American universities and technical advance in industry †

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Final version received September 1993

Over the past decade there has been an intensification of interest in how universities can play a more effective role in promoting technical advance in American industry. However, very little of the current discussion is solidly based on an informed analysis of the roles that universities actually play today or the historical circumstances that caused universities to assume these roles.

This paper offers an analysis, both historical and contemporary, that identifies the distinctive strengths, as well as limitations, of university research. Regarding the strengths, most of university research is basic research in the sense that it aims to understand phenomena at a relatively fundamental level. However, this does not mean that such research is uninfluenced by the pull of important technological problems and objectives. The lion's share of university research is in the engineering disciplines and applied sciences such as computer science and oncology which, by their nature, are oriented toward problem-solving. Despite its obvious usefulness, industry does very little of such basic research because the payoffs are of a long-run nature as well as difficult to appropriate. The vast bulk of industry R&D is focused directly on shorter term problem-solving, design and development. Universities are not particularly good at this sort of work. Industry is more effective in dealing with problems that are located close to the market place.

This paper argues that new policies will need to respect this division of labor.

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† The authors wish to acknowledge the able assistance of Scott Stern. Very helpful comments and suggestions on an earlier draft were provided by L.E. Birdzell, Jr., Harvey Brooks, Michael Crow, Stephen Kline, Walter Vincenti and Robert White.

Research Policy 23 (1994) 323–348
North-Holland

1. Introduction

Over the last decade, debate over the role of American universities in fostering technical advance has intensified. On the one side are those who argue that universities can and should play a larger and more direct role in assisting industry. Such enterprises as Stanford's Center for Integrated Systems, and hundreds of centers like it around the country, show a cluster of firms and a university attempting to make their connections more intimate and more effective [13]. The percentage of academic research funded by industry was estimated to be about 6.9% in 1990, up considerably from 3.9% a decade earlier [28]. In a recent study Cohen, Florida and Goe [8] estimate that 19% of university research is now carried out in programs that involve linkages with industry in a fundamental way. The federal government, through such programs as the Engineering Research Centers sponsored by the National Science Foundation, and a large number of state supported programs, have strongly supported these developments. Much of the discrepancy between 6.9% and 19% in the figures reported above is accounted for by governmental support of these programs.

On the other side, many academics and others see these developments as a threat to the integrity of academic research. They despair that greater involvement with industry and commerce will corrupt academic research and teaching, di-

SSDI 0048-7333(93)00754-H

vert attention away from fundamental research, and potentially destroy the openness of communication among university scientists that is such an essential component of academic research.

It is striking, however, that the present discussion focuses so closely on the here and now; there is very little examination of the roles traditionally played by American universities or of how these roles have evolved. Nor is there even much probing into the nature of the academic research enterprise as we know it today, or of the differences between academic and industrial R&D, or of the connections between universities and industry that are in place. Thus, the current debate is proceeding with surprisingly little grounding in what actually is going on now, and why and how we arrived at our present predicament.

A principal purpose of this paper, therefore, is to lay out the history of involvement of American universities in research that has been germane to industry, and the different kinds of connections that have existed between university and industry. Section 2 undertakes an historical discussion of these connections through World War II. A very important development that occurred during that period was the rise of engineering disciplines and certain other 'applied sciences' as fields of academic research and teaching. This is the topic of section 3. World War II was a watershed for American universities. Before that time the federal government provided little research funding. After the war the federal government became the universities' principal source of research funding. Section 4 discusses this development and its effect on the research efforts of universities and the connections between university research and technological advance. Section 5 considers the division of labor between industrial researchers and academics as it exists today, and the concluding section addresses the current debate.

2. An historical perspective

Today, approximately two-thirds of the research done at American universities is labelled as 'basic research' (Table 4). We shall argue in section 4 that this does *not* mean what many people think it does, i.e. that the bulk of university research today proceeds with no ties to nonacademic objectives. In fact, the preponderance of university research today is in fields that, by their nature, are oriented toward facilitating practical problem-solving in health, agriculture, defense, and various areas of civil industrial technology. On the other hand, the large fraction of university research that is classified as basic does indicate a certain distancing of much of university research from immediate, 'hands-on' practical problem-solving.

In this and the following section we will argue that this distancing is a relatively recent phenomenon, although it developed in stages. Several recent historical studies have documented that, until the 1920s or so, for better or for worse, a large share of American university research was very much 'hands-on' problem-solving [4,12].

This is not a new understanding. Over 160 years ago Alexis de Tocqueville commented, not specifically on this, but on the broader issue of the role of science and the attitudes toward science, in the young republic that he visited in the 1830s:

> In America the purely practical part of science is admirably understood and careful attention is paid to the theoretical portion, which is immediately requisite to application. On this head, the Americans always display a clear, free, original, and inventive power of mind. But hardly any one in the United States devotes himself to the essentially theoretical and abstract portion of human knowledge ... every new method which leads by a shorter road to wealth, every machine which spares labor, every instrument which diminishes the cost of production, every discovery which facilitates pleasure or augments them, seems [to such people] to be the grandest effort of the human intellect. It is chiefly from these motives that a democratic people addicts itself to scientific pursuits ... In a community thus organized, it may easily be conceived that the human mind may be led insensibly to the neglect of theory; and that it is urged, on the contrary, with unparalleled energy, to the applications of science, or at least to that portion of theoretical science which is necessary to those who make such applications [39].

This general orientation to science clearly molded what went on in American universities. Thus, Ezra Cornell, founder of Cornell Univer-

Table 1
Average years of formal educational experience of the population aged 15–64

Country	Year	Total	Higher
France	1913	6.18	0.10
	1950	8.18	0.18
	1973	9.58	0.47
	1984	10.79	0.90
Germany	1913	6.94	0.09
	1950	8.51	0.14
	1973	9.31	0.20
	1984	9.48	0.31
Netherlands	1913	6.05	0.11
	1950	7.41	0.24
	1973	8.88	0.39
	1984	9.92	0.58
UK	1913	7.28	0.08
	1950	9.40	0.13
	1973	10.24	0.25
	1984	10.92	0.42
US	1913	6.93	0.20
	1950	9.46	0.45
	1973	11.31	0.89
	1984	12.52	1.62

Source: Reprinted from [23].

sity, stated as his intention: "I would found an institution where any person can find instruction in any study." The quotation still appears on the official seal of his distinguished university. [1] British visitors long sneered at what they perceived as the 'vocationalism' of the nineteenth and early twentieth-century American higher educational system. These educational institutions assumed responsibility for teaching and research in fields such as agriculture and mining, commercial subjects such as accounting, finance, marketing and management, and an ever-widening swath of engineering subjects, civil, mechanical, electrical, chemical, aeronautical, and so on, long before their British counterparts and, in most cases, long before their other European counterparts as well.

There were a number of reasons for this more 'practical' orientation. American universities, it has been often observed, emerged in a new country with a culture strongly influenced by the need to vanquish a large, untamed geographic frontier. But there was much more to it than that.

One important additional factor was that the American university system has always been decentralized. There has never been centralized control, as developed in France after Napoleon. Nor, until quite recently, did 'scholars' come to dominate the universities, as they did in many European countries. While some 'finishing' and religious preparatory schools such as Harvard and Yale were clearly modelled after European institutions, a very large number of schools chose their missions, styles, and focus based on the idiosyncratic needs of the provincial environment. The consequence of this approach was that the funding and enrollment of these schools became heavily dependent on the mores and needs of the local community. And, as de Tocqueville indicated, these mores tended strongly to the practical. Further, American higher education has been noticeably more accessible to a wider portion of the population when compared with more class-rigid Europe (see Table 1). [2] Where the aristocracy in Europe expressed disdain for 'commercial affairs' (and this was reflected in their university curricula), American universities were perceived as a path to commercial as well as personal success, and university research and teaching were focused more clearly on these goals.

The passage of the Morrill Act in 1862 reflected and supported American views about the appropriate roles of university research and teaching. The purpose of the Act was eminently practical; i.e. it was dedicated to the support of agriculture and the mechanic arts. Moreover, control of universities was left to the states. The long-term prosperity and success of these state institutions was generally understood to depend upon their responsiveness to the demands of the local community. Thus, the leadership of state

[1] Cornell's founder and benefactor also expected students at his university to perform manual labor, including janitorial labor, while undergraduates.

[2] Of course, offsetting the high American enrollment figures in higher education has been the often inferior quality of teaching in its secondary schools. A distinguished French biologist who visited the United States in 1916 observed, "Secondary teaching seems to me to be the weakest point of the American system of education. The student who comes out of the high school at eighteen has not a sufficient intellectual training. A good part of his university studies consists in finishing his secondary studies" [7]. To which one can only add: Plus ça change, plus c'est la même chose.

universities were heavily beholden to the needs of local industries and to the priorities established by state legislatures. This responsiveness was particularly apparent in the contributions to the needs of agriculture that were provided by the land-grant colleges and, somewhat later, by the agricultural experiment stations. In general, intellectual innovations were likely to be quickly seized upon and introduced into university curricula, especially at those universities that were publicly supported, as soon as their practical utility was established.

