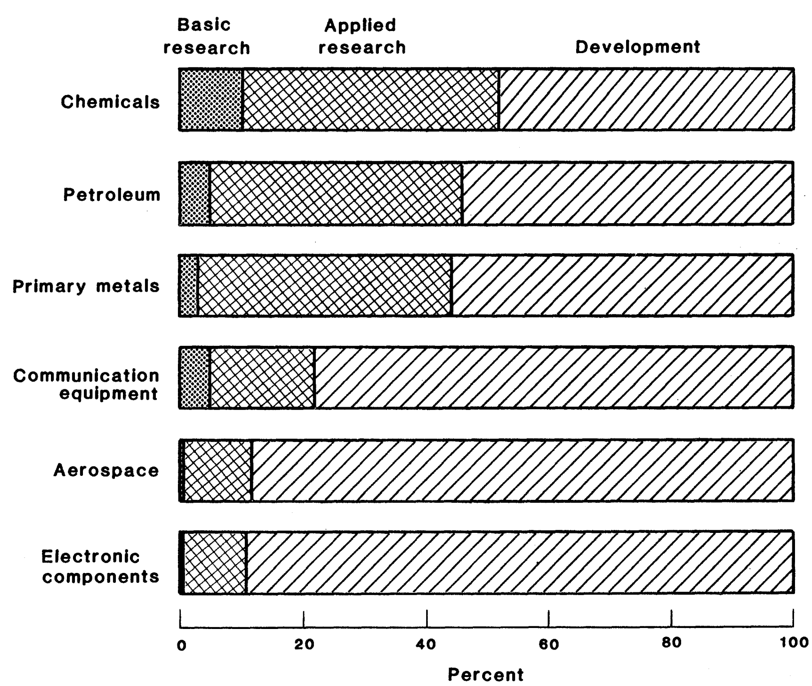


Fig. 1 (left). Spending on R & D related to size of firms within different industrial groups. Fig. 2 (right). Industrial mix of basic and applied R & D.

Table 2. Corporations leading in R & D expenditures in 1979. Data are from (*14*).

Corporation	Expenditure on R & D ($ million)
General Motors	1949
Ford Motor	1719
International Business Machines	1360
American Telephone & Telegraph	980
General Electric	640
United Technologies	545
Boeing	525
Eastman Kodak	459
International Telephone & Telegraph	436
E. I. du Pont de Nemours	415
Exxon	381
Xerox	376
Chrysler	358
Sperry	280
Dow	269

trial research. But it is surprising that these industries, which are so well known for technological innovation, are so oriented toward development.

This fact implies that the labels "research" and "development" may well obscure the basic creativity involved in the activities. It also illustrates the importance of the unity of science and engineering, research and development, design and production, as well as marketing and other nontechnical activities in technological innovation. Such integration is easiest to attain in small businesses, where artificial organizational barriers are not well developed and where the integration can be achieved among a small group of dedicated individuals. This may be the key to the recognized creativity of small businesses.

The differing emphases indicated in Figs. 1 and 2 bring out another point. Some industries are much more capital-intensive than others. They require a larger investment of dollars for a given level of revenues or sales. Replacement of a large fraction of such a capital base is a slow matter, since resources are not available for more rapid replacement. The total capital base of U.S. industry is about $4 trillion and is being added to at a rate of about $200 billion per year. Thus the more capital-intensive an industry, the more important is a long-range research strategy. An effect of this kind may well be reflected in the R & D mixes indicated in Fig. 2.

Not surprisingly, the largest R & D spenders are the large corporations. The 15 leaders are shown in Table 2 (*14*). Their total spending (own funds) in 1979 was $10.69 billion. The total spent by all industry was $24.0 billion. Spending on small business R & D has been estimated to be around $1 billion, with about half funded by federal agencies. Of course, it does not follow that if more were spent in any of these sectors, greater innovation would result. As noted earlier, that result would hinge on many factors other than R & D spending levels. Research quality and coupling to realistic applications are two critical ones.

