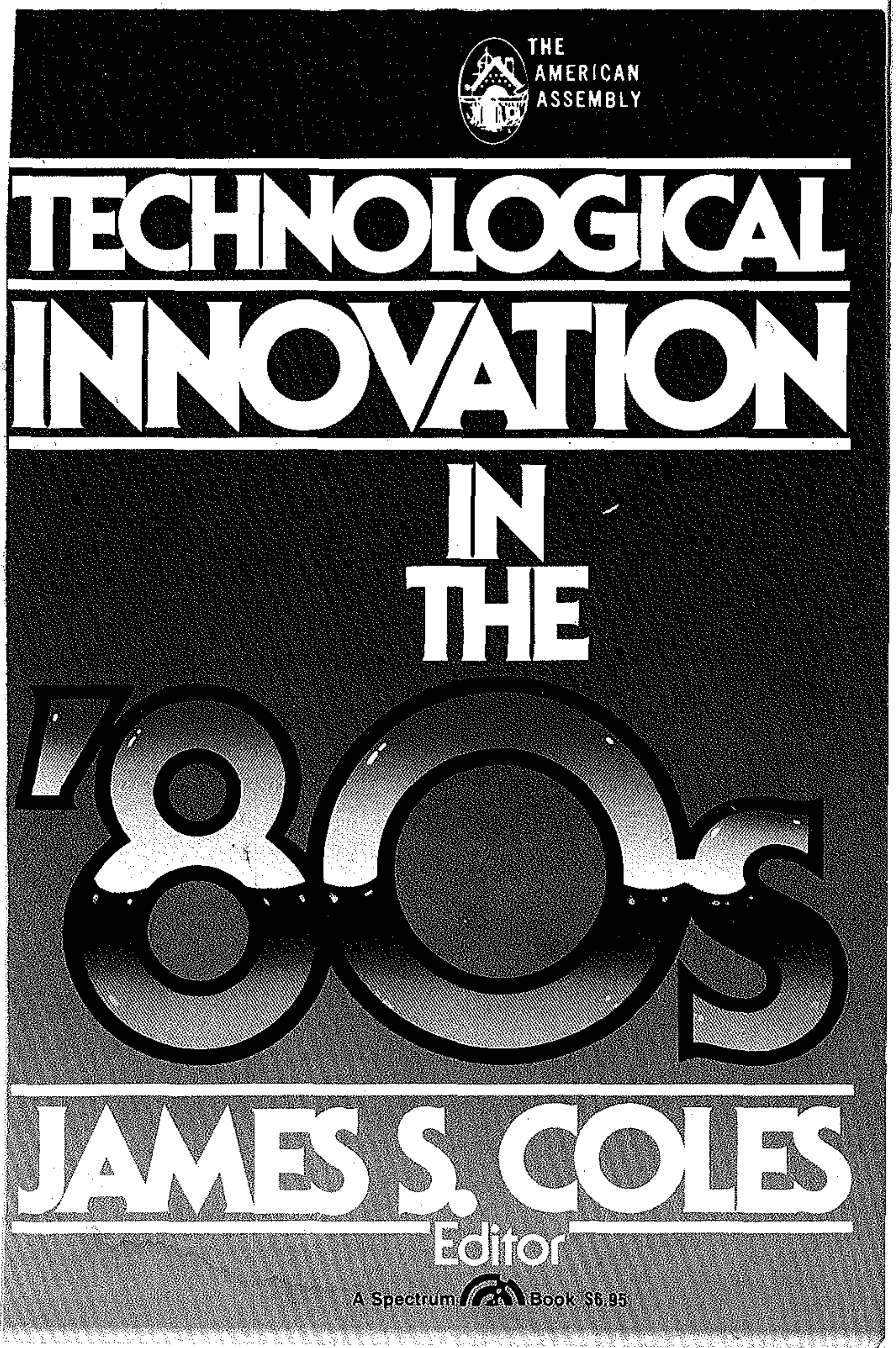

THE AMERICAN ASSEMBLY

TECHNOLOGICAL INNOVATION IN THE '80s

JAMES S. COLES

Editor

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Table of Contents

Preface

In recent years, especially in consequence of the economic recession, there has been considerable public lament that the United States has lost its edge in the fields of scientific and technological innovation. It has been alleged that other nations, notably Japan, have overtaken us in areas which we previously dominated and that we are doomed to a future as a second-rate service society.

The efforts to remedy these putative shortcomings have involved our government, our universities, and private industry. Much concern has also been expressed about the interrelationships of these institutions in the process and the roles that each should properly play in the future of an innovative economy.

In order to seek some consensus among various interested groups and institutions about the accuracy of the allegations and about recommendations for actions to address the situation as it is authoritatively perceived, The American Assembly convened a meeting at Arden House, Harriman, New York, from November 17 to 20, 1983. Participants attended from the legislative and executive branches of the government, from industry, from the universities, from organized labor, the law, and the communications media. In preparation for that meeting, the Assembly retained Dr. James S. Coles, formerly president of Bowdoin College and of the Research Corporation, as editor and director of our undertaking. Under his editorial supervision, background papers on various aspects of the issue were prepared and read by the participants in the Arden House discussions.

In the course of their discussions, the participants achieved a substantial consensus on their findings and recommendations. They did not accept the gloomy assessments that have colored some comment on the American scene. They felt that most elements of our climate for innovation were essentially healthy. However, they did note a number of troubling factors that require careful attention if our preeminence is to be preserved. They made a number of recommendations for action, especially in the arena of primary and secondary education, designed to avert a deterioration in our national capabilities. Copies of their report, *Improving American Innovation,* can be obtained by writing directly to The American Assembly, Columbia University, New York, New York 10027.

The background papers used by the participants have been compiled into the present volume, which is published as a stimulus to further thinking and discussion about this subject among informed and concerned citizens. We hope this book will serve to provoke a broader national consensus for action to regenerate and improve those elements of our society that have always inspired a strong measure of scientific and technological innovation.

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William H. Sullivan
President
The American Assembly

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The excerpt on pages 127-128 is from Eliot Marshall, "'Scelerosis' Blamed for Economic Stagnation," *Science,* 218, October 22, 1982, 357-58, copyright 1982 by the American Association for the Advancement of Science. It is used by permission.

Fig. 1, "The Electron Microscope" is adapted from Fig. 9 in *Technology in Retrospect And Critical Events in Science,* Vol. 1, December 15, 1968, prepared for the National Science Foundation by the Illinois Institute of Technology, Contract Number NSF C535.

The remaining figures are from National Science Foundation, *University-Industry Research Relationships: Myths, Realities and Potentials,* Fourteenth Annual Report of the National Science Board (Washington, D.C.: Government Printing Office, 1982). Their source lines are as follows: Fig. 2: NSF 81-311 and Science Indicators 1980; Figs. 3 & 4: National Science Foundation 81-311; Fig. 5: James D. Marver and Carl V. Patton, "The Correlates of Consultation: American Academics in 'The Real World,'" *Higher Education,* 5 (1976), 319-35. Used by permission of Elsevier Science Publishers, Amsterdam, Netherlands; Fig. 6: Council for Financial Aid to Education, Special Tabulation, March 1982. Used by permission of the Council; and Fig. 7: Special tabulation by the Foundation Center, May 1980.

James S. Coles

Introduction

"You can't do it, you fool! It's against the second law of thermodynamics," was Spike's immediate response to a query from Bob, a green, young local businessman trying to revive an old and faltering family business. From such an unpromising beginning was born a collaboration that, in retrospect, is almost a classic example of innovation. The result was a new, low-friction, long-wear, dry bearing material which needed no lubrication—something which the DuPont Company said couldn't be done.

Bob later recalled that "if there had been any point in his business career that marked an inchoate zero hour, yet a beginning in the right direction, it was then." Bob insisted on developing a dry bearing material. He was driven to perfect this original product that was, perhaps, not even imagined by engineers with much more technical training than he. His immediate motivation stemmed from failures in the recent past when Dixon Company had tried to use nylon in the manufacture of low-friction bearings.

JAMES S. COLES *is chairman of the executive committee of the Research Corporation (a foundation for the advancement of science) where he has been a director for twenty-four years and where he served as president for fourteen years. Before joining the Research Corporation, Dr. Coles was president of Bowdoin College. He is a director of several public companies as well as a trustee of private research organizations, including the Woods Hole Oceanographic Institution. Dr. Coles is the coauthor of a textbook,* Physical Principles of Chemistry.

(It was this attempt that provoked Spike's reference to the second law. Bob had wanted to take water—a good lubricant for nylon—from the moisture-laden atmosphere of a textile mill and deposit it on a friction-warmed bearing surface of nylon.)

From his boyhood days Bob had stubbornly insisted on being different and in his view original. His continuing idiosyncratic urge made him see life through a unique pair of lenses. This resulted in ". . . a rare overview, not so out of focus that what he undertook was preternatural, but neither was it orthodox." His childhood obstreperousness indicated early that he was to go his own way, and be his own individual person.

While Bob's baccalaureate major was English, Spike had the formal training of a physical chemist and was on the chemistry faculty of a nearby university. He had come but a short time before from three years of wartime research on underwater explosives, in which sophisticated applications of the most recent concepts in the design of experiments played a major role. This experience was most pertinent for the laboratory work he would recommend to develop the new bearing material. As Bob recalls:

> The plastic bearing material which would be developed was the result of necessity (Dixon having failed with other materials) and an outgrowth of Bob's individuality. The customers wanted it. The situation called for it. The time was ripe for it, and he believed the know-how, both mechanical and chemical, was available for it. As a result of this seemingly illogical insistence on a dry bearing, one entirely without the normal materials of lubricity such as oil or graphite, not only was a product developed for Dixon's textile industry customers, but an entirely new industry was born. For a time Dixon operated two businesses, textile machinery parts and dry plastic bearings for industry in general. The former sold to a limited market, but with the latter, the world was Bob's oyster. . . . Nevertheless it was a long, often losing, battle, profitless for several years and nearly so for several more.

With Spike's technical advice, the use of a specially designed apparatus, and an experimental design based on the concepts of R. A. Fisher, only eight months elapsed before a dry bearing material, trademarked "Rulon," was developed and marketed by Dixon Corporation. Bearings made of Rulon had a thousand times the wearability of Teflon (the principal ingredient) without significantly impairing the low coefficient of friction of the virgin Teflon.

These bearings were widely accepted by the textile industry and soon were widely used in such products as television tuners, household appliances, audio cassettes, and (with modification) nose cones of missiles. Rulon bearings, completely dry, would even run against stainless steel, a notably bad bearing mate. The company grew from but a dozen employees to several hundred, and annual sales jumped from $75,000 to $150,000 to $300,000 to $1 million in successive years, with the inevitable problems of operating capital for a rapidly growing company.

The preceding anecdotal example of a successful innovation includes all of the essential components of the innovative process within a comprehensible framework. There was the perception of a need for a new product, process, or service and the motivation to meet that need; the understanding of the fundamental laws of science; the availability of a new technology and new technologically based products; an appreciation of the research process and experimental design; a single-minded, unrelenting drive toward a steadfast goal; financing at appropriate levels and willingness to invest at significant risk; collaboration of colleagues toward a common goal; managerial skill; and, throughout all, an inclination to be different but yet accept the restraints of the laws of science, a refusal to take "no" for an answer, and a bit of the maverick.

The six chapters which follow all bear on these characteristics that generally relate to much more complex situations, such as those innovations originating in the research laboratories of large organizations, universities, and industrial corporations.

Since its beginnings, the American research university has been responsible for many innovations. Stephen Muller traces the rise of this institution from the days of von Humboldt in Germany during the early nineteenth century to its establishment in America several decades later. While new understandings of nature and new concepts in science were not long forthcoming and new scientific discoveries were soon to follow, their exploitation for the benefit of the society that supported these endeavors developed more slowly. Technology transfer from the university to a manufactured product or a new technological process did not really begin until early in the twentieth century, and only in mid-century did the value of such transfer from university laboratories generally become realized. Muller's pertinent conclusions emphasize the need for good marketing to benefit from those innovations we now are able to achieve.