Thus a primary activity of early American universities was the provision of vocational skills for a wide range of professions important to local economies. In many cases the training activities and research concerned with the problems of local industry went together. Not only did the University of Akron supply skilled personnel for the local rubber industry, but it in fact became well-known for its research in the processing of rubber. (Later on it achieved distinction in the field of polymer chemistry.) The land-grant colleges (and later the agricultural experiment stations) are rightly praised for fostering the high productivity of the American farm through the teaching of food production skills. And along with the training went research aimed to meet the needs of the local agricultural community. The Babcock test, developed by an agricultural research chemist at the University of Wisconsin and introduced in 1890, provided a cheap and simple method for measuring the butterfat content of milk, and thus an easy way to determine the adulteration of milk, a matter of no small consequence in a state of dairy farms.

State universities, in general, were likely to have programs addressing a diverse range of needs. After World War I, a college of engineering might offer undergraduate degrees in a bewildering array of specialized engineering subjects. In the case of the University of Illinois, this included architectural engineering, ceramic engineering, mining engineering, municipal and sanitary engineering, railway civil engineering, railway electrical engineering, and railway mechanical engineering. An observer has noted, "Nearly every industry and government agency in Illinois had its own department at the state university in Urbana-Champaign" [20].

While usually connected with training, university research programs aimed to meet the needs of local industry often took on a life of their own, and became institutionalized. We have already mentioned rubber research at the University of Akron. The University of Oklahoma has long distinguished itself for its research in the field of petroleum, and the universities of Kentucky and North Carolina have worked extensively on developing technologies that have been employed in the post-harvest processing of tobacco. For many years the Universities of Illinois and Purdue did work on railroad technologies, ranging from the design of locomotive boilers to their maintenance and repair. To this day the Purdue football team is called the 'boilermakers'.

The tradition of universities doing generic industrial research continues to the present. In the early 1980s, for example, there were no fewer than 37 universities in the United States that were performing research for local and regional forest products industries. In 1982 they spent approximately $12 million on such research, financed primarily by state governments. "The main focal points of research were wood moisture relations, wood chemistry including pulp and paper, mechanical properties, reconstituted products, and wood anatomy/microscopy" [42].

On occasions, university research on problems of industry involved large-scale, long-run commitments to the solution of a particular problem. One of the most important such projects was conducted at the University of Minnesota's Mines Experiment Station over the course of many years, ranging from just before World War I until technical success was achieved in the early 1960s. The problem arose in connection with the gradual exhaustion of the high-yielding iron ores in the Mesabi Range. As the supply of these ores declined, attention focused increasingly upon ores of lower iron content, specifically the taconite ores containing impurities to the amount of 50 to 70%, but available in gigantic quantities. Although no new scientific knowledge was required, the solution to innumerable engineering and processing problems turned out to require decades of tedious experimentation. The financing of this experimentation was provided primarily by the Minnesota State Government and channeled through the university to its Mines Experiment Station, which operated its own blast furnace in these experiments [9].

3. The institutionalization of engineering and applied sciences

In the nature of the case, much of research to help local industry is highly specific. Also, until the late nineteenth century, there was little in the way of a systematic disciplinary basis for such research and training that tied together intellectually the individuals and universities engaged in such activities. One of the major accomplishments of the American universities during the first half of the twentieth century was to effect the institutionalization of the new engineering and applied science disciplines. Thus, in the years after the turn of the century, fields like chemical engineering, electrical engineering, and aeronautical engineering, became established in American universities. In each of these fields, programs of graduate studies with certified professional credentials grew up, along with professional organizations and associated journals. These new disciplines and professions both reflected and solidified new kinds of close connections between American universities and a variety of American industries. The rise of these new disciplines and training programs in American universities was induced by and made possible the growing use of university-trained engineers and scientists in industry, and in particular the rise of the industrial research laboratory in the chemical industry and the new electrical equipment industries, and later throughout industry (see [18,26,30,32]).

Engineering education hardly existed in the United States before the Civil War. Obviously, many schools offered vocational education, but the systematic training of professional engineers was nearly unknown until the latter part of the century. Although Rensselaer Polytechnic Institute was founded in 1824, the first engineering school was in fact the U.S. Military Academy at West Point founded in 1802. The civil engineering skills of graduates of West Point made a major contribution to the vast construction enterprises associated with the building of an extensive, ultimately transcontinental, railroad system beginning in the 1830s. The needs of the railroad, the telegraph and, later, an expanding succession of new products and industries, brought a multiplication in the demand for engineers with specific skills. The response involved the establishment of new schools, such as MIT (1865) and Stevens Institute of Technology (1871), as well as the introduction of engineering courses into older universities. Here again, the American experience in higher education was distinctly different from that of the European scene. Whereas in Great Britain, France and Germany, engineering subjects tended to be taught at separate institutions, in the United States such subjects were introduced at an early date into the elite institutions. Yale introduced courses in mechanical engineering in 1863, and Columbia University opened its School of Mines in 1864 [15].

The introduction of highly varied engineering subjects highlights certain broad regularities in the focus of American universities. Not only did they tend to be intensely practical, and intensely specific to the needs of emerging American industries, but American engineering institutions fostered this practical approach in the very foundations of the teaching methodology.

Electrical engineering

The emergence of electrical engineering marked a distinct development among the engineering disciplines. It represented a discipline that was based entirely upon recent experimental and theoretical breakthroughs in science. Not surprisingly, physicists dominated the intellectual leadership in this new field [25].

The response of the American higher education system to the emerging electricity-based industries was swift. It is common among historians to date the beginning of the electrical industries in 1882, the year in which Edison's Pearl Street Station, in New York City, went into operation. In fact, by that year crude versions of the telephone and electric light were already in existence, and the demand for well-trained electrical engineers was beginning to grow rapidly. Electricity-based firms such as General Electric and Westinghouse were trying, with only limited success, to train their own employees in this new and burgeoning field.

The response of the universities was essentially instantaneous. In the same year as the Pearl Street Station opened, 1882, MIT introduced its first course in electrical engineering (courses in electrical engineering at MIT were taught in the Physics Department for 20 years, 1882–1902). Cornell introduced a course in electrical engineering in 1883 and awarded the first doctorate in the subject as early as 1885. By the 1890s "...schools like MIT had become the chief suppliers of electrical engineers" [41].

Throughout the twentieth century the American schools of engineering have provided the leadership in engineering and applied science research upon which the electrical industries have been based. Problems requiring research in such areas as high voltage, network analysis or insulating properties were routinely undertaken at these schools. Equipment for the generation and transmission of electricity was designed by professors of electrical engineering, working within university labs. [3] The qualitative difference between this research and research conducted earlier was that the emergence of the discipline of electrical engineering defined a community of technically trained professionals with connections across universities, as well as between universities and industry. The relationships were systematic and cumulative, rather than ad hoc and sporadic.

Although the establishment of new companies by university professors, intent upon commercializing their research findings, has been regarded as a peculiar development of the post World War II years, the practice has ample earlier precedent. The Federal Company, of Palo Alto, California, was founded by Stanford University faculty and became an important supplier of radio equipment during World War I [5]. The klystron, a thermionic tube for generating and amplifying microwave signals for high-frequency communication systems, was the product of an agreement, in 1937, between Hal and Sigurd Varian and the Stanford Physics Department. Stanford University provided the Varians with access to laboratory space and faculty, and a $100 annual allowance for materials. In exchange, Stanford was to receive a one-half interest in any resulting patents. This proved to be an excellent investment for Stanford. [4]

Thus, the development of electrical engineering as a discipline, and also as a profession, clearly has its roots in American higher education. The development of this discipline was in response to a national need, the emerging electricity-based industries, rather than the more provincial needs that motivated other research referred to earlier. Training electrical engineers became the province of universities, and the interface between universities and technical advance was fostered through the adoption of this role. Further, university research was influential in technical change, often through consulting relationships with industry and occasionally through the establishment of firms that were headed by academics.

Chemical engineering

The critical economic role of university research in engineering may be further observed in the emergence of the discipline of chemical engineering in the United States in the early years of the twentieth century. This discipline was associated, to a striking degree, with a single institution: MIT (see the excellent article by John W. Servos [35]).

The discipline of chemical engineering emerged precisely because the knowledge generated by major scientific breakthroughs frequently terminates far from the kinds of knowledge necessary to produce a new product on a commercial scale. This is particularly true in the chemical sector. Perkin's accidental synthesis of mauveine, the first of the synthetic aniline dyes, in 1856, was the initial, critical step in the creation of a synthetic dyestuffs industry, in addition to exercising a powerful impact upon research in organic chemistry. At the same time, however, the breakthroughs at the scientific bench did not disclose how the new product might be produced on a commercial scale, nor was it possible to deduce such information from the scientific knowledge itself. It proved necessary to invent the discipline of chemical engineering around the turn of the twentieth century in order to devise process technologies for producing new chemical products on a commercial basis.

The essential point to understand here is that chemical engineering is not applied chemistry. It cannot be adequately characterized as the industrial application of scientific knowledge generated in the chemical laboratory. Rather, it involves a merger of chemistry and mechanical engineering, i.e. the application of mechanical engi-

[3] For a detailed description of the contributions of MIT, see Wildes and Lindgren [41].

[4] See [19]. Over the years Stanford University received the equivalent of $10 million 1978 US dollars.

neering to the large-scale production of chemical products (see [11]). Chemical engineers acquire an idiosyncratic methodology for decision-making that allows them to become efficient at what might seem, at first blush, to be a quite straightforward calculus, translating laboratory results into commercially viable chemical processing plants. However, process plants are not merely scaled-up versions of the laboratory glass tubes and retorts in which discoveries were initially made. Chemical engineering is not properly understood as merely a scaling-up process, i.e. doing something on a very large scale that had originally been done on a small scale in the laboratory. That kind of enlargement is not economically feasible and often not even technically possible. Typically, entirely different processes have to be invented, and then put through exhaustive tests at the pilot plant stage, a stage that reduces the uncertainties in the designing of a large-scale, highly expensive commercial plant.