The ultimate result of industrial research is output of goods and services, in the spirit of Crowell's statement quoted in the preceding section. The fraction of this output assignable to technological innovation resulting from research is difficult to specify. One measure of output from research is patentable inventions. Patents are not the ultimate measure of innovation, but they do represent the level of proprietary technology available for marketable goods and services. The 16 industrial leaders in 1979 are shown in Table 3 (*15*). They obtained 3,936 patents out of a total of 55,418 granted in 1979. Foreign firms obtained 38 percent of the total; Japan led with 10.5 percent. Significantly, the Japanese are obtaining a much higher percentage of U.S. patents in fields such as electronics and instruments. Following Japan were West Germany, the United Kingdom, France, and Switzerland.

Small businesses are apparently well into patents. Note that 247 large U.S. companies accounted for 33 percent of all U.S. patents issued from 1969 through 1977. Further, 19 percent were issued to individuals. Thus between 19 and 67 percent of recipients were small businesses (*16*). Informed observers believe the actual number is between 40 and 50 percent.

Patents are an important index because they encourage the investment necessary to bring an invention to fruition in the market as a product or service. Even more important, patents establish proprietary rights so that the science and technology behind an invention can be published and not become a trade secret. Publication encourages further research and the development of competitive ideas and inventions, as well as follow-on patents and ideas which are usually essential to commercialization.

This philosophy has been classical industrial doctrine for many years. However, in fast-moving, low-capital industries, patents are much less important. More essential is the rapid development of new products to keep up with changing technology. This has been the dominant pattern particularly in electronic products based on semiconductor technology. Again, the theme of diversity emerges as a major feature of the industrial research scene.

Table 3. Corporate assignees of U.S. patents, 1979.

Rank	Assignee	Patents
1	General Electric	611
2	Westinghouse	349
3	International Business Machines	321
4	RCA	282
5	American Telephone & Telegraph	274
6	Exxon	258
7	General Motors	245
8	E. I. du Pont de Nemours	231
9	Phillips Petroleum	226
10	Dow	217
11	Union Carbide	197
12	Texaco	191
13	Monsanto	149
14	American Cyanamid	144
15	UOP	129
16	Chevron	112

Finally, we return to the matter of choice and priorities in industrial research. Perhaps the critical element is the involvement of working scientists and engineers themselves. It is they who can best evaluate the technical feasibility of a projected development. In corporate terms, this is a bottom-up influence. On the other hand, the corporate business strategy is often laid out with commercial objectives in mind, such as market share, commercialization, timing, available distribution channels, and the like. Such matters are often decided at upper management levels. The business strategy places certain demands and constraints on R & D; these are top-down influences. These influences tend to meet at the level of middle management, where they must be reconciled. Thus much critical technological decision-making resides at this level, making it vital for the health of both the firm and its R & D arm. No mechanistic system has yet been developed which can replace competent middle-management judgments.

Yet there are formal systems in use in industry which clearly aid the subjective processes involved in setting priorities and making choices. Perhaps the best known of these is Texas Instruments' Objectives, Strategies, and Tactics (OST) system (*17*). Although elaborate, it has served that firm well in keeping it at the forefront of its industry. The OST system imposes a formal discipline to separate the broad business objectives of the firm from the strategy and particularly the tactics used to reach those objectives. This separation facilitates comparison of proposed research programs (tactics) against corporate strategies with respect to relevance and value to the firm, assuming various degrees of success. The process often becomes an adversary one between factions supporting different approaches to the same objective or between those who value the prospective research results differently depending on their judgments of future markets and events. Justifying a prospective research or development program to one's peers and bosses usually requires arguments and logic well beyond purely scientific and technical considerations.

Accomplishments: Past and Future

The complex and diverse industrial research system in the United States has produced a remarkable series of products and services. A full list of even recent innovations would be book-sized. However, a few vital examples will illustrate the nature of industrial research.