As is also discussed in Muller's chapter, government has played an increasingly important role in the support of university research and, indeed, within government laboratories themselves. Donald Hornig draws from his own background in science, university research and administration, and the executive branch of government in reviewing the manner in which government has participated in technological innovation. The inclusion in the Constitution of provisions for promoting "the Progress of Science and the useful Arts" indicates that the nation's founders appreciated the potential value for the Republic of the sciences.

The early involvement of the government in technical concerns centered on exploration, geography, astronomy, and navigation. From such beginnings came the later developments in agricultural and mechanical science and government sponsored technology that led to the many alternative ways to support scientific research. In terms of government funding, the penultimate came with the development of nuclear energy; the capstone to date is undoubtedly the space program. Hornig sees a continuing government concern and participation in scientific research and technology that increasingly touches the lives of all of us.

The earliest technological innovations in America were developed almost exclusively by nonacademics—either lone individuals or those in agriculture, business, or industry. During this early period, little or none originated in academe. There are numerous examples: the cotton gin, the telegraph, the telephone, the steamboat, the internal combustion engine, the airplane, and so on. Much of this inventive genius was stimulated by what might be included in today's broad term, "market pull." We know, though, that had not men like Whitney, Fuller, Morse, Edison, Bell, Ford, and the Wright brothers had a flair for innovation and a determination to succeed despite all odds, our enjoyment of the fruits of their labors would have been long delayed.

During his career as a manager of scientific research and development within large organizations—government, nonprofit, and industrial—Robert Frosch has been concerned with a different type of innovation. His experiences in science, research, engineering, and development, as well as his knowledge of the psyche of the individuals involved with these tasks, provide insight into achievements, feasibility, motivations, and deterrents—without which good management of innovation cannot take place. He opines that we must look to better innovation management in order to take maximum advantage of our currently prolific and advancing technology.

Technology transfer from the university laboratory to public use is essential if we are to recover and benefit from our investment in academic basic research. Willard Marcy's long experience in the evaluation, patenting, licensing, and exploitation of inventions from university laboratories gives him a special insight into the manner in which this particular innovation path may be enhanced or restrained.

Typically, academic inventions are pioneer in nature; rarely, if ever, are they defensive, as are most industrial inventions. This poses its own problems. Often there is no industrial base for a new technology. This was the case for the Townes's patent on the laser. Yet countless innovations and a multitude of unforeseen industrial applications in diverse fields have since come from this single pioneer invention. Many times a new company has to be founded for the operation of the new process or the manufacture of the new product. Entrepreneurial and management skills are required, as well as risk capital. Alas, some inventions are no better than the well-established products or practices they would replace; others have so limited a market that they are left useless—"orphans," soon to be forgotten.

As director of Technology Licensing at Stanford University, Niels Reimers has not only been on the cutting edge of new technologies, but he has also brought industry and university into close, working partnerships. The skillful means by which he has solved difficult licensing problems advantageously for both industry and institution have been innovative in themselves. The management of the troika of government, industry, and university in the advancement of research and development is essential for effective research programs in large institutions. Reimers provides updates on these varied facets of the research process and its support.

Cecily Selby points out that our educational goals have not included technological understanding and the encouragement of innovative thought and practice. The talent within our youth for such thinking is there, ready to be developed, but new educational objectives, emphases, and strategies are needed to reach the potentials of all students. As other chapters have pointed out, we have the ability to bring conceptual innovations to the marketplace. However, how much more could we benefit if technology and innovation were among our teaching goals? From her perspective as a scientist and an educator, Selby emphasizes an underlying thought of some other authors herein—scientific and technological literacy is both a right and a need of citizens who wish to live happily and productively in an innovative and technologically oriented society. Our current deficiencies lie not with the education of those already identified as the best and the brightest, but rather with both the creation and maintenance of a larger and more broadly based pool from which to draw future scientists and engineers who are capable of innovative thinking and the development of a useful understanding of these fields in all citizens.

The recent report of the National Science Board's Commission on Precollege Education in Mathematics, Science, and Technology (cochaired by Selby) reviews the current status of the American educational system with respect to the objectives stated above and makes a number of recommendations for actions to achieve the goals explicated in Selby's chapter. Unfortunately, among the many other recent studies and reports by other agencies (both government and privately funded) on precollege education, little is said about science and technology.

A healthy redundancy is present among these chapters. At the same time there remains a variety of viewpoints from the authors' different backgrounds, experiences, and points of view. The totality of their chapters produces a reasonably consistent whole.

In the editor's judgment, greater and more explicit emphasis should be given in this country both to the transfer of technology from the university research laboratory to the market and to the public benefit that derives therefrom. With few exceptions, the significant technological breakthroughs or innovations of the last half century have come from university (or "university-like") laboratories. Thus, successful technology transfer, combined with the most essential basic research performed in university laboratories, justifies generous financial support. Funding by government agencies and from university endowments themselves presently poses few problems other than questions of adequacy.

Yet the need for even more support is recognized. Universities have turned to industry for additional funding. There is no question that collaboration between the university and industry can be mutually beneficial. However, there are hazards. Premises fundamental to the form and function of universities may be compromised by certain industrial requirements. A particular university-industry relationship could influence such factors as the freedom of inquiry and publication, licensing of trade secrets, conflicts of interest, loss of objectivity, direction of effort, and the choice of fields of research. These, among numerous other hazards in these relationships, deserve careful and thoughtful attention.

In their desire for industrial support, some institutions have rushed into relationships without giving these matters due regard. Fortunately, the strongest universities have anticipated these factors in developing industrial collaboration and funding. Much good can come from these new cooperative efforts.

Steven Muller

1

Research Universities and Industrial Innovation in America

Ever since the mid–1970s, a belief that the future well-being of the American economy depends on a renewed national commitment to technological and/or industrial innovation has become more pronounced and widespread. Those who profess this belief usually invoke the innovative character of past American economic development and then assert that in recent years the United States has begun to lose the role of international leadership in industrial, scientific, and technological innovation. In this context the idea also is advanced that American research universities have been vital contributors to innovation in science and technology in the past, and therefore a successful recommit-

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Steven Muller *became the tenth president of The Johns Hopkins University in 1972, and from 1972 to 1983 also served as president of The Johns Hopkins Hospital. He serves as chairman of the board of the Federal Reserve Bank of Richmond and is a trustee of both the Committee for Economic Development and the German Marshall Fund. Dr. Muller also sits on several boards of national organizations and was the founding chairman of the National Association of Independent Colleges and Universities. A specialist in comparative government, he is the author of a textbook and numerous articles in this field.*

ment to such innovation depends essentially on leading participation by American research universities. As usual, when a majority of the public subscribes to beliefs and ideas, there is some truth in them—but no one simple truth. Some reflections on the relationship of the modern American research universities to innovation in science and technology may help to sift out reality from unwarranted assumptions and reduce some confusion.

The Foundations of the Contemporary University

It is certainly true that the contemporary major research universities are distinguished by a great emphasis on science, and increasingly on technology as well. But the extent to which these universities are the fountainhead of innovation in science and technology is at least arguable. And on the record, major research universities have not been a major—not even a significant—direct source of new products for the marketplace. The major research universities do perform research, but they remain primarily teaching institutions, and their chief role is to develop and train human talent. The vital link between the major research universities and the advancement of science and technology in the United States, therefore, can be discovered mainly in the pool of talent which the universities both harbor and produce.

Today it is difficult to remember the only very recent origin of much that is taken for granted in the contemporary American university. As of now, for example, no one would argue that the whole university is dedicated to the spirit of free inquiry. Yet the fact is that this tradition is scarcely more than a century old—precisely as old, by no coincidence, as the scientific character of the modern university. In its beginnings, the university, of course, was already committed to knowledge and truth, but the knowledge was received knowledge, and the truth revealed rather than discovered. For centuries, the university as an institution was tied inextricably to established religion and served primarily to refine and transmit established knowledge and to train human minds to function within the confines of God's word and established faith.

Thus, in the early nineteenth century, when Wilhelm von Humboldt achieved the reform of the Prussian university by insisting on freedom of teaching and learning, he had in mind a highly specific concept of freedom: freedom from religious orthodoxy.

And—as important—learning took on a second meaning beyond the original definition of absorbing all that was already known: learning began to mean inquiry as well. It is useful to note that von Humboldt's reforms were of course achieved only with the support of the Prussian government, and the statesmen of Prussia supported him explicitly because they wanted to foster their state's industrial development. The Prussian government perceived the linkage between scientific training in the universities and the application of science to and in industry, and so they sponsored the emergence of the research university. Ideas that had earlier been heresy—that truth required proof rather than faith, that knowledge could be advanced by discovery, that to question the wisdom of the past was not only legitimate but indeed necessary, and that facts were so objective that *no* known fact was sacred—were ideas now embraced within the university. Professors and their students were set free to search for the new and to seek proof for discovery.

In the United States the modern research university was not fully established until the opening of The Johns Hopkins University in 1876, with an explicitly acknowledged debt to the ideas of von Humboldt. Within a few years thereafter, graduate research programs began to sprout throughout American higher education, atop the established collegiate foundations. Even before then, however, the government of the United States had also perceived the linkage between the education of talent and national development. The Morrill Act, enacted during the Civil War in 1862, fostered the establishment of colleges specifically to educate talent in the agricultural and mechanical arts so that farming and production could spread more effectively across a whole continent. The land-grant colleges were not founded as research universities, even though they later became such, but the emphasis on the practical and its application in their founding set their professors and students free from the old rigidity of religious orthodoxy and received knowledge as well.

The devices that symbolize the industrial and technological revolution of the nineteenth and twentieth centuries—whether one thinks of the steam engine, the cotton gin, the automobile, the telephone, the telegraph, the radio, the airplane—were not developed within or by the university. Indeed, the more venerable of these devices were invented before the university as an institution had itself been transformed by science. But the application, maintenance, and continued refinement of such devices throughout the American economy depended upon a pool of trained talent which was—and is—a product of the American research university. That statement requires amplification. But before that amplification can be most effectively performed, it is necessary to observe a major second stage in the evolution of the major research university in the United States—its mobilization into national service.

Transformation by Mobilization

Until World War II, the American research university as an institution became progressively more scientific, but it did not grow hugely in size, nor did it develop significant new ties to the industrial community. The most interesting evolution of the period occurred so quietly and naturally that no one ever seems even to have remarked upon it: namely, the employment of doctors of philosophy by industry. Before the 1890s, there were, in effect, no American Ph.D.s in existence, and the degree was introduced to mark the highest level of advanced preparation for an academic career. However, well before the outbreak of World War II, industry had research departments and laboratories, and, to staff these, employed Ph.Ds and used professors of science and engineering as consultants. Thus, the high quality of the research done, for example, by American Telephone and Telegraph, General Electric, and E. I. Dupont De Nemours & Company did not depend on close relationships to one or more particular universities as such, but rather on the fact that their leading scientists were drawn from the most advanced university graduates and had the same level of training as future professors.

With the outbreak of World War II, inevitably the mobilization of the whole nation also included the universities but went far beyond the traditional call of students to the colors and the enlistment of physicians, nurses, and other specialists into service. Technology played an unprecedented role in the war effort. Not only were university specialists called to work on technologically sophisticated projects, but universities were requested to sponsor new laboratories to do research for military purposes. Nor was this a short-term effort. While the war as such ended in 1945, it was followed immediately by the so-called cold war and the Korean War; and, in fact, the period of national mobilization lasted fully for at least thirty years—until the closing of the Vietnam War. To a significant extent, mobilization still persists into what is now a fifth decade. In addition to university laboratories, new government laboratories were established in large number and variety, and more and more these too drew for research staffing on the Ph.D.s coming out of the university graduate schools.