Thus, the design and construction of plants devoted to large-scale chemical processing activities involves an entirely different set of activities and capabilities than those that generated the new chemical entities. The problems of mixing, heating and contaminant control, which can be undertaken with great precision in the lab, are immensely more difficult to handle in large-scale operations, especially if a high degree of precision and quality control are required.

It has been true of many of the most important new chemical entities that have been produced in the twentieth century that a gap of several, or even many years, has separated their discovery under laboratory conditions from the industrial capability to manufacture them on a commercial basis. Eventually, to manage the transition from test tubes to manufacture, where output had to be measured in tons rather than ounces, an entirely new methodology, totally distinct from the science of chemistry, had to be devised. This new methodology involved exploiting the central concept of 'unit operations.' This term, coined by Arthur D. Little at MIT in 1915, provided the essential basis for a rigorous, quantitative approach to large-scale chemical manufacturing, and thus may be taken to mark the emergence of chemical engineering as a unique discipline. It was a methodology that could also provide the basis for the systematic, quantitative instruction of future practitioners. It was, in other words, a form of generic knowledge that could be taught at universities.

In Arthur D. Little's words:

> Any chemical process, on whatever scale conducted, may be resolved into a coordinated series of what may be termed 'unit actions,' as pulverizing, mixing, heating, roasting, absorbing, condensing, lixiviating, precipitating, crystallizing, filtering, dissolving, electrolyzing and so on. The number of these basic unit operations is not very large and relatively few of them are involved in any particular process. Chemical engineering research ... is directed toward the improvement, control and better coordination of these unit operations and the selection or development of the equipment in which they are carried out. It is obviously concerned with the testing and the provision of materials of construction which shall function safely, resist corrosion, and withstand the indicated conditions of temperature and pressure. [22]

Aeronautical engineering

The contribution of American higher educational institutions to the progress of aircraft design before World War II is an impressive additional instance of how universities produced information of great economic value to the development of a new industry. It is doubly interesting, for present purposes, because scientific leadership in the realm of aerodynamics was generally agreed to have been located in Germany, where Ludwig Prandtl was undoubtedly the central intellectual figure in providing the necessary analytical framework for understanding the fluid mechanics that underlies the flight performance of aircraft. Research in aeronautical engineering in the United States, at California Institute of Technology, Stanford and MIT, all drew heavily upon Prandtl's fundamental researches. [5] Research in aeronautical engineering, at a number of American universities, but primarily at the three mentioned, was of decisive importance to technical

[5] See Vincenti [40] for a penetrating analysis of the production and utilization of engineering knowledge in the case of aircraft. See also Hanle [17].

progress in aircraft design in the United States in the interwar years.

An excellent illustration of university engineering research that yielded valuable design data, and also knowledge of how to *acquire* new knowledge, was the propeller tests conducted at Stanford University by W.F. Durand and E.P. Lesley from 1916 to 1926 [40, ch. 1 and p. 137]. Extensive experimental testing was necessary because of the absence of a body of scientific knowledge that would permit a more direct determination of the optimal design of a propeller, given the fact that "The propeller operates in combination with both engine and airframe ... and it must be compatible with the power-output characteristics of the former and the flight requirements of the latter" [40, p. 141]. Thus, designing a propeller is not independent of the design of the entire airplane, and the ten-year research project not only expanded the understanding of airplane design but also increased confidence in the reliability of certain techniques utilized in aircraft design. An important consequence of the experiments, which relied heavily upon wind tunnel testing, was not so much the ability to improve the design of propellers as to improve the ability of the designer to achieve an appropriate match between the propeller, the engine and the airframe. [6]

As was eventually appreciated, what was essential to the successful design of aircraft was not just the experimental equipment or the requisite scientific knowledge. Indeed, the central point with respect to aircraft is precisely the complexity of the process of aircraft design because of the *absence* of such a body of scientific knowledge. The method of experimental parameter variation was necessary because a useful quantitative theory did not exist. The Stanford experiments led to a better understanding of how to approach the whole problem of aircraft design. In this sense, a critical output of these experiments was a form of generic knowledge that lies at the heart of the modern discipline of aeronautical engineering. As Vincenti has astutely observed:

> In formulating the concept of propulsive efficiency, Durand and Lesley were learning how to think about the use of propeller data in airplane design. This development of ways of thinking is evident throughout the Stanford work; for example, in the improvement of data presentation to facilitate the work of the designer and in the discussion of the solution of design problems. Though less tangible than design data, such understanding of how to think about a problem also constitutes engineering knowledge. This knowledge was communicated both explicitly and implicitly by the Durand–Lesley reports. [7]

The greater degree of sophistication in aeronautical research methods that resulted from the Stanford experiments made an important contribution to the maturing of the American aircraft industry in the 1930s, a maturity crowned by the emergence of the DC-3 in the second half of that decade. But the success of the DC-3, the most popular commercial transport plane ever built, owed an enormous debt to another educational institution, the California Institute of Technology. Cal Tech's Guggenheim Aeronautical Laboratory, funded by the Guggenheim Foundation, performed research that was decisive to the success of Douglas Aircraft, located in nearby Santa Monica. Both technical features such as durability and reliability of components, and economically important features such as passenger carrying capacity, were largely the product of the Cal Tech research program, highlighted by their use of multicellular construction, and the exhaustive wind tunnel testing of the DC-1 and DC-2. [8]

One final point of general significance to aeronautical engineering research is worth noting. As Vincenti points out, what the Stanford experiments eventually accomplished was something more than just data collection and, at the same time, something other than science. It repre-

[6] Durand and Lesley actually began their experiments by designing and constructing the necessary wind tunnel equipment, since American capabilities with respect to wind tunnels were well behind European capabilities at the time.

[7] [40, p. 158]. Durand himself eventually prepared a six-volume aeronautical encyclopedia with the encouragement of the Guggenheim Fund, which had financed much of the Stanford research [10].

[8] "Cal Tech ran more than three hundred wind tunnel tests on the airplane before test pilot Carl Cover, on December 17, 1935, the thirty-second anniversary of the Wright brothers flight, completed the first flight of the DST. The DST, later designated DC-3, first went into service with American Airlines on June 7, 1936" [16]. Details of Cal Tech's contribution to the aircraft industry and to aeronautical development appear in Appendix I of this book.

sented, rather, the development of a specialized methodology that could not he directly deduced from scientific principles, although it was obviously not inconsistent with those principles. One cannot therefore adequately characterize these experiments as applied science.

> ... (T)o say that work like that of Durand and Lesley goes beyond empirical data gathering does not mean that it should be subsumed under applied science ... (I)t includes elements peculiarly important in engineering, and it produces knowledge of a peculiarly engineering character and intent. Some of the elements of the methodology appear in scientific activity, but the methodology as a whole does not. [40, p 166]

Computer science and engineering

Computers have been probably the most remarkable contribution of American universities to the last half of the twentieth century. Important work on computers had of course been performed elsewhere (one thinks of Alan Turing in Great Britain and Konrad Zuse in Germany) but, for reasons closely connected with the impact of World War II, the emergence of a practical, electronic, digital computer was largely the product of research and development activities conducted at American universities. More precisely, this research was overwhelmingly concentrated in schools of engineering. Further, these schools were decisive in transforming a logical possibility into a technical reality. In the process, a new discipline emerged, computer science, that was strongly influenced by the historical development of disciplines such as electrical engineering and physics, yet has nurtured its own particular research methodology.

The first fully operational electronic digital computer, the Electronic Numerical Integrator and Computer (ENIAC) was built at the Moore School of Electrical Engineering at the University of Pennsylvania over the period 1943–1946 (Howard Aiken, working at Harvard in conjunction with IBM, completed his Mark I in 1944; but his device, which had powerful computational capabilities, was still electromechanical, not electronic). The work conducted at the University of Pennsylvania owed a great deal to earlier research at other American universities, particularly to research at electrical engineering departments, or research on the part of people who had very close ties to engineering departments. Of special importance was work by John Atanasoff, a mathematician and physicist, at Iowa State, and Vannevar Bush, an electrical engineer at MIT.

John Mauchly, who was to play a critical role in the development of the ENIAC at the University of Pennsylvania, visited Atanasoff in Ames in 1941, a visit that was to figure prominently in a later lawsuit challenging the validity of the ENIAC patent (Honeywell vs. Sperry Rand). Atanasoff's device was designed for a single, specific purpose, the solution of systems of linear equations, although he appears to have given a good deal of thought to the possibility of a general purpose electronic digital computer. However, Atanasoff's machine never became operational and existed only in crude prototype form (see [38]).

Another important predecessor of the ENIAC was the differential analyzer that had been developed at MIT by Vannevar Bush and his associates during the interwar years. The differential analyzer was especially important for the practical reason that the Moore School's visibility in the field of computation had been considerably enhanced by its construction, in 1939, of a differential analyzer that was directly modelled after the MIT device. In fact, the Moore School's analyzer was really a more powerful version of that analyzer [38, pp. 9–10]. Bush's work grew out of problems arising in electric power transmission, especially problems associated with transient stability as electric power systems became increasingly interconnected. His device was used for solving differential equations that could not readily be solved in other ways. "Though others had attempted such machines before, the MIT differential analyzer was the first practical and useful computational machine; though an analog (not digital) machine, it marked the beginning of the 'Second Industrial Revolution,' the Information Revolution" [41].