Electronics is certainly one of the most influential developments. The modern electronics era began with the discovery of the transistor at Bell Laboratories in 1948. Subsequent pioneering by the semiconductor industry led to the microcircuit—the computer on a chip. The underlying philosophy and modus operandi of industrial research are evident in this chain of events. The discovery of the transistor was the result of a directed search for a solid-state amplifier by the inventors. This invention subsequently generated an explosion of research in solid-state physics. Not that this field of physics was nonexistent beforehand, but the invention stimulated the field profoundly. This pattern is quite typical: a disciplinary field is spotlighted by a commercial application. Existing knowledge is insufficient to support the desired applications. That leads immediately to increased research. Thus innovation stimulates research as well as the reverse. Neither can prosper long without the other.

Electronic digital computers have a similar history, dating back at least to Charles Babbage, an English mathematician of the 19th century. The modern era of computers began during World War II, when massive electromechanical calculators, based on telephone relay technology, were built for defense purposes. Again, needs (military in this case) generated much fundamental research in both hardware and software.

The most startling result of industrial research in electronics has been the profound decline in costs which has been achieved. Costs of computing and communications functions today are several orders of magnitude less than they were 25 years ago. An important part of this reduction has been due to research on the production process itself. The use of light and electron optical techniques to achieve small size and precision in microcircuit details has been a major achievement. The other vital facet of production technology is quality control, including on-line automatic testing and feedback controls from the measurements so achieved. These ideas are now being applied widely in many industries, with salutary effects on productivity. This cost trend illustrates an important dynamic in industrial innovation. Decreased costs hinge on extensive use in the marketplace. That leads to improved production techniques through reinvestment of profits to take the enterprise up the "learning curve."

Equally significant have been the industrial developments in chemicals and materials. Industry has produced new alloys, synthetic fibers and plastics, composites, synthetic liquid and gaseous fuels, and new coating techniques for achieving high performance while conserving resources. The impact of these developments is profound, and most of them follow the same pattern of fundamental research tied to ongoing enterprise.

Perhaps the most admirable product of industrial research has been instrumentation. It has affected every field of enterprise and has opened entirely new fields of science, engineering, and health care. Surface science, solid-state metallurgy, and new diagnostic methods based on computer tomography and ultrasound are some of the specific outgrowths of instrumentation research. Even more central to future applications are so-called smart instruments, which incorporate stored-program logic devices. Many of these instrumental developments arose from production or laboratory requirements. The importance of automatic testing equipment in production has already been mentioned. Laboratory research is increasingly costly, and so increasing productivity by applying advanced instrumentation becomes an urgent strategy.

Systems engineering and design is a field which originated because of industrial need. In this approach, overall performance and reliability of a collection of subunits are achieved by systematic allocation of design parameters to each component and attention to their interfaces. This approach was pioneered by industries employing complex engineering entities, including communication systems, computers, chemical and petroleum manufacturing plants, aircraft, missiles, and space systems, particularly satellites. The technique has given rise to a theoretical field of analysis and synthesis techniques that can be applied to bring order to systems which involve millions of individual components.

A field of research which appears to be on the verge of industrialization is recombinant DNA. Its commercial importance is speculative but it is clearly promising. The techniques existing today are based on research done in molecular biology over the past 20 years without reference to commercial applications (*18*). As applications develop, a lively growth of research activity, as in other instances described above, is likely.

This is a budding example of industrial research founded on basic knowledge. Purposeful research always rests on fundamental work done earlier for reasons which may or may not be related to utility. The great streams of industrial research, such as those described briefly above, all are founded on a synergy between science and invention. Goal orientation is feasible only because of scientific research, often done in the universities and private or government research institutions; likewise, modern scientific research is channeled and depends on the results of industrial research and commercial activities.