As defense technology kept widening to include space, chemical and biological warfare, electronics, and virtually all materials, the concept of the national interest irresistibly expanded to include the whole range of science and technology within the university. Public investment by government in the growth and development of university science and technology came to be regarded as a perfectly natural—indispensable—ingredient of national security. First millions, soon billions, of dollars annually were appropriated for this purpose. At the same time, access to higher education was being expanded by means of a succession of congressional enactments and appropriations. As a result, existing colleges and universities grew greatly in size, and new colleges and universities were established. In the quarter century between 1945 and 1970, American higher education more than tripled in size and capacity, and within the major research universities the federal government became the established patron of advanced research and training over the entire range of fields in science and technology.

The Government-University Partnership in Research

Selected aspects of the way things were done in the process, or of the way in which matters turned out, appear worthy of comment. For example, it can be noted that the interaction between representatives of government and the university community began in the 1940s on an extraordinarily high level of mutual trust and commonality of purpose. World War II was—at least after Pearl Harbor—a "popular" war in the United States. Subsequently there was widespread consensus that the best way to counter Stalinist expansionism and avoid renewed global war and the use of nuclear weapons was to create effective deterrent capacity. Cooperation in the national interest was not then controversial. In other words, motives were not initially in question. As a result, problems that might otherwise have led to long and vexed negotiations were settled quickly and effectively in order to get the job done. An enduring network of personal connections between individuals in government and those in university science grew in this agreeable climate, and those helped to lubricate relationships later when some friction began to develop.

It must be assumed that the high degree of mutual trust at the outset had much to do with the easy adoption of the peer review systems in the distribution of increasingly vast amounts of government sponsored research. There is, in retrospect, a near miraculous purity in the concept that the best way to assure the funding of good science is to allow good scientists to review applications and select the best. And—most of all—it is worth noting that it was possible for government to deal directly with university scientists and technology experts themselves, with only relatively minor involvement on the part of the universities or institutions. It is more than doubtful whether university administrations could have motivated professors to cooperate with government nearly as effectively as was in fact the case, where the motivation arose within the professional initiative combined with the appeal of the national interest that largely swept the institutional university along in its train.

In the well-known story of the growth of government sponsored university research, the involvement of industry is seldom mentioned or emphasized. While this may be easily explained because industry involvement was indirect, it is a grave distortion not to recognize explicitly the major stake on the part of industry in the burgeoning government-university partnership. Even if one were to look only at national defense in a narrow sense, it is obvious that the ever more sophisticated and complex national defense systems—developed with the advice of university specialists—called for an ever greater range of sophisticated and complex products—products procured by government and produced by industry. The wider the range of government needs—beyond weapons systems and into, for example, space and communications technology—the greater became the involvement of diverse industrial enterprises in providing the means growing out of research and development. It is, of course, true that in response to the situation, more and more of the affected industries began to set up elaborate research and development programs of their own—also often with government assistance. But here too the staffing of these industrial research and development programs depended on the availability of university trained talent—talent at the core, trained at the doctoral level. The great investment on the part of the federal government in university science and technology, therefore, produced not only ideas and techniques that resulted in industrial contracts, but also—and with far greater total impact—provided the funds and facilities within universities to train great new numbers of highly advanced technologists and specialists, who found employment in industry and government, as well as within the university system itself.

To the extent, however, that the federal government was not only the principal sponsor of science and technology in the major research universities, but also the principal consumer of so much of the applicable result, it can be remarked that the need to *market* ideas and techniques was generally—and notably—absent. To a large extent, government was willing to sponsor basic research, i.e., the conduct of scientific inquiry for its own sake and where an applicable outcome was neither promised nor expected. However, where the government sponsored targeted research, the government was also likely to be the consumer or purchaser of the result; hence there could also be a certain indifference as to whether the result was ever purchased or consumed—that decision was, after all, up to government. There was *competition*—among investigators for research support and among industrial enterprises for procurement contracts, but there was very little marketing.

University Attitudes toward Research

In this connection it should also be pointed out that research as a *product* is not—or, at least, not yet—an accepted notion even within the contemporary American research university. To understand this, it is useful once again to go back to Wilhelm von Humboldt and the germinal reform of the Prussian university which he achieved. Von Humboldt spoke not only of freedom of teaching and learning, but also of the identity of research and teaching. His credo was that inquiry was an indispensable part of teaching: only someone engaged in inquiry was best qualified to teach, and learning involved engagement in inquiry as much as absorption of subject matter. The twin identity of research and teaching has since become—and remains—gospel within the American research university. And this twinning needs to be understood in light of the fact that the university has been—and remains—primarily a research institution. Research without teaching is still versity styles itself as a research university, what is meant is that its teaching mission is distinguished by a research component of the highest quality. What is not meant is that the university is primarily a research institution. Research without teaching is still as heretical an idea within the contemporary American university as teaching without research.

To understand this confluence of teaching and research within the university supports the notion that the university as an institution is generally ill-suited to perform research: it is the professor *at* a university who performs research, not the institution. The key relationship which evolved as government became so prominent a sponsor of research was—as noted earlier—between government and individual professors identified as principal investigators. The inner logic of this arrangement lies in the linkage of research and teaching as well as in the freedom of inquiry: only the researcher/teacher could appropriately determine the proper mixture of inquiry and instruction that is inevitably a cardinal feature of an academic research project. Thus, on the face of it, a particular university can be identified as "doing" on the order of $100 million annually of federally sponsored research, and it is accountable to government and the public for the whole of it. But in reality so great a total is merely the accumulation of hundreds of individual projects, solicited and executed under the guidance of principal investigators, normally unrelated to each other, and scattered throughout the university. A major research university is one whose faculty is composed of many persons of such distinction so as to be able to bid successfully for research awards—grants and contracts awarded by government in the name of the institution but awarded in fact to the principal investigators. Universities did not and do not *assign* research to members of the faculty any more than they assign the courses to be taught. Instead, professors select the research they wish to do just as they select the content of their teaching, and, if funded, they thereby put the university into that particular research activity. When professors—principal investigators—move from one university to another, their research awards follow them and do not remain at the university of origin. As a result, a university widely known for research of a particular kind could—and does—suffer loss of competence with the departure of a principal investigator, whose arrival at a different university would then lend to it the distinction lost by the institution from which the move originated.

There were—and continue to be—some exceptions to this prevailing situation in that some universities did set up special laboratories, dedicated to particular lines of inquiry, which sought and received support as such, i.e., not on the basis of individual grants and contracts. In most instances, however, there was a controlling reason for such action by the university: the need for secrecy. When government insisted on secrecy in the national interest, the university faced—and still faces—a dilemma. On the one hand, it is obvious that certain types of research involving national security require the protection of secrecy lest they aid foe as well as friend; on the other hand, secret research is anathema to academic practice. Precisely because of the fundamental credo that research and teaching are inextricably linked, research that—for reasons of secrecy—cannot be related to instruction is academically illegitimate. Academic research *must* serve—or at least be capable of serving—as a teaching base and, therefore, *must* be open. By definition, then, secret research cannot be academic research. To resolve this dilemma, universities willing to engage in secret (classified) research set up nonacademic laboratories, physically isolated from the rest of the campus, in which secrecy could be maintained—but at the sacrifice of the academic mission. At the same time a decision was reached that individual faculty members could engage in secret research as a matter of individual choice, but *not* on the campus. Professors can, in other words, serve as consultants on secret or classified projects, but only if the work they did on such a basis was located outside the academic campus and as long as their laboratories and offices on campus remain entirely open. This mode of operation made it possible to achieve some academic linkage between an off-campus secret research project sponsored by a university and the same university's academic departments. By means of joint appointments, an investigator primarily engaged in secret research can come onto the academic campus as a part-time faculty member, at least to teach, but possibly to perform nonclassified research as well; a regular faculty member can leave the academic campus and engage in secret research at the classified project site, serving as a part-time consultant.

Corrosion in the Government-University Research Partnership

In the course of the 1970s, a gradual sea change occurred in the relationship between the federal government and the major research universities—a sea change hard to define both because it took place gradually and because so much on the surface remains the same, but also it was sufficiently severe so that, in effect, it seems to mark the end of an era. A series of circumstances coincided to produce this effect. First, the constant dollar level of federal government appropriation to support university research in science and technology ceased to rise, and on occasion had even fallen, not only from one year to the next but over several years in succession. A form of the cold war continued; the nation's investment in national security remained extremely high; even the countrywide mobilization in the national defense remained a constant of sorts. But as far as the universities were concerned, the context of federal research support changed from growth and renewal to contraction. And this came about in combination with the end of that earlier sustained period of growth in student and faculty numbers. Overall, most of the level of effort reached in the past still continues, but the steady acceleration of support of the previous twenty-five years has halted.

Of greater importance may be the fact that substantial corrosion has appeared in the process of government-university research interaction. This is not surprising in that it is only a natural occurrence when a relationship goes on for so protracted a period, but an understanding of this reality merely explains problems without attenuating them. To a significant degree, the initial trust and shared common purpose between government and the university community have been substantially dissipated for all sorts of reasons. The unpopularity of the Vietnam War produced sharp differences between government and the majority of the academic community. The sheer volume of federally sponsored research became so great that inevitable problems appeared in the auditing and accountability for so huge and diverse an annual effort. With the enormous growth of the professoriate over a quarter of a century came some dilution in quality. Where, early on, a relatively small elite of faculty members at relatively few institutions had dominated the interaction on the university side, there were now much larger numbers of persons from many more institutions involved, and the quality of peer group evaluation became somewhat arguable in the process. Over time, just enough instances of poor fiscal management and/or questionable performance occurred to corrode some degree of faith and confidence. And, after all, a process dependent on annual appropriations from so highly political a body as Congress could not expect indefinitely to remain miraculously untainted by political consideration. Additional corrosion therefore occurred when, on occasion, Congress began to tie strings and ribbons to federal grants and contracts. Recently, there has also been a tendency—still unchecked—to make some awards on political grounds by simply and blatantly operating outside the regular process of research proposals and peer-group review.

Other considerations entered the picture as well. Quite apart from inflation, the absolute cost of pursuing research has become steadily greater as the technology of research itself became ever more complex. The scientist doing equations on a blackboard—as fixed symbolically in the public eye by the ineradicable image of Einstein in his study—has been superseded by the research team operating with a vast laboratory array of instruments whose cost and complexity are awesome. And furthermore, the range of science and technology far outstrips even the most all-inclusive definition of national security, and the result is that real argument is now possible as to the priority for research support when weighed against the whole array of other public priorities.

The Industry-University Partnership

In the wake of this major revision in the relationship between government as principal sponsor of research in science and technology and major research universities, a still increasing effort developed to establish a new level of direct partnership in research between the university and private industry. No one has ever suggested that private industry should eventually replace the federal government as principal research sponsor; nor has it been assumed that federal research sponsorship would cease. But the assumption that federal research support in constant dollars would at best level off and perhaps also be less comprehensive has led the university to be interested in industrial research sponsorship as a supplement to—not substitute for—federal support. As for industry, the trigger comes in the field of biotechnology and genetic engineering, whose results in many instances have greater promise for commercial rather than national security development. (However, this interest may well be of limited duration. Recognizing the potential in these fields for the production of pharmaceuticals, foods, and chemicals and, initially, the almost total absence of in-house expertise in industrial laboratories, industry turned to universities and their faculties for knowledge and expertise. As in-house expertise is hired or developed, this dependence on outside university expertise will diminish and may, within a few years, be of only minor importance.) By the beginning of the 1980s, therefore, discussion among representatives of universities and private industry began to be intensive and continuous. A number of large industrial commitments for sponsorship of university research received national publicity, accompanied by a host of smaller scale, less well publicized commitments of great diversity. It appears extremely likely that direct university-industry partnerships in research will continue to proliferate. However, this new linkage has significant limitations and problems. Some have already been widely discussed; others, less so. An interesting and useful way to appraise them may take the route of comparison with the process of research sponsorship by the federal government.