As a result of the construction of a differential analyzer at the Moore School, based on Bush's work at MIT, the University of Pennsylvania developed a close relationship with the Ballistics Research Laboratory, belonging to the Army Ordnance Department, at the Aberdeen Proving

Ground in Aberdeen, Maryland. The construction of the ENIAC was financed by an Army contract over the years 1943–46 as part of the Army's determination to accelerate the speed with which it could calculate solutions to ballistics problems. [9] As it happened, by the time the ENIAC was ready for testing, in the fall of 1945, the war had just ended, and the need for firing tables was vastly diminished. As a result of the intercession of John Von Neumann, the ENIAC's first major task consisted of extensive calculations to establish the feasibility of a hydrogen bomb [38, p. 62]. From these rather apocalyptic beginnings, the computer has become an ubiquitous feature of modern life, and computer science has come to be respected as one of the most important and energetic fields in academia today.

How should the university research that led to the postwar emergence of the digital electronic computer be categorized? What of the discipline of Computer Science today? What of Artificial Intelligence? The early participants were trained in engineering, mathematics and physics. Mauchly and Bush taught and performed their research in schools of engineering. Atanasoff taught physics and mathematics at Iowa State. Howard Aiken was a mathematician who had, earlier, worked in engineering. But it is the peculiarity of the *object* of their research that it is difficult to categorize in the conventional R&D boxes of 'basic research,' 'applied research' and 'development.' Although the term 'computer science' is common enough in university curricula today, the discipline, if it is indeed a science, is a distinctly different kind of science. It is certainly not a *natural* science. Nor does it qualify as basic research if one employs the NSF definition as research that has as its objective 'a fuller knowledge or understanding of the subject under study, rather than a practical application thereof.' It may, however, be appropriately regarded, in Herbert Simon's apt phrase, as a 'science of the artificial.' Research activities in computer science, however classified, are directed towards the design and construction of an artifact, or machine.

[9] "The ENIAC was to be designed with a special application in view. That is, it would be designed expressly for the solution of ballistics problems and for the printing of range tables, though, as originally envisioned by Mauchly, the device could have had wider applicability" [38, p. 15].

The applied and engineering sciences more generally

Indeed, the same may be said of the other engineering disciplines. Designing is precisely what the domain of the engineer is primarily about. Sciences of the artificial, a subset of which have been outlined above, consist of purposive, goal-directed activities. Their explicit design orientation seems to exclude them from the usual definition of basic research. Basic research involves the quest for fundamental understanding and, in the traditional natural sciences, such a quest has often been identified with research that was significantly distanced from any immediate concerns with practical applications. However, a widely accepted definition of basic research has come to focus on the absence of a concern with practical applications rather than the search for a fundamental understanding of natural phenomena. This is unfortunate, indeed bizarre. In the applied sciences, and in engineering, some of the research is in fact quite basic in the sense of a search for understanding at a very fundamental level. Most of the research in the medical sciences is undertaken with specific practical applications in view. Medical studies of carcinogenic processes necessarily involve research into fundamental aspects of cell biology.

The definition of basic research should not be made to turn upon the absence of a useful goal in the motivation of the individuals performing the research. By such a construction, research oriented toward the design and improved performance of computers, airplanes, or plants, involving such activities as massive parallel processing or extensive parametric variation, would have to be excluded from the category of basic research.

However, research directed toward such practical goals has made important contributions to areas that are unhesitatingly categorized as basic. Consider computer science, which has emerged as an interdisciplinary subject lying between engineering and mathematics. In an effort to develop organizing principles for computer architecture, computer science had to branch out to explore deep questions of logic, linguistics, perception, cognition and, ultimately, intelligence itself. Similarly, aeronautical and chemical engineers have posed important questions for their colleagues in physics, materials science and chemistry, while focusing on the development of practical design tools. In some cases, the questions have been pursued by members of the engineering disciplines; in other cases, the questions have been passed along to other members of the academic research community. In aircraft design early in the century, a standard problem involved calculations of the flow over wings. In solving these problems, Ludwig Prandtl devised what has come to be essentially a new branch of mathematics, now known as asymptotic perturbation theory. That theory, in turn, eventually found applications in radar design, the study of combustion processes, astronomy, meteorology, biology and pharmaceuticals. More recently, the field of turbulence research, which involves some quite fundamental issues, is being studied by researchers trained in aeronautical engineering, physics and mathematics.

If we review the history of the development of a number of important engineering disciplines, it seems apparent that engineering education in the US has consistently attempted to provide reference points for inquiry into the details of very practical problems. At the same time, university research has been instrumental in providing an appropriate intellectual framework for training efficient professional decision-makers. Once again, Herbert Simon reminds us of an often insufficiently recognized aspect of modern university education:

> The intellectual activity that produces material artifacts is no different fundamentally from the one that prescribes remedies for a sick patient or the one that devises a new sales plan for a company or a social welfare policy for a state. Design, so construed, is the core of all professional training; it is the principal mark that distinguishes the professions from the sciences. Schools of engineering, as well as schools of architecture, business, education, law, and medicine, are all centrally concerned with the process of design ... [37]

There are a large number of academic disciplines that, like engineering, are consciously and deliberately oriented toward specific useful goals. This would include research directed toward improving human nutrition through the enlargement of the food supply, an explicit goal of the life sciences as they are utilized in schools of agriculture. It would include statistics, certainly one of the most useful of disciplines. And statistics, it should be noted, achieved curricular and department status in the United States long before such developments occurred in Europe. [10]

By the start of World War II the applied sciences and engineering disciplines, that is, the sciences of the artificial, had established firm places in the American university system. A few of the old ivy institutions, like Harvard and Yale, tended to resist or to isolate them, but they were strong at most of the land-grant universities, which, after all, accounted for a very large share of American university research. The presence of the engineering disciplines and the applied sciences came on top of, and significantly molded, but did not replace, the longer standing tradition in American universities of research in the service of local industry and agriculture, and the training of people to go out into industry.

Of course, American academic research strength was not solely in the engineering disciplines and applied sciences. During the interwar period, American universities came into their own in astronomy, as well as in certain areas of fundamental physics and chemistry. This was the outcome of a long struggle by American academic scientists against what they regarded as an excessively practical orientation to American university research and teaching, and a weakness in the fundamental sciences, as compared with the United Kingdom and, particularly, Germany. Ben-David, Geiger and Bruce tell this story well. Nevertheless, prior to World War II, as I.B. Cohen has stressed, the bulk of the frontier research in theoretical physics and chemistry was being carried out in Europe. American students who wanted advanced training continued to get it on the other side of the Atlantic, if they could arrange to do so.

[10] Nor is it an accident that the pioneering roles in the introduction of techniques of statistical analysis were carried out far from the elite universities, at places such as Iowa State University and the University of North Carolina. Both of these universities had strong agricultural experiment stations where sophisticated statistical techniques were indispensable in evaluating the results of agricultural field research [2].

4. The post-World War II era and the emergence of the federal funding commitment

World War II was a watershed in the history of American science and technology and, in particular, led to a dramatic change in the roles played by American universities in scientific and technical enterprises. During the war the lion's share of the country's scientific and technical capabilities was mobilized to work on projects aimed at hastening the successful termination of the war. The nation's university scientists and engineers played a central role in these endeavors. Academic researchers, often working closely with scientists and engineers from industry, achieved advances in electronics which greatly advanced the allied defensive and offensive causes, in military medicine which made possible the saving of thousands of lives, and in many other areas [1]. Of course the Manhattan Project, which successfully developed the atomic bomb, was the most dramatic of these research endeavors, and the one that most caught the imagination of the American people.

As a result of all this, the prestige of American academic science was lifted enormously among those in government, and among the American electorate. While large-scale public support of university research was unthinkable prior to World War II, the war-time successes completely changed that picture. Vannevar Bush, whom we have met in another context, was the director of the war-time Office of Scientific Research and Development, which was responsible for mobilizing much of this effort. Bush wrote an influential document, *Science, The Endless Frontier*, which put forth the case for large-scale post-war support by the federal government of the American scientific enterprise [6]. There were three major parts to the Bush proposal.

First, the US government should not let the capability for military R&D, assembled during the war, atrophy, but rather should continue to sustain a level and mix of funding adequate to preserve those capabilities. With the rise of the Cold War in the late 1940s and early 1950s this policy became manifest in large-scale funding of military R&D. While the bulk of that funding went to support work on military systems and components carried out in industry, a sizeable amount of money flowed to universities to support work on computers, electronics more generally, materials, and the applied sciences and engineering disciplines that were relevant to military technologies.

The second part of the proposal was for significant public support of medical R&D. Here the universities from the beginning have been the largest recipient of government funding, with the National Institutes of Health the principal funder.

The third part of the post-war strategy articulated in *Science, The Endless Frontier*, was for the federal government to assume responsibility for supporting basic research at the universities, in a broader sense. After several false starts, this responsibility became manifest in the establishment, in 1950, of the National Science Foundation.