Industrial Research in the 1980's

The evolution of industrial research in the 1980's will depend on an interplay of forces, private and governmental. But a central factor will be corporate attitudes toward innovation. These will determine the market for new technology. That market in turn will hinge on the economic health of industry. The economic outlook for the 1980's projected by most knowledgeable observers is hardly encouraging. At best, slow economic growth and continued inflation are foreseen. Availability of capital for speculative, long-range projects is questionable. All activities except those with very high returns may be ruled out by high interest rates, high risks, regulatory uncertainties, and inflation. Also, industry will not fund R & D if the resources for utilizing its results are unavailable, or if its results are unlikely to be used because of legal or regulatory constraints. Such situations mean that real resources available for R & D will continue to be tight. A recent NSF study indicates that industry was increasing R & D as the 1970's drew to a close (*19*). But we must face the possibility that it may well decline in the 1980's. In any event, there will be increased emphasis on selecting research topics and setting priorities on them. The present focus on quantity of research will likely be inappropriate for the 1980's. Quality of effort and rapidity of response will become the touchstones.

The possible role of the federal government in stimulating industrial innovation for commercial markets has been studied. Such a role would be distinct from the traditional federal one of funding R & D aimed at government's own needs. In justifying direct federal funding of commercial R & D, advocates often say that industry tends to underinvest because its investment (particularly in fundamental research) cannot be fully recovered. This statement seems to be drawn from economic theory, and there are other viewpoints (*20*). Even if it is true, the statement by itself would not justify direct federal funding of research or development targeted at a particular industry when indirect methods are available. Furthermore, direct federal funding is unlikely to be particularly effective in stimulating commercial innovation. The separation of such activity from the market for its results is a barrier to the necessary coupling between research and application. Nevertheless, the health of industrial research will continue to depend on current federal policies on supporting basic research, particularly as it augments education.

Beyond direct federal actions there are numerous indirect actions appropriate for stimulating commercial innovation. The 1980's are likely to see a surge of academic-industrial cooperation aimed at catalyzing the synergy between fundamentals and applications. This movement is likely to be spontaneous, since there are needs in both universities and industries for each other's products. However, the government could play an effective role in encouraging this relationship through incentives to reduce the net cost to industry of company-sponsored research in academic institutions.

Further, federal actions aimed at offsetting the effects of slow economic growth and other factors mentioned above would be wise, considering the vital contribution of technological innovation to productivity and economic health. Principal among such possible actions are financial incentives for firms—and for those who invest in them—to allow more rapid recovery of costs and investments, particularly for first-of-a-kind plants. Introduction of more rapid depreciation for R & D plant and equipment could help ensure up-to-date research facilities, which have become quite capital-intensive. There are many other possibilities for indirect federal actions. Programs to encourage innovation in the spartan atmosphere of the 1980's may well become prime tools of economic policy.

Industrial research is at the threshold of a new era. A new synthesis of national, corporate, and academic resources to sustain innovation is essential because of recent influences which decrease the innovative potential of research wherever it is carried out. The negative influences of federal regulations and other social actions on technological innovation are well documented (*21*). The academic sources of creative research people and new knowledge are losing ground because of stagnant faculties, obsolete research equipment, federal regulations and red tape, and eroding salaries. Research in federal laboratories is looked on with suspicion as competitive with the private and academic sectors. Industries, influenced by economic woes, are taking fewer R & D risks. In attempting to offset these trends, the federal government should recognize and reinforce the strengths of each sector. For industrial research, these strengths are diversity and purposefulness. Preserving these essentials should be the major consideration in fashioning strategies and tactics to create this new synthesis.

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Operations Research and Systems Analysis

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Operations research, unlike most sciences, is able to point to a well-defined combination of circumstances and events that not only began its activities as a coherent development but also caused its name to be coined. After Hitler rose to power in Germany, England sought to prepare a suitable defense against possible air attack, with the result that, by late 1937, the key elements of an effective defense had been devised: radar and the Hurricane fighter plane. But combining them into an effective system could not be left to improvisation, as the disappointing results of an air exercise showed in July 1938. Consequently, A. P. Rowe, then leader of the radar development work on England's east coast, proposed that research into the operational—as opposed to the purely technical—aspects of the

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