Partnership grows out of mutual interest. And as noted, the foundation of the partnership between government and the universities lay in shared devotion to the national interest—specifically to national security in time of war. The analogous shared concern between industry and the universities appears to revolve substantially around financial gain: most fundamentally, profit for industry, research support for the university. How sound is that analogy? It can be argued well that financial gain represents at least as much of a mutual incentive as patriotism or even that gain can exceed patriotism in intensity. However, it may be more difficult to argue that financial gain as motive can parallel patriotism in serving as the basis for mutual trust. That, in turn, may be particularly relevant to the potential of industry-university relationships because of the dichotomy involved in university participation. As was and is true in the government-university partnership, the operative university partners are the researchers themselves—the principal investigators. In the partnership with government, the basic assumption was not only that everyone within the university shared a common commitment to the national interest, but—especially at the outset—financial gain beyond the mere generation of support for research scarcely was perceived as a factor; the concept of profit did not usually enter into consideration.

In the partnership with industry, however, profit does enter into consideration, either actually or potentially. On the one hand, it would be unfair if a corporation made large profits from an application of university based research and there were no sharing whatever with the university partner. On the other hand, insofar as the university partner is both the individual researcher and the institution, how is profit shared between these two? At first blush one might think that this question is easily answered by drawing on a long history of institutional patent policies that represent both a tradition and experiential base for profit sharing on the part of the industry as well as for profit sharing between principal investigator and university institution. But in practice there is the complexity involved, for example, in stock ownership by professors and/or universities as institution and in profit sharing by corporations with scientists who serve only as consultants on an individual basis and not as participants in a university sponsored relationship.

It is not relevant at present to explore this and other complex entanglements further; however, it should be noted that a great degree of mutual trust is more apt to develop and be sustained over protracted periods by the generation of common concern based on patriotism than by those based on financial gain. In fact, without excessive cynicism one must note the effort to evolve a common industry-university concern much more analogous to wartime devotion to national security, as at least a complement to the profit motive. The common concern invoked in this view is technology transfer—a phrase that stands for the common humanitarian impulse to strive to make the benefits of applied research available to the public as rapidly and effectively as possible. (This was the impulse governing Professor Frederick Gardner Cottrell when he established Research Corporation as a nonprofit technology transfer agency in 1912.) More recently this concept has also been directly related to the national security—by referring precisely to the discussion of economic innovation with which this chapter began. Patriotism, as well as profit, can be invoked by the argument that the welfare—and security—of the United States depends on sufficient technology transfer directly from university to industry in order to assure not only that discovery results in new benefits to the quality of human life in the best and quickest manner, but also to assure that American industry thereby remains so consistently innovative as to reclaim and retain world leadership.

The profit potential in this context then becomes a desirable but secondary enhancement of a more noble primary goal. And even those who might be reminded—skeptically—of the now famous old assertion that "what's good for General Motors is good for the country" may find it difficult to deny that there is truth in the argument that university research relates positively to innovation in industry. Obviously, however, any argument linking industrially sponsored university research to American national purpose is awkward to justify when the sponsoring corporation is a major multinational enterprise based abroad. And the fact is, of course, that at least a few of the most prominent new linkages between particular industrial corporations and American research universities have involved foreign, rather than American, enterprises.

POTENTIAL HAZARDS

There are other problems that emerge when industry-university research relationships are compared with the government-university research partnership, particularly those relating to the absence of overriding national interest as basic justification. On occasion, for example, industry would like to impose secrecy on research, but for proprietary purposes rather than by reason of national security. Universities, committed (as already indicated) to the inseparability of teaching and research, cannot appropriately accommodate industrial interest in confidentiality any more than government interest in secrecy. Ideally, therefore, confidential industrial research should be carried on by professors only off-campus, in industrial laboratories, just as was and is done with secret government research. But the presence of the profit motive makes the easy parallel more difficult to apply. What happens, for instance, when the principal investigator is also the entrepreneur? What happens when the university as an institution stands to profit through a contractual arrangement or as an investor? Are patents the answer? It is generally assumed (most conveniently) that the time required to obtain a patent is just about as long as that required for the publication of a piece of research. But will this result in an erosion of time-consuming testing because of a rush to publish? And what happens if the research in question involves unpatentable techniques that are best protected as trade secrets?

Questions such as these raise the more fundamental issue of whether the anticipation of financial gain will tend inevitably to draw professors away from the concept of research as pure inquiry toward the goal of research for profit. Earlier, goal oriented research had become something of an issue in the course of the government-university research relationship. Often, however, because the goal was classified, the research took place away from the university in any event. In the case of other goals, such as "the war on cancer," the goal was so broad and humane as to cause no problem.

Financial gain is more suspect, particularly because the university as an institution is as directly involved as the principal investigator. In the case of government sponsored research, it is assumed that the university as an institution has only a minor interest in the substance of any particular piece of research being done as long as it is not secret and as long as the principal investigator who solicited support is appropriately funded and committed. But will university administrators, representing the interests of the university as an institution, remain in such a position of benign indifference when there is a prospect of financial gain for the institution? Will there, in other words, be a tendency by the university to push professors not merely to perform research and obtain support for doing so as has long been the case, but to perform particular kinds of research with financial gain in mind?

This line of inquiry compels recognition of another relevant difference between the government-university and industry-university relationships. As noted earlier, the essence of the government-university relationship was government sponsorship through a process of open application by principal investigators whose applications were subject to a peer review process. Relationships between industrial corporations and universities increasingly have taken on an entirely different form. First, the diversity of industry and of the professoriate is so great that some sort of brokerage was required to match potential sponsors and investigators; university administrations began to play the role of broker. Second, a marketing approach emerged—a corporation marketing its interest in sponsorship and a university marketing its interest in receiving sponsorship. Third, instead of a nationwide application process and competition by application, corporate research sponsorship with a university tends to be negotiated on a one-on-one basis, and in most cases it contains no form of peer review. Fourth and finally, the result for the universities was a new and highly competitive race for industrial sponsorship in which university administrators were actively marketing the skills of their professors. It is against this background that questions are asked as to whether or not the university as an institution will attempt to impart guidance to principal investigators when the factor of financial gain is present.

Fundamental Issues for Industry-Government-University Research Interactions

Problems of this kind are significant and awkward, and they continue to be both explored in practice and debated in the abstract. They are, however, dwarfed by two other considerations that may be even more fundamental and as yet have received very little discussion. The first of these derives from further consideration of the enormous cost of research instrumentation in the universities. As noted earlier, the aggregate sum required for adequate instrumentation already appears to be growing beyond even the capacity of the federal government to sustain at public expense. And large as the collective resources of private industry may be, they fall short of the resources available to government; and in fact, no way exists (nor is likely to be found) for a *collective* application of industrial resources to support research in the universities. Even industry-by-industry collective collaboration is hamstrung by antitrust legislation; company-by-company approaches are the rule. At the moment, such approaches appear to be feasible only as long as the application of corporate resources remains a marginal supplement to a much larger volume of support from government. It follows, however, that the significant future decreases in government research support are not likely to be offset by a sufficient increase in support from industrial corporations. Instead of industrial resources rising to balance out shrinking federal allocations, a more likely prospect would be that major reductions in federal support for instrumentation and its installation and maintenance would make university laboratories *less* attractive to corporations because, rather than complementing government support, available corporate resources would become submarginal under these circumstances.

The future requirements of support for instrumentation have practical consequences for the universities, for industry, and for government. For the universities, assuming that the twin pressures of need and practical possibility will, over the long run, impose their own logic, the most likely answer would appear to lie in the type of sharing that has already evolved in the field of high-energy physics. Just as, for example, only a finite number of nuclear accelerators exists and just as these are governed by consortia of institutions so as to provide access to investigators across the entire discipline, so it seems probable that truly large-scale instrumentation resources in other scientific and technical fields will evolve along similar lines. The university or universities in conjunction with which such resources are located will, on the one hand, develop special strength in the relevant particular area of inquiry; on the other hand, colleagues from the rest of the university world will also have access to the facility and its resources.

And, at a different level, universities will need to consider more effective sharing of resources with colleges that operate on the undergraduate level only. The issue in this respect is not research—professors located in colleges will already have access for research purposes to highly advanced instrumentation resources at major research universities—but teaching. The universities draw on the collegiate sector for their graduate and professional students. Universities thus have an interest in preventing the decline of instrumentation in undergraduate colleges to the point where college graduates would be so underprepared in science and technology as to be dysfunctional in graduate and professional schools. As a result, universities will see the need to share the most expensive and sophisticated instrumentation with colleges for teaching purposes. There are new lines of sharing within higher education that as yet have barely begun to appear.

As for private industry, corporations dependent on science and technology have an unavoidable stake in the adequacy of instrumentation and the quality of research in the major research universities. The *essential* linkage between the universities and industrial innovation and vitality consists of people-related as opposed to product-related research. The article of faith within the university community which insists on the inseparability of research and teaching is not merely sacrosanct—it is practical wisdom as well. To the extent that its consequence puts limits on the direct applicability of university research precisely because that research must also serve a teaching mission, those limits are an asset rather than a liability. Both government and industry are inescapably dependent on a flow of talent which the universities produce. To a large degree, the quality of government and industry in the age of technology is determined by the quality of available talent; the stream of the most highly trained, specialized, and scientifically and technologically advanced talent flows out of the university pool.

Industry recognized long ago that innovation in science and technology depended on the creation of industrial laboratories. These laboratories, rather than university laboratories, are the proper and best source of product development. But industrial laboratories are staffed by university graduates. Under ideal circumstances, universities are the source of graduates trained in the methods of inquiry with state-of-the-art instrumentation, who are eligible to be hired by industry for its laboratories. Technology transfer occurs as well informed and highly skilled human talent moves constantly out of teaching laboratories into applied research laboratories. Nor is this a one-way street. New techniques and results from industrial laboratories move over into the teaching laboratories of universities, not only by the maintenance of personal contacts, but also because university scientists already consult sufficiently with industry to stay current with industrial advances in science and technology. Under less than ideal circumstances, universities would lack the resources for the adequate and most up-to-date preparation of graduates in science and technology; the pool of the most highly trained talent would then be not fresh but stale. At the worst, industry would itself have to offer the ultimate in advanced training if industrial laboratories alone were to offer advanced instrumentation no longer available in university laboratories for research and teaching.

If this is the correct perspective, then at least a good deal of the prevailing industrial and public fixation on the *substance* of university research appears to put the accent on the wrong syllable. The most fruitful outcome of the now protracted experience of government sponsorship of university research has been in fact the splendid enhancement of the nation's pool of most highly developed talent, not the research results obtained in any single instance or in aggregate. Clear recognition that universities exist to teach and that the contemporary university must do research in order to teach—not do research for its own sake—provides the best guidance for future courses of action. Such recognition implies that government, industry, and the universities fully share a common purpose: to assure the ability of the universities to attract, nurture, and prepare human talent at the most advanced level of science and technology so that the goals of government and industry will not be impeded for lack of human resources. Industry, therefore, should move beyond the current emphasis on the possibility of product development directly from university laboratories to a more fundamental emphasis on the preservation and enhancement of the teaching mission of the university. In practical terms this would mean supportive concern by industry with the continuation of public investment by government in the strength and quality of university research—and hence, teaching—in science and technology and less effort on the part of corporations to leverage the prospect of financial gain for universities into pressure to unhinge university research from the teaching mission so as to move it closer to a more goal oriented character with directly applicable results in view.

The future of innovation in the American economy does indeed depend on the American university. The dependence, however, rests far less on the results of university research per se than on the indispensability of research to the training mission of the university. The university's role in the development of human talent transcends by far the university's role in discovery—or, explicitly, the goal oriented quest for discovery. It follows, then, that the future of both national security and national prosperity depends significantly on a continued investment in university science and technology, supported by both government and industry, with the primary emphasis on the development of human talent.

American Shortcomings: Innovation, Productivity, or Marketing?