Federal funding of academic research, which probably amounted to about a quarter of total academic research support in the mid-1930s, increased enormously, and by 1960 was accounting for over 60% of the total. The total academic research enterprise increased more than tenfold in nominal terms between 1935 and 1960, and more than doubled again by 1965 (see Table 2). Over this same period the Consumer Price Index (CPI) increased more than twofold from 1935 to 1960 (from 41.1 in 1935 to 88.7 in 1960, where prices in 1967 = 100) and more than 6% between 1960 and 1965. While the CPI is not fully adequate as a research expense deflator, it is quite plausible that by 1965 real resources going into academic research were more than twelve times

Table 2
Support for academic R&D, by sector: 1960–91 (millions of current dollars)

Year	Total academic R&D ($)	Federally supported R&D ($)	Federal percentage of total
1935 [a]	50	12	24
1960 [b]	646	405	63
1965	1474	1073	73
1970	2335	1647	71
1975	3409	2288	67
1980	6077	4104	68
1985	9686	6056	63
1990 (est.)	16000	9250	58

[a] Data for 1935: [27]
[b] Data for 1960 and after: [28].

what they were in the mid-1930s. Rapid growth continued from 1965 until 1980 or so. It is estimated that real academic research funding grew at a rate of about 3% a year over this period.

With the vast expansion of resources employed in the university enterprise, and the very great expansion in the funding role of the federal government, there came about an equally dramatic transformation in the character of university research.

We shall argue shortly that solutions to practical problems continue to dominate the articulated rationale for most university research. However, there was a major shift in the nature of university research towards the basic end of the spectrum. In contrast with the pre-World War II era when proponents of basic research had to fight hard against a dominant applications orientation, in the environment after World War II 'basic research' became not only respectable, but widely perceived as what the universities ought to be doing. By the mid-1960s the American system was clearly providing world leadership in most fields of science. Statistics of Nobel Prizes tell part of the story, but the best indicator is the flow of students from Europe to the United States for their graduate training, a reversal of the situation prior to the war.

But while American universities became the pre-eminent centers of basic research and graduate education, the dominant rationale for most of the research funding continued to be the expectation that the research would yield practical benefits. The National Science Foundation is indeed committed to the support of basic research for its own sake, with the broad rationale that the research sooner or later will yield social benefits, but the NSF has accounted for less than one-fifth of federal support for university research over the post-war period. The Department of Defense and two other government agencies that are allied with Defense in many ways, NASA and the Department of Energy (earlier the Atomic Energy Commission), have accounted for much more, roughly one-third in total (see Table 3). This share has remained virtually constant since 1960, but is likely to fall significantly in the coming years. In the years through 1960 the National Institutes of Health provided roughly comparable funds, about a third of the federal total. After 1960 NIH funding of university research increased greatly, and the NIH presently is by far the largest federal supporter of academic research, now accounting for almost half of total federal support.

The mission orientation of the biggest funders of academic research, and their particular fields of interest, is reflected in the distribution of research funding by field. Funded research in the engineering disciplines exceeds funded research in the physical sciences (see Table 5). The interests and money of the DoD and kindred organizations thus show through very clearly. We should note, however, that research in academic engineering now tends to be quite basic, as suggested by the frequency with which the term 'engineering sciences' has been employed in recent years.

The interests of NIH (and to a lesser extent the Department of Agriculture) can be seen in the fact that more than one-half of academic research is in the life sciences, and most of that is in the medical and agricultural science areas. While it is officially called 'basic research,' the research is motivated by practical problems, the helplessness of doctors and hospitals in dealing with various kinds of cancers, or AIDS, and is

Table 3
Agency funding of academic research [a]

Percent of federal research funds originating within particular agencies							
Year	NIH	NSF	DoD	NASA	DoE	USDA	Other
1971	36.7	16.2	12.8	8.2	5.7	4.4	16.0
1976	46.4	17.1	9.4	4.7	5.7	4.7	12.0
1981	44.4	15.7	12.8	3.8	6.7	5.4	11.0
1986	46.4	15.1	16.7	3.9	5.3	4.2	8.4
1991 (est.)	47.2	16.1	11.6	5.8	4.7	4.0	10.7

[a] *Source*: [28, p. 360].

Table 4
Expenditures for academic basic research, applied research, and development: 1960–90 [a] (millions of current dollars)

Year	Total academic R&D ($)	Basic research ($)	%	Applied research ($)	%	Development ($)	%
1960	646	433	67	179	28	34	5
1965	1474	1138	77	279	19	57	4
1970	2335	1796	77	427	18	112	5
1975	3409	2410	71	851	25	148	4
1980	6077	4041	67	1698	28	338	6
1985	9686	6559	68	2673	28	454	5
1990 (est.)	16000	10350	65	4845	30	805	5

[a] *Source*: [28, p. 347].

aimed at providing a better understanding and framework for arriving at solutions to these very real problems and priorities.

This orientation is of course consistent with the intentions of the funders of the research, and it is further reflected in the research funding mechanisms. Thus, proposals sent to the National Institutes of Health are rated in terms both of their intrinsic scientific merit *and* their possible contribution to dealing with various health problems. Similarly, the Departments of Defense and Energy choose the academic projects that they finance with a strong sense of their own practical, mission-oriented priorities. Put another way, while the fact that a research project is called 'basic' indicates a certain distance from immediate particular practical applications, it should not be interpreted to mean that the research projects have been selected without an explicit concern for eventual usefulness. [11] Indeed, in the applied sciences and engineering disciplines research seldom proceeds without some attention to potential practical payoffs.

It should also be noted that, even when basic research is defined this broadly, except for the period between the mid-1960s and the mid-1970s, over 30% of university research has been on projects that are explicitly labelled as 'applied research' or even 'development' (see Table 4). Here the Department of Defense and related agencies would appear to be the principal clients.

The changing composition of funding sources is additionally reflected in the changing output of university research. In view of the fact that more than half of the university research funding since the 1960s has come from DoD, DoE, NASA and the NIH, one would expect that this would be reflected in an increase in the role played by university research in defense and space technology and in health and medicine. Indeed, the role of universities in these areas has been very substantial since 1945.

In fact, a large part of university defense-related research funding in the postwar years built directly upon an earlier military research program that has already received brief attention:

Table 5
Federal and non-federal R&D expenditures at universities and colleges, by field and source of funds, 1989 [a]

Field	Thousands of dollars	Percent
Total science & engineering	14987279	100.0
Total sciences	12599686	84.1
Life sciences	8079851	53.9
Physical sciences	1643377	11.0
Environmental sciences	982937	6.6
Social sciences	636372	4.2
Computer sciences	467729	3.1
Psychology	237945	1.6
Mathematical sciences	214248	1.4
Other sciences	337227	2.3
Total engineering	2387593	15.9
Electrical/electronic	600016	4.0
Mechanical	340280	2.3
Civil	249552	1.7
Chemical	185087	1.2
Aero/astronautical	146548	1.0
Other	866110	5.8

[a] *Sources*: [29]; and unpublished tabulations.

[11] It would be interesting to know what percentage of federal funds in support of basic research are awarded solely on the basis of peer review, and with no consideration of potential usefulness. We suspect that, outside of the NSF, that percentage is very small.

the development of the electronic digital computer. MIT, which had done important earlier work on techniques of electronic computation in the late 1930s (work with which Vannevar Bush had been closely associated), played an even more prominent role in the postwar years. MIT's research in this field had been supported by the Rockefeller Foundation and then, on a substantially larger scale, as part of Project Whirlwind. Project Whirlwind, supported by the Office of Naval Research for the development of general-purpose computer programming capabilities, had achieved some important successes. These included Jay Forrester's invention of a magnetic storage system in 1949. After the Soviets detonated an atomic bomb in August 1949, the Air Force proposed that Whirlwind be incorporated in a highly ambitious national air defense system, called SAGE (Semi-Automatic Ground Environment). The first portion of the SAGE system went into operation in June 1958 (see [41, Ch. 17]).

MIT, whose postwar prominence owed a great deal to DoD research support, also served as the location for another military-supported project that led to a major improvement in machining capability. One of the most important advances in machine techniques for shaping metal originated with an Air Force contract for MIT to design and build a numerically controlled milling machine. This resulted in the emergence of numerically controlled machines that were capable of performing highly complex machining operations of a kind that were critical to the manufacture of aircraft components, especially wings. The technology essentially consisted of attaching a digital computer to the machine tool. The computer was capable of being programmed to 'instruct' the machine tool to conduct a sequence of complex operations with a minimum of human intervention.

MIT provided the first demonstration of the numerical control of machine tools in 1952. While the technology successfully met the needs of the military sponsor, its complexity and cost hampered the diffusion of numerical control for about two decades. [12] It was only in the early 1970s that the advances in the field of solid state technologies favoured the widespread development of commercial applications of numerical control. [13] In the era of microcomputers, the basic technology is being joined to improvements in robotics, automated handling and transfer systems, into what are called flexible manufacturing systems.

The link between federal research priorities and university research's contribution to technical advance is further strengthened by an examination of the biotechnology revolution. Since World War II, the federal government has devoted substantial resources toward medical research and the life sciences. The genetic engineering revolution that began in the mid-1970s represents a clear payoff from this investment. However, over 20 years passed before university researchers were able to synthesize the first human genes, a synthesis based upon the identification of the double helix structure of the DNA molecule in the early 1950s. Research at Stanford, UCSF, and Harvard was critical in the development of the methods for this pathbreaking innovation. In fact, a share of the revenue from the primary patent for the genetic cloning process, the Cohen-Boyer patent, is currently received by Stanford University. The scientific research that went into the creation of biotechnology products, such as human insulin or human growth hormone, required close links between university research and industrial development. For example, Herbert Boyer, a university researcher, was a founding partner in Genentech, the first private biotechnology firm. Other early firms, such as Cetus, were (and are) heavily reliant on access to university research results and have developed intimate consulting relationships with prominent molecular biologists.