Tempting as it is to end here, some brief concluding observations may be useful on the innovative character of American society in comparison to other national societies. On the one hand, there *is* evidence that the United States has no monopoly among the countries of the world on innovation in science and technology. On the other hand, there is no evidence that to date the United States lacks the ideas or the talent to retain world leadership in the advancement of science and technology, provided that adequate resources are supplied. The record of recent international economic experience shows little evidence that other national economies are more innovative than that of the United States insofar as the substance of science and technology is concerned. What that record does reveal, however, is that other nations have been and remain more innovative and successful in production, manufacture techniques, and international marketing of new products than the United States. Japan, for example, in addition to superior production and quality control, appears to be applying a genius for the identification and exploitation of world markets through a combination of highly innovative and effective product development and marketing far more than striving for original discovery in science. In contrast, American industry continues to draw on original discovery but may be falling behind in international market share. For this there may be several reasons. First, American corporations may be too comfortable with a domestic market of continental size which for decades has been familiar, as well as sufficient to sustain profits and growth. Second, American corporations have relied heavily on foreign employees when selling abroad, not only on the assumption that indigenous citizens of other lands will get the best reception within their domestic markets, but also because American talent familiar in depth with foreign markets is in extremely short supply. Third, there has been a reluctance to invest in new manufacturing facilities and an inability to control quality of product.

The simple fact appears to be that aside from innovation in the manufacturing process, American corporations need to cultivate foreign markets more effectively on a global scale and, in the process, rely more on American talent that knows the area, its culture and history, and, above all, its languages. To the extent that this is true, American universities may have a major contribution to make to national economic prosperity, not only through teaching and research in science and technology, but also through foreign language and area studies for far greater numbers of students than have participated in the past. It is not true that worldwide marketing is a new concept for American industry, but it may be true that worldwide marketing falls short when it is executed and supervised by Americans who speak only English and on behalf of products designed primarily for an American market. The major research universities in America are among the most cosmopolitan, least parochial institutions in the country. Their ability to provide human talent familiar in depth with any and all areas of the world may need greater recognition and support in the context of national prosperity within a global economy. The earlier research partnership between government and the universities included language and area study centers and fellowships, long and successfully supported by the National Defense Education Act. It is worth considering whether American industry has a major stake in reviving and supplementing that experience as well.

In summary, then, the power and strength of American industry in a global economy depends both on future innovation *and* the capacity to market the results worldwide. Innovation in this era of science and technology depends on numerous factors—one of which without doubt is human talent of appropriate high quality. The American university has become the proper training ground for such talent by virtue of the effective linkage of scientific research to its traditional teaching mission. Thus, industry and government have a joint stake in university research, less for the sake of applicable results than for its indispensable educational function. And if there is truth in the thought that American industry may be more deficient in marketing than in innovation, the universities have the capacity to contribute to the solution of that problem as well.

Donald F. Hornig

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The Role of Government in Scientific Innovation

Introduction

The notion that innovation is a virtue to be fostered in its own right is a very recent one. In fact, the whole idea of progress as something that can be systematically fostered is largely a twentieth century phenomenon. To be sure, the ideal of systematically acquiring knowledge and using what is learned to develop an understanding of the physical world goes back 500 years or more, but the current concern with innovation goes much further. By scientific innovation we mean the process by which new knowledge and skills are generated and applied to the social, economic, and intellectual operations of society. Innovation, then, is more than discovery and theorizing, more than speculation and invention, and more than engineering design. For until the

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new "know-how" is incorporated into what is done by our economy and our society, innovation in our sense has not occurred.

The problem to which this chapter is addressed is what the role of government can be in encouraging scientific and technological innovation. Other governments have gone beyond the encouragement of innovation to attempts to guide the innovative process or even to carry it on in government agencies or laboratories. Our concerns are whether or not the U.S. can remain technologically competitive in the face of the more or less centralized technology policies of Japan, West Germany, and France and what role the government can play. We shall look at our own experience to date and later explore possibilities which are available, some of which have been tried elsewhere.

BENJAMIN FRANKLIN

Before proceeding it is interesting to remind ourselves that while fostering innovation may be predominantly a post–World War II phenomenon, it actually has roots in the eighteenth century. In 1743 Benjamin Franklin circulated "A Proposal for Promoting Useful Knowledge. . . ." With a foresight and vision which is rare in developing countries and often in short supply in the advanced industrialized countries, he wrote:

> The English are possessed of a long Tract of Continent, extending . . . thro' different Climates, having different Soils, producing different Plants, Mines and Minerals, and capable of different Improvements, Manufactures, etc.
>
> The first drudgery of Settling new Colonies . . . is now pretty well over; and there are many . . . in Circumstances . . . that afford leisure to . . . improve the common stock of Knowledge. To such of these who are Men of Speculation, many Hints must from time to time arise, many Observations occur, which if well-examined, pursued and improved, might produce Discoveries to the Advantage of . . . the British Plantations, or to the Benefit of Mankind in general.

He goes on to propose a "Society of ingenious men" to maintain a constant correspondence concerning:

> All new-discovered Plants, Herbs, Trees, Roots, etc. and their Virtues, Uses, etc.; Methods of Propagating them, and making such as are useful but particular to some Plantations, more general; Improvements of vegetable Juices, as Cyders, Wines, etc.; New Methods of Curing or Preventing

> Diseases; All new-discovered Fossils in different Countries, as Mines, Minerals, Quarries; etc. New and useful Improvements in any Branch of Mathematicks, New Discoveries in Chemistry, such as Improvements in Distillation, Brewing, Assaying of Ores; etc. New Mechanical Inventions for saving Labour; as Mills, Carriages, etc.; and for Raising and Conveying of Water, Draining of Meadows, etc.; All new Arts, Trades, Manufactures, etc. that may be proposed or thought of; Surveys, Maps and Charts of particular Parts of the Sea-coasts, or Inland Countries; Course and Junction of Rivers and great Roads, Situation of Lakes and Mountains, Nature of the Soil and Productions; etc.; New Methods of Improving the Breed of useful Animals; Introducing other Sorts from foreign Countries. New Improvements in Planting, Gardening, Clearing Land, etc.; And all philosophical Experiments that let Light into the Nature of Things, tend to increase the Power of Man over Matter, and multiply the Conveniencies or Pleasures of Life.

This proposal led to the establishment of the American Philosophical Society. But it is also an agenda for innovation which in spirit could guide us today, even if the details need some updating. Of course, correspondence is no longer enough. Our question is, what more needs to be done to achieve such goals in the twentieth century?

THE EARLY REPUBLIC

Despite these ideas, science did not find its way into the Constitution of 1789, even though Franklin and Jefferson participated in writing it. Along with universities, canals, a central bank, and other such projects, scientific projects were thought of as "internal improvements," public works which might lead to centralization of power in the federal government and which were therefore best left to the states. The Constitution of 1789 mentions science only once, in the power of Congress to "promote the Progress of Science and useful Arts, by securing for limited Times to Authors and Inventors the exclusive Right to their respective Writings and Discoveries." Thus was patent and copyright protection born.

President Thomas Jefferson hoped for more. His love for science was such that he had a room in the new executive mansion in which he worked on fossil bones, one of many scientific projects he undertook before, during, and after his Presidency. To involve the government, he proposed in 1806 that "public education, roads, rivers, canals, and such other objects of public improvement as it may be thought proper to add to the constitutional enumeration of Federal powers" be carried out with federal funds, and he sought a constitutional amendment to that end. His favorite project was a national university which would conduct both "research and instruction." None of this came to fruition since the constitutional amendment failed.

Jefferson did succeed in two important projects. In 1803 the Lewis and Clark expedition to the Pacific Northwest explored the continent and made significant findings in botany, zoology, and ethnology. As well as being successful in itself, the Lewis and Clark expedition paved the way for a long period of exploration of the continent, the Arctic, and the surrounding seas—supported by the federal government. Related to the explorations was the organization of the Coast Survey in 1807. Better charts, navigational aids, and topographical information were henceforth to become a federal responsibility. An era of exploration and surveys was inaugurated which continues to the present day in the Coast and Geodetic Survey, the explorations of Antarctica, and the mapping of the solar system.

Not mentioned in these generalizations is how continual political opposition to the involvement of the federal government in "internal improvements" led all of these ventures (and others) to proceed in fits and starts. The institutions to carry science forward evolved slowly from these fragments, and the most durable organizations were the army and navy. That is a lesson which is still with us—that it is easier in many cases to undertake new ventures under the guise of security than of the general welfare.

The role of the federal government in science was brought into special focus in 1836 by the then enormous bequest of $500,000 by English chemist James Smithson to the United States of America to establish a Smithsonian Institution "for the increase and diffusion of knowledge among men." Eight years of debate followed in which the idea of a national university was considered and ruled out. Instead, the federal government, in 1844, created an independent institution, under a board of regents, thus avoiding the political problems of whether the government should support a museum, a library, or scientific projects. The institution subsequently became a major force in promoting science, e.g., astronomy, in the U.S.

To review the historical development of the federal role would be interesting, but for present purposes it is sufficient to note that in case after case the federal government became involved only in response to specific needs which could not be met by private interests or state governments. In addition to the Patent Office, the Coast and Geodetic Survey, and the various explorations which we have mentioned, work was undertaken, for example, in 1818 on weights and measures, leading eventually to the creation in 1901 of the modern Bureau of Standards.

In the same spirit the Army Medical Department was created in 1818, the Naval Observatory founded in 1842, and meteorological work was begun by the Army Signal Corps in 1870. However, only the Smithsonian Institution looked to the development of science per se.

Agriculture—A New Departure

The scientific organizations and activities discussed above dealt with quite specific problems. Enlisting science to serve the farmer is a much more general problem. It involves not only basic research but research directed to a seemingly infinite array of crops, soils, climates, and pests. It involves the education of the farmers, the transfer of research results to the farmers, and the transfer of practical experience to the schools and research stations. Finally it involves the economics of the U.S. farm system as a component of the U.S. economy and a world market for food and fiber. The problem was and is to adapt and even to create a productive system based on a large number of independent producers.

How the U.S. coped with that problem is a great success story which is frequently cited in discussions of industrial policy. First of all, though, we should note that the solution was not designed by scientists or systems analysts, and it was not conceived as a whole. Rather, it was born of political pressures as, first, the farmlands of the west were settled and farmers encountered problems for which they were unprepared and, later, when output could no longer grow by opening new lands, by the need to enhance farm income through higher productivity.

The ingredients of the system were not dissimilar from those faced now in industrial development. The first item of infrastructure is the training of people with suitable skills. This was undertaken in a revolutionary way by the Morrill Act of 1862, an "act donating public lands to the several States and Territories which may provide colleges for the benefit of agriculture and the mechanic arts." Morrill said the act envisioned not agricultural schools but "colleges in which science . . . should be the leading idea." Thus were born the land-grant institutions which, though they took many forms and took decades to develop, were devoted to practical problems and to public service rather than to the training of an educated elite.

At the same time Congress established the Department of Agriculture. In establishing a Department of Agriculture and granting public lands for colleges, Congress proceeded on the assumption that its power "to lay and collect taxes . . . for the common defense and general welfare" obviously warranted federal sponsorship of scientific research. Thus, a new era was opened. The Department of Agriculture began to undertake research of various sorts but not without opposition; in 1881 the journal *Science* suggested that agricultural research be turned over to universities and private organizations.

A different solution evolved—a series of bureaus directed toward practical problems: bureaus of entomology, animal industry, and plant industry. They were the core of the research program and pioneered the idea of a stable corps of scientific personnel which could be shifted to various problems as they arose. As a source of trained personnel they looked to the universities, which also collaborated in research. Since, for the most part, those universities were the "cow colleges" set up under the Morrill Act, agriculture in effect evolved a special university system.

The ties to land-grant colleges meant dealing with states, and still another facet evolved. Because the bureaus became collectors of local information and got closer to local problems, they became central information repositories. At the same time, success in their scientific effort made them central sources of information. Finally, the bureaus inevitably became involved in providing other services to the farm community.

These trends culminated in a second major federal step—the Hatch Act of 1887, which created state experiment stations funded in part by the federal government. Since each was attached to a land-grant college, the ties to the states were tightened, and the Department of Agriculture became the focus of a system of semiautonomous research institutions permanently established in every state.

The last feature of the agricultural innovation apparatus came into place as the department became an institution for popular education, as well as of research and regulation. To produce innovation in the sense of new practices, research results have to get into the hands of farmers, and the farmers have to use them. This is not always easy since farmers are often wedded to traditional ways and are contemptuous of prescriptions emanating from the land-grant colleges. This problem was dealt with by an institutional innovation, the establishment of the Extension Service in 1914, to work directly with the farmers. It carried on demonstrations and brought new varieties of crops and new practices to the attention of farmers. The county agent became available as a consultant and the channel for a wide variety of services to the farmer.

The result of all of this is that American agriculture is now a high-technology enterprise which accounts for a substantial portion of the U.S. export trade. The combination of federal and state governments has led the way in generating a system including basic research at centers such as the Beltsville Research Center and the land-grant universities; applied research at the experiment stations directed toward local problems; an information dissemination system; close links to a university system which is a source of supply for the personnel of the Department of Agriculture, for the various state agencies, and for farm managers; and an extension service which reaches to individual farmers. In addition, the research and education system has developed links to the political system and to the large agro-business community. The political system has evolved incentives of various sorts as well as restraints through regulation, all designed in principle to enhance productivity.

The system is probably the most successful government effort to date in stimulating the innovative process. With farming divided into so many small individual units, it is difficult to visualize such an establishment growing to comparable stature and effectiveness in private hands. The question we must ask is whether there are features of the agricultural experience which can contribute to other needs of society. Other sectors which are similarly diffuse and lack private organizations to lead them include the health care delivery system and small businesses. The idea of an organization analogous to the extension service to serve small businesses which lack research resources and management skills is frequently proposed.

Some Alternatives

The early experience, and particularly that of agriculture, points the way to a variety of potential governmental roles in stimulating scientific and technological creativity and innovation.

1. Government can foster the training of people who can serve to staff the scientific and technological enterprise, both in and outside of the government.
2. By supporting basic research, it can foster the development of knowledge and understanding on which all innovation ultimately depends.
3. It can expedite the transfer and availability of information.
4. It can foster the development of infrastructures, of institutions to do what is needed by the whole society and which cannot be or are not undertaken by the private sector, such as the Coast and Geodetic Survey, the Geological Survey, the National Oceans and Atmospheres Program, the National Bureau of Standards, and so on.
5. It can fund and, in some cases, carry on research, development, and even production of items needed by the government itself, such as military and space equipment.
6. Through patent and copyright laws, tax laws, antitrust laws, regulations of many sorts, purchasing policy, and other indirect means, it can provide incentives or restraints which serve to guide the course of innovative activity in the nongovernmental sphere.

Except in the military, space, and nuclear power spheres, we have very few, if any, examples of the development of end products and their introduction into use by government. Whether there are opportunities for such development now is a matter of debate. Even the question of the extent to which "spin-off" (the transfer of technologies from military and space activities to civilian pursuits) stimulates industrial innovation is unresolved. Since military research and development (R&D) is the biggest single category of federal expenditure, we shall consider this question, as well as the impact of the space program, later at greater length.

A persistent question is whether there are categories of industrial activity which for any of several reasons, such as the degree of fragmentation into small enterprises, or the magnitude of the investment required, need governmental leadership or assistance.

For example, would a "Building Research Institute" be fruitful? Related to this question is whether government can make private research more effective, as is alleged to happen in Japan, through the encouragement of "precompetitive" cooperative research by industry.

As we examine some of these possibilities, it is important to remember that the political inhibitions, which led the federal government to spend a total of only $40 million on R&D in 1939, and none at all on research in universities (other than agriculture), vanished after World War II. By 1981 the federal government spent $33.8 billion on R&D (compared with $35.9 by industry), of which $6.8 billion was spent in colleges and universities and $15.9 billion in industry. Since only 33 percent of the federal expenditures were civilian related and 66 percent were defense or space related, the latter deserve special attention in weighing the governmental impact on innovation.

ACADEMIC SCIENCE AND GRADUATE EDUCATION

Before 1940 there was little interaction between the government and universities other than in agriculture. However, it became apparent during World War II that academic scientists provided a major impetus in developing radical new technologies such as radar, the proximity fuse, the nuclear bomb, and new materials. In doing so they called on scientific knowledge which had only recently emerged from basic research laboratories. As a consequence, when the war was over, the armed forces, notably the Office of Naval Research (ONR), funded research in universities and, with it, the training of doctoral students in order to build a foundation for the future security of the country. The ONR program supported a very broad spectrum of work in the physical sciences and mathematics. At about the same time, the National Institutes of Health (NIH) began their extramural program which presently supports almost all biomedical research in universities. The Atomic Energy Commission (AEC) supported nuclear physics, nuclear engineering, and high-energy physics research in universities.

Starting from that base, basic research in all fields has become an accepted responsibility of the federal government. The National Science Foundation (NSF) was set up for this explicit purpose in 1951. However, a number of agencies continue to share in the support of basic research, each cultivating areas believed to be related to the long-term progress of the areas germane to their mission. The 1984 budget, for example, planned expenditures of $6.3 billion on basic research. The distribution of this expenditure among agencies is shown in Table 1.

TABLE 1. APPROXIMATE EXPENDITURES FOR BASIC RESEARCH, 1984

Health and Human Services	$2,200
National Science Foundation	1,100
Department of Energy	1,000
Department of Defense	775
National Aeronautics and Space Administration	660
Department of Agriculture	380
Other	250

Basic research augments the knowledge pool from which scientific and technological innovation draw. Since the results of basic research are disseminated as widely as possible, the benefits of this knowledge are not retained by any single enterprise or industry. They cannot even be retained nationally, but constitute a world treasure which is basic to progress everywhere. It follows, though, that basic research provides benefits only to those who are prepared to make use of it. In itself basic scientific advance does not produce scientific innovation as defined at the beginning of this chapter; however, if the other elements of the innovative process are coupled to it and are sufficiently skilled, it is an essential part of the innovative process, especially for the most radical departures. We have had dramatic examples in the utilization of semiconductor physics in hand calculators and especially in the silicon chips at the heart of computers.

The chief issues involving academic research revolve around the choice of fields, institutions, and projects to be supported. On the one hand, one might select projects as much as possible by the scientific merit of a proposal as judged by peer review. On the other hand, one might temper those judgments by the desire to build or maintain institutions or to achieve other goals. For example, since research experience is at the heart of the education of doctoral scientists, concentrating the research in a small number of elite institutions would expose only a small number of students to the best research minds and techniques. Therefore, it is argued that by carrying on high quality research in a large number of institutions ("spreading it out") the educational benefits will extend to many more students.

A related question concerns the choices among fields. From a purely academic point of view, one looks for areas ripe for scientific advance. But shouldn't other fields be supported because of their continuing importance and relevance to health problems, to environmental problems, or to industrial progress? If active research programs are not maintained might they lose their vigor? They may be needed because their practitioners are essential to industry (for example, metallurgists); other fields may be needed as a base in applied science in defense or industry (for example, materials science). These debates will continue, and one of the great virtues of our pluralistic system is that the various government agencies approach such problems from differing points of view, the results of which can be compared for effectiveness.

In any case, by all measures, such as Nobel prizes awarded, publications cited, or major discoveries made, basic research in America is thriving. There is certainly room for improvement, but if there is a lag in scientific and technological innovation, it is not likely that it results from a deficiency in basic science.

The picture is not quite so clear with regard to either the condition of graduate education or the governmental role in producing doctoral scientists. In one way or another most natural scientists are supported in graduate school by such devices as research assistantships, teaching assistantships, traineeships, or fellowships. The availability of teaching assistantships is chiefly related to the number of undergraduates who take courses in any given field; as a consequence the distribution is not related particularly to the demand for trained manpower. The situation with respect to research assistantships is somewhat better. Their number is roughly proportional to some mixture of faculty research interest in a field and the interest of sponsoring agencies. While that results, in some cases, in training people in fields of great academic but little commercial interest, such as high-energy physics, and possibly directing people out of fields of great applied importance but lacking the highest intellectual stimulation, for the most part, this mode of support has served the country well.

In particular, people have been trained to staff rapidly growing fields such as aerospace engineering or solid-state electronics in the 1960s and computer sciences in the 1970s and 1980s. There are those, however, who feel that in the process talented people were diverted from such areas as machine design and production engineering.

Traineeships and Fellowships—The government has been very ambiguous about the direct support of students or programs to improve the quality of scientific education or the strength of graduate departments. The Atomic Energy Commission supported a program of fellowships to train students in areas important to the development of nuclear energy for a number of years in the 1940s and 1950s. Beginning in the 1950s, NSF offered around a thousand fellowships each year based on the merit of the candidates and their geographical distribution, but for a variety of reasons that program was largely abandoned by 1983. The largest direct fellowship program has been that of NIH. It has been a key ingredient in building up the very large and very successful program in biomedical research in the United States.

Direct support of students has also been undertaken by the government through traineeships. These are coupled to institution building and the maintenance of stable research organizations in universities. The traineeship grant is therefore coupled to a research program. The recipients are chosen by the institution on a merit basis to study and do research in designated fields. As of 1983, NSF had given up its traineeship program, but that of NIH was thriving.

Both fellowship and traineeship programs were based on the idea that it is in the national interest to encourage the most able students to study in areas important to health, national security, and the economy. The approach, which subsidized students going into science and engineering, has been superseded by the argument that the salaries in these fields are good enough to make the expense of advanced study a good personal investment. Unfortunately, the reward occurs so much later that students who have few resources may not be able to continue.

Centers of Excellence—Lastly, the government has undertaken sporadically to assist in building academic departments and new centers of excellence. Such programs have been undertaken by the

National Aeronautics and Space Administration (NASA), Department of Defense (DOD), Atomic Energy Commission, National Institutes of Health, and the National Science Foundation. Most programs have been targeted on areas of science and engineering of interest to the agency. A variety of such programs continue, e.g., the center grants of the National Institute for Environmental Health Sciences (NIEHS). NSF and DOD have set out to broaden the base of American science by strengthening second-rank institutions and departments which show promise of rising to first rank. However, as of 1983, the NSF program had been abandoned; efforts by other agencies were undertaken only as a secondary part of the research program.

In sum, the funding of basic research, and especially that carried on in universities, has become a government responsibility. At the present time it is, for the most part, in a healthy condition, and it is hard to relate any deficiency in industrial innovation to a weakness in this sector.

Whether the supply of a highly trained work force is adequate in the critical fields is less certain, but it is safe to state that work force shortages have not been especially evident. More subtle questions, such as the quality and nature of their training, and the balance among doctoral candidates, baccalaureate students, and students in technical and vocational schools, may be important, but there is little evidence one way or another. In any case, this is not a matter the federal government has addressed directly.

DEFENSE AND SPACE

During the two decades from 1964 to 1984, defense accounted for over half of the federal R&D expenditures in every year. In 1983 these expenditures, 66 percent of which are devoted to the development of military hardware, amounted to more than $24 billion. Another $6.5 billion was devoted to space, principally for the development of rockets and space vehicles. Since most of this R&D and all of the resulting production are carried on in industry and since both defense and space strain the existing limits of technology in their requirements, the degree to which they stimulate civilian industry is an important question. Perhaps more important is whether the degree of stimulation can be notably increased.

During the 1960s it was widely believed in Europe that the experience of American industry in developing and producing sophisticated electronic and communications equipment, new materials, advanced construction and quality control methods, etc., was providing the U.S. with a widening qualitative technological superiority. This outlook gave rise to the perception of a "technological gap" in the 1960s and the fear that this would ultimately result in American dominance. These fears, dramatized by Jean Jacques Servan-Schreiber's *Le Defi Americain,* were so vivid that "the gap" became a political issue which colored relations between the U.S. and Europe for some years.