However, numerous 'start-up' firms with close connections to universities have operated on the assumption that the performance of good science was a sufficient condition for the achievement of financial success. Biogen, whose CEO in the early 1980s was a Harvard Nobel Prize-winning biolo-

[12] See David Noble [31] for a critical treatment of MIT's role in the development of this technology.

[13] During that later period though, America's historical eminence in the machine tool industry declined drastically, as Japan, Germany and other countries emerged as leading producers. The coordination of development efforts and a closer interaction between producers and users seem to be most important among the reasons for such a shift in the comparative advantage in the industry.

gist, is symptomatic of biotech firms that concentrated on good science with little financial discipline or attention to 'downstream' product development. It survived after its stock fell from $23 in 1983, when it first went public, to around $5 by the end of 1984, only as a result of drastic managerial reorganization. As will be explored further below, biotechnology represents an important industrial sector with a strong contemporary reliance on university research. Not surprisingly, the links between university research and industry are closer in this industry than in many others.

As a result of the changes we have been describing, research aimed at helping local civilian industry and agriculture, which was the hallmark of the American university research enterprise prior to World War II, became a much smaller part of the total picture in the postwar era. American university research that was aimed at solving practical problems for local economic needs dwindled (at least relatively) because defense and health-related problems became the dominant foci and the rationale for university research funding. Large parts of the earlier traditional enterprise were, as we have noted, very much hands-on, dirt-under-the-nails work, and the post World War II notion that the proper role for academic research was to make scientific and technical breakthroughs militated against this kind of work.

Deborah Shapley and Rustum Roy comment critically on this change in orientation of university research and also on the low prestige of engineering relative to pure natural science that they saw prevalent in academia [36]. But we believe that they overstate their case. As we noted, whatever its standing in terms of prestige, engineering is receiving more resources than physical science. Research at medical schools receives far more resources than research in Arts and Sciences biology departments.

And while the relative share of university research directly aimed to help civilian industry has declined greatly from what it was before World War II, many universities did remain in the role of helping local industry. Engineering schools like RPI and Georgia Tech continued to serve local industry, even if MIT and, even more so, Cal Tech drew away from that function. Federal and state funding for agricultural research actually increased over the postwar period, even if it became a relatively very small part of total university research funding.

The rise of concerns about the competitiveness of American industry that marked the 1980s rekindled notions that a major explicit objective of American universities ought to be to service civilian industry. The end of the Cold War and the erosion of the credibility of national security as a rationale for public support of universities has also led to a rethinking of old missions. Before offering our commentary, however, it is important to look more directly at the roles American universities are currently playing in technical advance.

5. The contributions of university research to technical advance in industry

In the preceding sections we have followed the American university research enterprise over the past century and a half, and called attention to two major structural transitions that have occurred. The first, which began to occur toward the end of the nineteenth century, was the rise and institutionalization of the engineering disciplines and applied sciences as accepted areas of academic teaching and research. This development regularized and brought into the main line academic structure the programs of research and training for industry which earlier had been proceeding on a more or less ad hoc basis with each university being a special case. The second major change occurred after World War II which saw massive increases in federal funding of academic research. One consequence was a shifting of emphasis of university research from the needs of local civilian industry to problems associated with health and defense. Another result was a shift of academic research toward the basic end of the spectrum, and the development of a strong belief, at least in academia, that basic research is the proper role of the university.

Over the last half century there has developed a relatively clear division of labor between academic and industrial research. R&D to improve existing products and processes became almost exclusively the province of industry, in fields where firms had strong R&D capabilities. So too the work directly aimed at bringing into practice and commercial use the next generation of prod-

Table 6
Percent of patents by universities by patent classes ranked by university share of total [a]

Class title	Rank	Class	Univ. pats.	Total pats.	1990 share
Genetic engineering, recombinant DNA	1	935	58	321	18.1
Chem.: natural resins; peptides or proteins	2	530	91	583	15.6
Chemistry: molecular biol. and microbiol.	3	435	171	1417	12.1
Surgery	4	600	12	105	11.4
Organic compounds	5	536	66	615	10.7
Superconductor technology	6	505	25	233	10.7
Drug, bio-affecting and body treating comp'n	7	424	147	1490	9.9
Chem.: analytical and immunological testing	8	436	67	688	9.7
Prosthesis (artificial body parts)	9	623	25	399	6.3
Drug, bio-affecting and body treating comp'n	10	514	181	3003	6.0
Coherent light generators	11	372	27	531	5.1
Robots	12	901	12	251	4.8
Surgery	13	128	90	2149	4.2
Plant patents	14	PLT	13	317	4.1
Organic compounds	15	556	13	326	4.0
Compositions: ceramics	16	501	18	462	3.9
X-ray/gamma ray systems/devices	17	378	13	343	3.8
Optics: measuring & testing	18	356	36	1012	3.6
Organic compounds	19	549	26	715	3.6
Chemistry, inorganic	20	423	33	965	3.4
Chemistry: electrical & wave energy	21	204	41	1263	3.2
Electricity: measuring and testing	22	324	40	1259	3.2
Organic compounds	23	558	14	433	3.2
Surgery	24	604	38	1223	3.1
Organic compounds	25	540	16	518	3.1
Radiant energy	26	250	60	1987	3.0
Organic compounds	27	548	34	1141	3.0
Semiconductor device manufacturing	28	437	23	755	3.0
Surgery	29	606	18	621	2.9
Organic compounds	30	544	27	1037	2.6
Organic compounds	31	546	28	1128	2.5
Coating processes	32	427	43	1801	2.4
Process disinfecting, deodorizing, preserving	33	422	23	953	2.4
Organic compounds	34	564	13	546	2.4
Synthetic resins or natural rubbers	35	528	28	1230	2.3
Organic compounds	36	560	15	640	2.3
Measuring and testing	37	73	46	2056	2.2
Active solid state devices (e.g. transistors)	38	357	34	1535	2.2
Metal treatment	39	148	17	765	2.2
Liquid purification or separation	40	210	28	1499	1.9
Catalyst, solid sorbent or support	41	502	13	699	1.9
Organic compounds	42	568	12	628	1.9
Optics: systems and elements	43	350	41	2280	1.8
Food or edible materials	44	426	18	1008	1.8
Plastic/nonmetallic article shaping/treating	45	264	32	1946	1.6
Synthetic resins	46	525	22	1495	1.5
Adhesive bonding & miscellaneous chem. mfgr.	47	156	28	1982	1.4
Compositions, miscellaneous	48	252	26	1844	1.4
Stock material or miscellaneous articles	49	428	40	3196	1.3
Gas separation	50	55	14	1606	0.9
Electrical transmission/interconnection	51	307	11	1288	0.9
Electrical computers and data processing	52	364	53	6474	0.8
Electric heating	53	219	10	1268	0.8
Communications, electrical	54	340	14	2026	0.7

[a] Data gathered by Jonathan Putnam and Richard Nelson (unpublished data).

ucts and processes. Industrial R&D is almost totally concentrated on this kind of work. In a few industries, some industrial firms may engage in longer run research more broadly oriented toward advancing understanding. But basic research in industry, although it accounts for more than one-fifth of all US basic research, constitutes only 5% of industrial R&D.

Basic research became increasingly viewed as the task of universities. The policies of the DoD and the NIH, as well as the NSF, supported this view of the universities' appropriate roles. Today, except for those fields where, in effect, university work is substituting for industrial R&D, as in forest products, university research is 'basic' research.

However, by this we do not mean that such research is not guided by practical concerns. As our discussion in the preceding section showed, it is a gross misconception to think that if research is 'basic' this means the work is not motivated by or funded because of its promise to deal with a class of practical problems. Nor does it mean that university scientists and engineers are not building and working with prototypes of applicable industrial technology. Indeed this is a central part of academic research in many engineering fields. Academic medical scientists are centrally involved in exploring the efficacy of new treatments. However, cases like the taconite project of the interwar period, and SAGE, where university work brought new industrial processes and products fully to practice, are rare and so too are cases where academic medical scientists carry their work close to the point of operational practice.

What university research most often does today is to stimulate and enhance the power of R&D done in industry, as contrasted with providing a substitute for it. By far the largest share of the work involved in creating and bringing to practice new industrial technology is carried out in industry, not in universities.

One good way of seeing what it is that universities do not do is to recognize that in most technologies the bulk of the effort that goes into R&D is D, not R. If we consider total R&D spending for the American economy, D has constituted approximately two-thirds of that total for many years. Except when special institutions or projects are established (as in the Ag schools, and in certain special DoD projects) academic institutions are not motivated by or likely to be good at D.

Usually, moreover, most of the science employed in achieving the objective of a marketable new technology is rather old science [33]. This is not the kind of work that naturally excites academics, and its successful completion generally does not lead to publication and tenure. Moreover, the understandings that are most important in guiding the R&D efforts are often those associated with detailed familiarity with prevailing technology, and of user needs, rather than familiarity with the most recent research findings. Universities are not set up to do this kind of work. The exceptions are where university projects or laboratories have been established to perform an industry service function, as in the case of the University of Minnesota's Mines Experiment Station, and in a number of the university-affiliated agricultural experiment stations, and in places like Georgia Tech and RPI which have set up industry-servicing engineering facilities.

As we described in the previous section, over the post-World War II period the Department of Defense and the National Institutes of Health energetically built up the academic research enterprise in fields of particular interest to them. Academics in these fields have developed many prototypes of new technology which were subsequently developed in industry, and on some occasions have been involved in development work as well. This shows up in the patent statistics, where academics account for a significant share in several areas of medical science and electronics (see Table 6).

Patents of course provide only a partial and necessarily biased picture of the contributions of university research. Many of the kinds of contributions discussed earlier do not generally result in patents.

A survey of industrial R&D managers, undertaken in the mid-1980s by one of the authors of this article and several of his colleagues at Yale, provides a wealth of data that make it possible to see more clearly into how university research contributes to the advance of industrial technology, and into the industrial fields where this role is most important. The respondents to the questionnaire were asked to rate the importance of research done at universities to technical advance

Table 7
Industries rating university research as 'important' or 'very important' [a]

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
Processed fruits and vegetables
Engineering and scientific instruments
Millwork, veneer and plywood
Synthetic rubber
Drugs
Animal feed

[a] *Source*: Previously unpublished data from the Yale Survey on Appropriability and Technological Opportunity. For a description of the survey, see [21].

in their lines of business. Table 7 lists the industries (for which there were three or more responses) that rated the contributions of university research as very important or important.

There are several particularly interesting features displayed by this table. First, a striking number of the industries are related to agriculture or forestry. This clearly reflects the long standing 'service' research role of universities for the industries that provide key inputs for agriculture or which process agriculture or forest products. While in the postwar era such service R&D has been dwarfed by university research funded by agencies like the DoD and NIH, it is apparent that for the agriculture-related industries, university research efforts aimed to help them continue to be critical. This shows up, among other places, in the significant university role in such fields as plant patents.

The presence of drugs was to be expected, in view of the prominence of NIH funding of university research. The major electronics industries are also on the list, as well as the scientific and measurement instrument industries. In these broad areas the university contributions apparently are often patentable.

What fields of university science are important to these industries? Table 8 shows the number of industries giving various fields of university research a high relevance score.

It is striking what a large fraction of the fields of university research rated as important by a

Table 8
The relevance of university science to industrial technology [a]

Science	No. of industries with scores		Selected industries in which the relevance of university science was large
	≥ 5	≥ 6	
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	Opt. instrmts., 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, fab. 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

[a] *Source*: Previously unpublished data from the Yale Survey on Appropriability and Technological Opportunity. For a description of the survey, see [21].

number of industries are applied sciences or engineering disciplines. Very few of the more basic sciences are much mentioned. An exception is chemistry. However, those knowledgeable about academic chemistry know that a significant fraction of such work is done in appreciation of practical industrial problems. In some cases, as in the research on catalysis, such work may win a Nobel Prize, as well as contributing importantly to the ability of chemical companies to produce products more effectively. That is to say, among the basic sciences on which there is extensive university research, chemistry appears to be closest to certain on-going needs of the industrial community.

The fact that university research in fields such as physics and mathematics shows up so little in Table 8 should not be interpreted as indicating that academic research in these fields makes little contribution to technical advance. Rather, Table 8 should be interpreted as attesting that it takes a long time before fundamental advances in physics, mathematics, and kindred fundamental sciences, have an impact on industrial technology. In our view, that impact also tends to be indirect. Thus, advances in physics and mathematics are picked up and used in fields like chemistry, electrical engineering and material science, and through these applied fields they ultimately work their way into influencing industrial technology.

Some evidence for this interpretation is provided in Table 9. The responses reported in the Table are not to questions about the importance of academic research in a field, but rather simply about the importance of the field itself. Note that many more respondents tended to give physics and mathematics a high importance rating as a field of science than gave university research in those fields a high importance rating. In our view this is a crucial distinction which reflects two things. First, the fundamental science learned by industrial scientists and engineers when they attended university plays a very important role in their problem-solving in industrial R&D, even though recent publications in those fields may find little direct use in those endeavors. Second, the respondents understood very well that, while the academic research findings that were of direct use to them were in fields like electrical engineering and medical science, those disci-

Table 9
The relevance of science to industrial technology [a]

Science	No. of industries with scores		Selected industries in which the relevance of science was large
	≥ 5	≥ 6	
Biology	14	8	Drugs, pesticides, meat prods., 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 prods.
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

[a] *Source*: Previously unpublished data from the Yale Survey on Appropriability and Technological Opportunity. For a description of the survey, see [21].

plines were, in turn, drawing from, and enriched by, the more basic sciences such as physics and molecular biology.

It is useful and valuable to compare the findings discussed above, drawn from the Yale questionnaire, with those of two other recent studies that have probed the connection between university research and technical advance in industry. One of these was a series of interviews conducted by the Government-University-Industry-Research Roundtable, in which the present authors participated. The other is a study by Edwin Mansfield.

The GUIR Roundtable study was carried out through discussions with 17 senior industrial research managers, mostly from large successful industrial companies [14]. A few of the companies were heavily involved in biotechnology. There was reasonable representation from the pharmaceutical and electronics industries. A number of the respondents were from companies that designed and put together large 'systems,' and some were from companies that produced commodities like metals or household products.

Once one sorts through the interviews, biotechnology stands out almost uniquely as an area where corporate managers look to university research as a source of 'inventions.' Here the respondents stated that this was largely because the technology was very new, and that they believed that, as the industry matured, the direct role played by university research in inventing would diminish. We would add that the technology itself was born in a university setting, which actually is quite unusual. The respondents from the electronics companies tended to make a distinction between what they called 'breakthrough inventions' and normal incremental inventions. They took the position that, in the field of electronics, academic research is often the source of radically new designs and concepts. However, they argued that the bulk of the total inventive effort in their field, and the bulk of the practical payoffs, came from incremental advances, and that this was almost exclusively the domain of industrial research, design, problem-solving and development.

Respondents discussing drugs other than those emanating from biotechnology stated that university research was almost never the direct source of a new drug; in virtually all cases the key work was in industry. However, they also noted that, in a number of cases, academic research had illuminated the kinds of biochemical reactions the pharmaceutical companies should look for in their search for new drugs, or permitted the companies to make a more effective assessment of the possible uses for drugs that they were testing. Respondents from the pharmaceutical and several other industries observed that a major function of academic research was to improve understanding of technologies, particularly new technologies, so that industry could more effectively go about improving them.

It should be noted that only one of the executives interviewed was from a company with products based in agriculture or forestry; and that person did stress the important role of university research to his company. The kind of local com-

Table 10
Percentage of new products and processes based on recent academic research, seven industries, United States, 1975–1985

	Percentage that could not have been developed (without substantial delay) in the absence of recent academic research		Percentage that was developed with very substantial aid from recent academic research	
Industry	products	processes	products	processes
Information processing	11	11	17	16
Electronics	6	3	3	4
Chemical	4	2	4	4
Instruments	16	2	5	1
Pharmaceuticals	27	22	17	8
Metals	13	12	9	9
Petroleum	1	1	1	1
Average	11	9	8	6

Source: [24].

pany that state universities and regional engineering schools traditionally have served was not represented at all.

Mansfield's recent study provides still another window into the role of university research in technical advances in industry [24]. Mansfield asked respondents in 76 large American firms the percentage of new products and processes introduced and commercialized by that firm over the period 1975–1985 that could not have been developed without substantial delay in the absence of recent academic research. Then he asked about the percentage whose development was substantially aided by recent academic research. His findings are summarized in Table 10.

Executives in the pharmaceutical industry reported strong dependence on academic research. They stated that over one-quarter of the new drugs commercialized by the companies could not have been developed, or only with substantial delay, absent academic research. Close to another 20% were acknowledged to have had their development substantially aided by academic research. The discussions reported above with the pharmaceutical executives interviewed by the GUIR project almost surely accurately characterizes the nature of the dependence. Academic researchers are seldom directly involved in the development of new drugs. Rather, they are primarily creating knowledge that enables drug companies to search for and develop new drugs more expeditiously.

After pharmaceuticals, the reported fraction of new products that were heavily dependent upon academic research for their introduction drops off dramatically. The executives from the companies producing information processing equipment, and from those producing instruments, report a 10% to 15% figure. In the information processing field, in all likelihood, a good share of university contributions are in the form of the prototype 'radical breakthroughs' discussed by the GUIR respondents. For instrumentation, the likely mechanism was that university scientists created new or improved old instrumentation for their own research uses. The respondents from the metals industry also report that over 10% of the new products and processes could not have been developed in the absence of recent academic research.

While Mansfield did not stress the matter, a striking finding was that three of the industries in his set, electrical equipment, chemical products, and oil products, report that only a small percentage of their new products (6% or under) were significantly dependent upon recent academic research. This is not to say that technical advance in these fields is not science based. Rather, the implication is that the science used is not particularly new, or is not the stuff that academics are now doing.

Let us summarize. Several recent studies provide a broad picture of the role academic research is presently playing in technical advance in industry. While the coverage and methodology are different, by and large the studies provide a coherent picture.

The old service role to local industry, and in particular industry tied to agriculture and forest products, clearly is much smaller as a part of the total than was the case before the war, and these industries themselves have dwindled in importance. But the evidence shows a continuing dependency of these industries on research done at universities.