With the reemergence of intense international competition in high technology, the "gap" has receded as a political force, but the question of the impact of defense and space on industrial innovation is still important. One can look to many possible sources of stimulation by the military and space programs.

1. Both DOD and NASA have supported exploratory research and applied research in both industrial and university laboratories. DOD is our most experienced supporter of research and, in general, has been a very effective sponsor. Its program managers generally could relate their efforts to long-term needs. The NASA program was similar but not as broad. Their long-term interest in high technology in such areas as electronics, aeronautics and astronautics, ships, communications, materials, fuels, etc., provided them with the insights needed to judge the quality and appropriateness of applied research activities. They had the ability to respond quickly, and they understood the value of groups of scientists working together on related problems. The DOD research directors had a degree of venturesomeness which was extremely valuable to the health and progress of U.S. science and technology. The Advanced Research Projects Agency (ARPA), for example, inaugurated a very successful program in materials science.

2. DOD has recognized the desirability of contractor owned technology in its policy and has taken the enlightened step of recognizing R&D on future products as a legitimate cost of doing business. It has done so by allowing independent research and development (IR&D) as a part of overhead. It is a way of hitching the company's commercial interests to government programs.

3. In particular, DOD has supported generic technology pro-

grams to improve the technological base for the production of military equipment by having a supply of advanced technologies "on the shelf." These have included areas such as welding, automated assembly, techniques for forming and cutting metals, and many others. The efficacy of such programs has been a matter of debate, but they clearly contributed to the electronics, computer, and aerospace industries. They deserve further attention since generic technology programs are frequently proposed for civil industry.

4. DOD and NASA have both supported quality and reliability improvements through the development of advanced, nondestructive inspection techniques such as X-rays and ultrasound.

5. Through their large R&D programs DOD and NASA have expanded in high-technology areas the pool of scientists and engineers, many of whom migrate into civilian industry beyond the numbers which would have been available in their absence. On the other hand, they have driven up the cost of research and have drawn people out of less glamorous, less well financed fields financed by industry alone.

6. Above all, by providing a very large market for the most sophisticated, high-technology products, manufacturing skills have been developed. Defense and space programs, for example, have provided the first market for the largest, most capable computers at each stage of development of the industry. They have provided a large-scale demand for miniaturized devices with very high reliability.

In a general way in the areas of electronic devices, communications, computers, light-weight structures, etc., defense and space force the state of the art in many fields through their requirements for high-quality, high-performance production items and their willingness to pay for them. Needless to say, cost plays only a small part relative to performance in military and space equipment so that it has frequently been noted that many of the best production sources for defense and space have not successfully entered the commercial market. That is true, of course, for some, but others, such as General Electric and Westinghouse, also have large civilian businesses, and several industries derive their commercial positions from prior military research, development, and production.

THE AIRCRAFT INDUSTRY

It is probably reasonable to assert that the predominant position of the U.S. aircraft industry in the world market would not have been achieved without direct support by the government. Systematic aeronautical research in the U.S. began with the creation of the National Advisory Committee for Aeronautics (NACA) in 1915 and the laboratory set up at Langley Field. In the succeeding years, its wind tunnels became the source of progressively more efficient wing sections, and it led the way in research for the aircraft industry in aeronautic engineering, propulsion, and structures. Eventually NACA evolved into NASA, but its leadership in aeronautical science continued. Not only did the government carry on research in its own facilities, it funded most of the university work in aeronautical science and engineering and most of the R&D carried on by the aerospace industry.

Above all, it purchased thousands of aircraft, ranging from high-performance fighters to long-range, heavy-lift cargo planes. It bought specialized planes such as the U-2 and the RX-70 (a very high-altitude, very high-speed reconnaissance aircraft). It bought helicopters of all sizes and capabilities. Jet engines came to maturity in military aircraft before they were used in civilian aircraft. Substantially all commercial engines are derived from military engines, and, until recently at least, most commercial aircraft were derived from earlier military designs. Most of the new alloys and structural features were first employed in military planes.

In short, military aircraft was the large-scale proving ground for most of the innovations in the industry, and it seems apparent that innovation in the commercial aircraft industry is, in large part, built on prior innovation in aircraft for military purposes.

COMMUNICATIONS SATELLITES

What has just been said about the aircraft industry is also true of perhaps the most important communications advance of modern times—the communications satellite. The rockets which carry them aloft were developed under the aegis of NASA and DOD, and the early versions of the satellites themselves were developed and built for NASA and DOD. DOD is still the largest purchaser and user of communications satellites. It is plain that except for DOD and NASA the industry would not exist, and its continued progress still relies heavily on the government programs. One additional government contribution should be noted since it may also be important in other connections. As a major purchaser of satellite communication channels the government helps to maintain the economic viability which makes commercial operation feasible.

Spin-Off—In sum, the Department of Defense and the National Aeronautics and Space Administration have played a crucial role in the innovations essential to the aircraft and communications satellite industries. They have also made significant contributions to the innovation process in the electronics industry. In all of these cases applied research and technology development related to end products which were directly relevant to their own mission. Despite the success of the jeep in civilian use, there is little evidence for spin-off of the technology to commercial enterprises in general, although NASA tried very hard to effect such transfer of technology. It is hard to know how much the early DOD and NASA experience with integrated circuits or miniaturized equipment eventually affected the consumer electronics market.

Nuclear Power

The only example known to the author of a deliberate effort by the government to establish a new industry is the attempt by the AEC to bring a nuclear power industry into being. The Oak Ridge National Laboratory not only carried out basic and applied research, but it studied the properties of materials for power reactors and designed and built successively larger nuclear reactors of a variety of designs. At the same time, AEC instituted collaborative programs with industry, which was also involved in building nuclear propulsion units for submarines. In these ways the development of industrial skills was heavily subsidized. In 1957 the Shippingport demonstration reactor was built at government expense, industry being charged only for the value of the steam produced. After a number of further subsidized demonstration plants, nuclear power became fully commercial in 1968.

However, even since then R&D in materials and reactor design have continued in government laboratories and received government subsidies in industrial laboratories.

The result of this governmental effort has been to put together a nuclear power industry which leads the world. Both France and the United Kingdom have adopted American pressurized water designs. On the other hand, with much less governmental investment, they and West Germany have become competitive with the U.S. in the world market. Whether the billions of dollars invested in establishing a nuclear power industry will eventually be regarded as a wise expenditure remains to be seen.

Direct Support of Industrial Ineffective Development

For the most part, the government has not been involved in the selection and management of technological development programs aimed at commercial applications. When it has undertaken demonstration projects to stimulate new industries, the results, with the exception of nuclear power, have been disastrous. For example, the Morgantown, West Virginia, personal rapid transit project assumed that technical demonstration was all that was required. Such demonstrations tend to ignore such necessities as capital, production, distribution, servicing, and repair. Success requires an experienced enterprise with a high stake, and these considerations received little attention in planning and executing the Morgantown project. It eventually sank without a bubble, carrying with it well-intentioned millions of dollars.

Another such government effort was the attempt to develop a commercial supersonic transport aircraft in the 1960s under the aegis of the Department of Transportation. Fortunately, the program was abandoned before we had been committed to a production program, but not until after the expenditure of several hundred million dollars. The British and French governments were not so fortunate, and the Concorde has continued to be a costly white elephant without even producing national prestige.

The vulnerability to arbitrary oil pricing and even to actual interruption of the oil supply, demonstrated in 1973 and again in 1978, led to direct action to develop alternative energy supplies. In this case the government funded research on alternatives such as solar energy and the construction of pilot-scale solar energy plants. It also offered tax credits for the installation of solar heating equipment. In addition, it fostered applied research on the gasification and liquefication of coal and, through the Synthetic Fuels Corporation, collaborated with industry in the construction of large-scale plants to produce liquid fuel from coal and oil shale. The subsequent drop in the price of oil caused the abandonment of most of this program, and it remains to be seen whether it will not be needed in the long run.

Other governments have gone further than we have. Putting aside the matter of nationalized industries in France and England, France has attempted to accelerate the development of high-technology industries through such means as the Plan Calcul, a scheme to promote the manufacture and use of advanced computing equipment. England has founded the National Research and Development Corporation whose greatest success has been the antibiotic cephalosporin; its commercialization of the Hovercraft has been marginal at best. None of these examples has been sufficiently successful to warrant emulation.

Japan, of course, is most often cited. However, the Japanese government has not entered the commercial market directly. Rather it has attempted to encourage and assist industry through various collaborative schemes. It has also supported R&D in areas targeted for commercial development, such as automated manufacture and robotics and computers. It remains to be seen whether such targeted efforts will be successful in the long run.

Health and Biomedical Research

One area whose success derives very largely from government support is that of the biomedical sciences. Beginning in the 1950s, the fields of biochemistry, molecular biology, biochemical genetics, immunology, virology, and so on were almost entirely supported through the National Institutes of Health. This so-called genetic revolution, which transformed our understanding of health and disease, grew exponentially, and the federal government financed the training of people, the conduct of research, and the providing of jobs for the people.

For many years this basic research had little impact on health statistics, the treatment of disease, or the pharmaceutical industry. Now all of that has changed. The mode of action of pharmaceuticals is being understood, and they are acquiring a rational foundation. Organ transplants are made possible by the advances in immunology, and, above all, a new industrial frontier in genetic engineering has been opened which will have great impact on both health and agriculture and, in the long range, other segments of industry.

The government has not participated in the commercialization of the products of the basic, applied, and clinical research it fostered, but it can legitimately claim to have set the stage for the most dramatic and radical new scientific innovation of our time.

Indirect Government Roles: Incentives and Restraints

Many analysts are of the opinion that while government action in supporting research and advanced training, as well as providing backup services, is essential to the innovation process, the greatest impact of government comes through its general social and economic program. Most often mentioned for their impact on industrial innovation are:

1. inflation and interest rates,
2. tax policies,
3. environmental health and safety regulation,
4. the patent system,
5. the disposition of patents resulting from federally funded research,
6. antitrust policy,
7. federal procurement policy,
8. policy toward small and innovative firms, and
9. transfer of technology from federal laboratories.

Inflation and high interest rates are commonly thought to inhibit innovation and reduce productivity growth by reducing the rate of return on new ventures. Though inflation obviously does reduce the rate of return, Harvard economist Dale W. Jorgenson notes that the real rate of return (above inflation) has been comparable in the period around 1980 to the average of the post–World War II period so that it, in itself, is not the major problem. Nonetheless, if capital flow into innovative ventures is to be maintained, government policy should insure that the real rate of return remains adequate despite inflation.

Nearly all analysts focus on the lag in capital formation in the United States, and Jorgenson traces the decline in productivity growth in recent years largely to this cause. The essence of this argument is that the lag is not so much in generating technology as in the fact that we do not use the R&D which is already available to us. In this case the highest priority for government action is to take such steps as will stimulate capital formation and, especially, the generation of venture capital. The principal governmental tool for doing so is through tax policy. (A detailed discussion of tax policy is beyond the scope of this chapter.) However, among the measures most commonly suggested to spur capital formation are accelerated depreciation schedules for investments in plant and equipment and the use of replacement costs rather than historical costs. A variety of other tax moves to stimulate investment, among them reduced capital gains taxes, have been advanced.

One of the interesting features of scientific and technological innovation is that a very high proportion (perhaps 50 percent) originates with individual inventors and small enterprises. Therefore, a particular goal for government policy should be to stimulate both the formation and the health of such enterprises. Direct investment in new ventures, which involves detailed commercial choices, is not well suited to government action. But tax and security laws can be rewritten to encourage equity investments in small companies, and the government generated red tape involved in running a small new business can be cut back.