The massive funding by DoD and kindred agencies shows up clearly in various measures of the contributions of university research to technical advance in electronics. Similarly the funding of the NIH in health-related fields. However, in these fields the university contribution is largely R, with industry doing almost all of the D.

And there are a large number of industries that seem to be relatively untouched by university research. These include such basic industries as steel, autos, and textiles.

6. Conclusions

We began this essay by remarking on the significant increase in the fraction of academic research funded by industry over the past two decades, and the rapid growth in the number and size of university–industry research centers. Many in universities clearly see all this as just the beginning, and anticipate a significant further increase of industry funding of academic research. Many of those concerned with government policies towards universities also foresee this development, anticipating that in the coming years industry funding will reduce the need of government funds to support the academic research enterprise. But while at first this sounds like a harmony of consistent anticipations and expectations, there are strong reasons for skepticism.

In the first place, many of the academics hoping for a significant further increase in industrial funding also hope for this to occur without much change in what academics actually do or in how their research is oriented. Many academics clearly have a firm belief in what has been called the 'linear model' of technological advance, seeing unfettered research by academics as providing the basis for technological innovations in industry, with the process not calling for strong industry influence over what the academics actually do. The new government programs buy into some of this, but increasingly are insisting upon significant industry involvement in the processes by which research funds get allocated, and therefore influence over the composition and nature of academic research, as well as strong links to assure 'technology transfer.'

While many academics believe, as noted above, that business as usual should be the order of the day, other academics clearly welcome the notion that there should be close ties to industry, along with more industry funding. They are quite eager to reorient their work to make it more commercially relevant and rewarding. Indeed among some there seems to be a belief that, if they put their minds to it, with financial support from industry, academic researchers can provide industry with a cornucopia of new product and process prototypes and restore the lost competitiveness of American industry.

The industry views drawn forth by the Roundtable interviews suggest, on the other hand, considerable industry skepticism over the ability of academics to contribute directly to industrial innovation, which probably reflects a drawing back from more hopeful and less realistic beliefs held earlier in the 1980s. To a considerable extent the industry views expressed to the Roundtable were that the academics should stick with the basic research they are doing, and heed their training functions, and stop thinking of themselves as the source of technology. These views also suggest that it is highly unlikely that industry funding of academic research is going to increase much in the coming years.

We believe that expectations held by some about what university research, if suitably reoriented, can contribute directly to industrial innovation, are quite unrealistic, and so also beliefs about how much funding of academic research private industry is likely to shoulder. At the same time we disagree with those academics and others who argue for a simple continuation of the status quo. We do think that the times call for a major rethinking about what Americans ought to expect of their university research system and in particular about how university research ought to relate to industry. We believe the issue of competitiveness is a serious one. We also believe that American universities can help restore competitiveness in those technologies that their research illuminates. However, it is important to sort out when universities are capable of helping and where, while there may be problems, university research does not seem to be an appropriate answer.

While much of the attention recently has been on the weakness of American industry in product and process development, we think it a mistake to see universities as a likely source of solution here. Less attention has been given to the erosion of industrial research, as contrasted with design and development, in a number of industries where industrial research traditionally has been very strong, particularly in electronics. Here university research can be of more help [34].

Actually, as we have noted, the present danger is that the university contribution may decline. The end of the Cold War has eroded the rationale that has served over the past 40 years to provide the justification for government support of university research in a number of fields of vital importance to American industry. The first order of business, in our view, is to assure that government support of university research in the engineering disciplines and applied sciences, such as materials and computer science, not be orphaned by sharp cutbacks in military R&D that are almost certain to occur over the coming years. One element that is essential is to articulate clearly that a major purpose of government funding of university research in these fields is to assist American industry.

But we also believe that more is needed than a mere change in rhetoric. We need to establish university research support programs that have that objective expressly, and that also have allocation machinery that can achieve a sensible allocation of funds, given that objective. This would require advisory committees knowledgeable about industry needs, and decision criteria and proposal evaluation systems that are sensitive to those needs.

And probably more than that. As the experience over the past quarter century with industrial research clearly indicates, if such research is to be fruitful there must be close communication and interaction between those who do research, and those who are responsible for product and process design and development. If university research is to pick up more of the role that industrial research has been serving, this would seem to mean that there needs to be close links between university researchers doing the research, and their scientific and technical colleagues in industry. These exist in important areas of defense technology, and in technologies relating to agriculture and health. The new university–industry research centers extend the range of such connections. If university research is to play a more helpful role in industrial innovation, the connections need to be further extended and strengthened.

Does this mean, as some people seem to argue, that universities should get much more into the business of helping industry develop particular new products and processes? As a general rule, we don't think so. There are several reasons.

First, as we have stressed, the development over the past century of the applied sciences and engineering disciplines has, in many fields of technology at least, led to the establishment of a fruitful division of labor between universities and industry. Universities have taken the responsibility for training young professionals, most of whom will go on to work in industry. And they have performed much of the research that has led to theories, concepts, methods and data that are useful to industry in the development of new products and processes. In some fields this has involved developing and experimenting with pilot versions of radically new products and processes, as well as research into fundamental scientific questions relating to what is going on inside some particular industrial technology. But by and large it has not involved putting academics in the position of having to make commercial judgments.

Industry has also undertaken some quite fundamental research, and in some fields a good deal. Corporate research laboratories such as Bell Labs, IBM Yorktown, Dupont Central Lab, and others have performed at or sometimes even above the level of top universities. But the returns from such research are hard to make proprietary and reserved for the funder. As we have noted, many companies have been cutting back on their research. While corporate research may recover from its recent slump, in many fields universities will remain the dominant site of such research.

Sustained strong public support of university research in fields such as electrical engineering, computer science, and materials science, will continue to benefit mostly the 'high tech' industries, whether the funding be civilian or military. Although the shifting of objectives certainly should be associated with changed mechanisms for setting priorities, and a changed pattern of university–industry interactions in these fields, it does not seem to us that the change would involve breaking new institutional ground.

Based on the surveys and interviews reported in section 5 it is evident, however, that university research in the engineering and applied sciences is strongly servicing only a limited range of industries, specifically, those connected with electronics, chemical products, health and agriculture. This ought not to come as a great surprise. By and large these are the fields where government agencies have been supporting the underlying sciences for a long time. A policy of consciously broadening the range of industries under which there is university research is quite reasonable to contemplate. However, if that is to be a policy, it must be policy that looks to practical returns in the long run, not the short. It must, in brief, be a patient policy.

Except under special circumstances, we think it ill-advised to try to get university researchers to work on specific practical problems of industry, or on particular product or process development efforts. In general, university researchers are poorly equipped for judging what is likely to be an acceptable solution to a problem and what is not. University researchers are almost always insufficiently versed in the particulars of specific product markets to make good decisions about appropriate tradeoffs. Equally important, such work provides few results that are respected or rewarded in academic circles, unlike research that pushes forward conceptual knowledge in an applied science or engineering discipline.

What of the practical problem-solving that marked earlier days of American university research, the research on boilers or the processing of ores, that used to be quite common on university campuses? That kind of work is still there, often associated with education programs for engineers who will go out into local industry, or in business 'incubator' programs at places such as Georgia Tech. It is there in larger scale and more systematic form in institutions affiliated with universities, but not an integral part of them, where research is undertaken to serve the needs of particular national industries (e.g., Carnegie–Mellon's Center for Iron and Steelmaking Research, or the Forest Products Laboratory at the University of Wisconsin).

By and large, these programs have grown up in fields where industrial research is not strong. They are a substitute for industrial R&D, or represent a locus for it outside of industry itself. The industries in question tend to be, although not always, made up of small firms without R&D facilities, and often the technologies in question lack a sound underlying scientific base. As our earlier discussion indicated, university involvement in this kind of research often has its historical origins, and much of its current basis, in training programs. Larger scale research organizations, such as the agricultural experiment stations affiliated with many universities, tend not to be central integral parts of the university, but partially detached. Often many of the researchers are not university faculty members, although some may teach courses. Their interactions with their industrial clients, on the other hand, may be very close.

These kinds of programs can be very valuable to industries whose firms do little R&D of their own. They are an important part of the activities of many universities. However, after a certain size is surpassed, their locus at universities becomes more a matter of historical happenstance or convenience than a particular source of strength. They could exist just as well as separate organizations. [14]

[14] Harvey Brooks [3], who takes a position on these issues similar to our own, suggests that, when universities are associated with such work, it should go on in somewhat separated institutions. In fact, this is mostly the case.

In any case, we do not think that the emphasis of university research ought to be here, or that a revamped policy of federal support of university research which places the emphasis on contributions to industrial technical advance ought to be oriented to this kind of work. It is in research, not commercial design and development, that universities excel. While many of the problems of American industry may reside in product and process development and improvement, this is the kind of work they have to do largely themselves, or in specialized industry-linked institutions, which may or may not be associated with universities.

A shift in emphasis of university research toward more extensive connections with the needs of civilian industry can benefit industry and the universities if it is done in the right way. That way, in our view, is to respect the division of labor between universities and industry that has grown up with the development of the engineering disciplines and applied sciences, rather than one that attempts to draw universities deeply into a world in which decisions need to be made with respect to commercial criteria. There is no reason to believe that universities will function well in such an environment, and good reason to believe that such an environment will do damage to the legitimate functions of universities. On the other hand, binding university research closer to industry, while respecting the condition that research be 'basic' in the sense of aiming for understanding rather than short-run practical payoff, can be to the enduring benefit of both.

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