Accelerated depreciation schedules for equipment and structures would provide incentives for private R&D as well as for investments in facilities and equipment for production. Other incentives to private R&D might include tax credits for R&D expenditures, and these stimulants have been recommended by some. However, it is not evident that this is a serious problem since R&D expenditures by industry have been rising steadily. For example, from 1973 to 1983 they have risen from $13.3 billion to $44.3 billion.

Although there are instances where regulation has been a stimulant, it is, by and large, seen as a restraint on innovation. For example, it is alleged that capital diversion to meet the requirements of environmental health and safety regulations constitutes a serious brake on innovative capacity. It is also felt that the uncertainties engendered by regulation and possible changes in regulations inhibit the establishment of new ventures. There is no doubt of the nuisance effect of regulation, but the overall effect is less certain. Jorgenson points out that the capital diversion is only a very small part of the total rate of capital formation. In another study, economists Gregory Christiansen, Frank Gollop, and Robert Havemann concluded that the impact of environmental health and safety regulations on macroeconomic performance and productivity growth was not important. Nonetheless, even if the average effect is not large, the impact on individual sectors and particular enterprises may be very important. In the future the impact on innovation needs to be considered in developing regulations, and this needs to be done separately for the various sectors.

Still another facet of governmental policy arises from antitrust laws. As presently interpreted, collaboration between competing companies is very difficult at any level. The question which arises is whether such restraint is necessary to sustain competition, especially when the domestic industry is faced with vigorous foreign competition. To what extent should members of an industry be allowed to cooperate in R&D which will enlarge the technological capacity of the entire industry? It is widely believed that the current barriers to collaboration between competitors at this level are excessive.

Patent protection for inventors and entrepreneurs was written into the Constitution and has always been the principal guarantee to inventors and users of inventions that a return could be realized. Yet most patents are actually weak, and the time and expense of establishing their validity through litigation are excessive; in addition, the uncertainties involved increase the risk to the entrepreneur. Most observers agree that the innovative process could be improved through patent reform which would strengthen patents, once issued. This, however, would require greater vigor in the examination of patent applications.

Related to this is the question of the disposition of patents issued to contractors or grantees resulting from government funded research, as well as those patents on inventions in government laboratories. This has been a subject of debate since at least 1945, and the practices vary widely between agencies. DOD grants title to its contractors for patents taken out as a consequence of federally funded research, recognizing that the cost of reducing inventions to practice, setting up production lines, and marketing the product is usually much greater than the original research. Moreover, it usually involves substantial risk.

The other point of view, that the results of publicly funded research should remain in the public domain and be made freely available to the public, characterized the Atomic Energy Act of 1946; the NASA legislation; the Department of Agriculture; the Non-nuclear Energy R&D Act of 1974; and, historically, the Department of Health, Education, and Welfare (now Health and Human Services). Under this policy, the government retains title; only nonexclusive licenses are granted, except under special circumstances. Although a few government patents, such as the aerosol can and frozen orange juice, were successfully commercialized under this policy, the main result was that literally thousands of government patents have never been exploited, thus wasting the possible benefits of the investment in the research on which the patents were based.

Some progress was made in this respect when, in 1963, President Kennedy issued a statement on patent policy which attempted to state a rationale for the diverse patent policies then in existence. It called for a flexible patent policy rather than a uniform one, balancing the various objectives: to stimulate R&D, attract contractors, avoid monopolization, and recognize the equities of both the government and the contractor. Under a number of circumstances the government would take only a license to inventions, leaving ownership and commercial rights to the contractor, who was thought most likely to develop the inventions for commercial use and practical benefit to the public. In 1971, President Nixon reaffirmed the Kennedy statement but amplified it to encourage agencies to grant exclusive licenses to government owned patents where necessary to stimulate commercial applications of these patented inventions. In addition, agencies working in areas of public safety, health, or welfare, which were normally instructed to seek title, were encouraged to consider leaving title to contractors in exceptional circumstances.

In 1980, this trend culminated in Public Law 96–517, which provides that universities, nonprofit organizations, and small businesses could elect to retain title to inventions resulting from government funded research, subject to certain disclosure requirements. It provides "march-in" rights for the government if an effective effort to achieve practical application of the invention is not made in a reasonable time. This law also defines the conditions under which government owned patents, both those resulting from grants or contracts and those emerging from government laboratories, may be licensed. It allows for exclusive licensing when it is necessary to call forth the investment of risk capital and expenditures to bring the invention to practical application.

The most recent step has been a memorandum from President Reagan encouraging all agencies to transfer title to the R&D contractor when it is consistent with their enabling legislation. Under this policy, the Department of Defense continues to transfer title routinely to large industries while the Department of Energy grants only licenses.

Today the federal government is industry's largest single consumer and customer. Consequently, it has frequently been suggested that government procurement policy can be a potent tool in stimulating innovation. This has already been the case in the aircraft industry, the satellite communications industry, the computer industry, and many elements of the electronics industry. Federal procurement played an important role in development of both transistorized IBM computers and Xerox copiers. The question is whether or not it can also be effective in the housing industry, the automotive industry, or other consumer industries. DOD has attempted such stimulation by replacing the usual construction specifications with performance specifications for military housing. However, it has had no appreciable impact, probably because the volume of purchases was too small and specialized. Despite the success of the jeep in the civilian automotive market, the same lack of impact would probably apply to any attempt to influence that market via military purchases. The outlook for a widespread government role by this route does not seem promising, but where incentives for the development of advanced products can be supplied, the attempt should be made.

GOVERNMENT LABORATORIES

Aside from its role in funding and guiding research and development in universities and industries, the federal government operates several hundred laboratories. These include the NIH;

the large NASA centers; DOD laboratories, ranging from important scientific centers like Naval Research Laboratory to a large assortment which have no mission; agricultural laboratories; the Bureau of Standards; and the national laboratories of the Department of Energy (actually managed under contract). Together they represent an important national resource. Where they have had a role in supporting major missions of their parent agency (for example, advancing space travel), they have been successful. But frequently their absence would not be missed. In any case, they have not contributed significantly to industrial innovation in general.

Some have made the attempt. Former AEC laboratories, notably the Oak Ridge National Laboratory (ORNL), have reacted to the decreased emphasis on nuclear reactor development by attempting to broaden their base and become a general purpose national resource. ORNL, for example, has built a very strong biology division based on its expertise in the medical and biological uses of isotopes. When President Johnson sought to push the desalination of water to meet the needs of arid regions, ORNL became the principal R&D center for the effort, but nothing of real industrial importance emerged. Nonetheless, these efforts have resulted in broadening the research base and made it possible for some of the laboratories to recruit and hold high-caliber scientific staffs. To date they have not contributed significantly to industrial innovation.

Conclusions

Any discussion of scientific and technological innovation in the United States must take account of the major role played by the government in that process, both in stimulating and restraining it. The government plays a predominant role in both the conduct of basic research on which the future of technologically advanced industry depends, and in the education of technical people at all levels. In areas related to its responsibilities, notably health, agriculture, energy, defense, and space, government is also the principal supporter of applied research. Through the patent system it offers essential protection to inventors and entrepreneurs. It carries on research in areas upon which industry depends but which would not be sponsored by the private sector.

Lastly, the government organizes information services and encourages the transfer of knowledge and technology.

It has not successfully stimulated the development of particular industries except as a by-product of large-scale defense, space, and nuclear programs. However, in at least one area, agriculture, it has been the nerve center around which a highly successful, scientifically advanced, and very productive agro-industrial enterprise was built.

In the context of scientific and technological innovation to develop industry and promote the general welfare, the present question is whether it can or should attempt to promote and stimulate designated industries and play a role such as that of the Ministry of International Trade and Industry in Japan. One must conclude that we have not yet found a way to do so.

On the other hand, the agricultural experience suggests that it might be possible to provide scientific, technological, and managerial assistance to small industries whose creation and survival are essential to innovation.

Another question is whether government support should be given to programs of technological development as opposed to scientific research. The goal of such programs would be to have a wider variety of technologies "on the shelf" for adaptation to particular tasks by civilian industry. However, it has not yet been established that such development is effective in the absence of specific challenges and goals.

Aside from specific interventions, the government has a tremendous indirect role. It can stimulate and guide capital formation through its tax and economic policies. It can shape the direction of innovations through its regulatory policies. It affects the conduct of innovation through antitrust policy and the steps it takes to promote small, innovative ventures.

In sum, the government cannot step aside. It has long since been too much involved. It should still lead the way, seeking out the things it must and can do, and providing incentives for action by the private sector in the areas which industry does more efficiently.

Robert A. Frosch

3

Improving American Innovation:

The Role of Industry in Innovation

> *A thing of beauty is a joy forever:*
> *Its loveliness increases; . . .*
> Keats, *Endymion*

Introduction

It seems clear that it is the aspiration of the United States to continue to produce a flow of products, new products, which will dominate world markets and make profit and reputation for the manufacturer. Our traditional world business role has been to produce new products with a reputation for being the most innovative and advanced in their fields; generally for a market-dominating combination of quality and price.

All of the adjectives in the previous statement seem to be important in maintaining the competitive position. Reputation for past products is not independent of the ability to acquire sales with new products.

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Apparently our nearly effortless ability to provide this continuing flow of innovative products and to maintain our reputation for them and, thus, our sales seems to have declined, perhaps almost to have vanished in some key areas. We perceive our reputation and competitive edge to have slipped badly and to continue to slip in world markets. Worse, foreign competition has invaded a number of U.S. market sectors (e.g., automobiles, consumer electronics, and a variety of household appliance lines and industrial goods) with products that are perceived to be, and frequently are, technologically more advanced and of higher quality than our domestic production. Even in fields in which Americans are the original inventors and developers, we are overtaken within a short time by foreign versions of our original ideas. We no longer necessarily dominate markets, even with our own inventions.

This difficulty persists, and may be growing, despite an extremely strong scientific enterprise, and there is evidence that our research in advanced engineering continues to be very strong. Something appears to have changed, and it is not completely obvious what it is.

What is the nature of innovation, its environment, its enemies? All these concerns should be considered in determining what innovation should be and how it should work. This will lead, implicitly at least, to thoughts about what could be done to improve our position.

The problem will be divided into several parts: the research and development (R&D) process (where the ideas come from), the innovative process (how things get to market), the organization (its alternatives and its effects on the innovative process), and, finally, some discussion of external factors and sectoral relationships (who does what, and with which, and to whom).

The R&D Process

> ***To be, or not to be: that is the question:***
> **Shakespeare, *Hamlet***

The research and development process is the generation of ideas and their development into technologies that can become major contributors to the innovation of new products. It is fundamentally a creative process in which people, who frequently have little or no product development motivation, try to build a body of knowledge in subjects of interest to them and try to turn that knowledge into new technological capabilities building upon previous technology.

Research and development must be somewhat distinguished in their motivation. Research people are concerned particularly with ideas and knowledge and not necessarily motivated to produce means for the use of these ideas other than as part of providing the technology required for their own search for knowledge.

Development people, on the other hand, are frequently motivated by an interest in making things work, in turning knowledge into some useful technique or capability. We distinguish between two kinds of development: technology development and product development. Technology development usually arises only from a motivation to make things work and may not be well coupled to the creation of a salable product. Indeed, as will be seen, deciding when to shift from making something that works in principle to making something that works as product may be an important timing choice in the innovative process.

All aspects of the research and technology development process are creative processes in the artistic sense. They are difficult or impossible to schedule because they depend upon a flow of ideas and inspiration much more than on systematic processes and the carrying out of procedures. Procedure and process are important in demonstrating the validity and usefulness of ideas, but in the early R&D stage the really good ideas are much harder to come by than the processes for testing them.

Because research is an artistic process, having a research laboratory is rather like owning a stable of poets. People engaged in this work are likely to be individualistic, somewhat "unreliable" in their rate of production (even in their behavior), and rather variable in their performance. They vary greatly in their characteristics and, on the whole, are likely to impress systematic managers as being extremely untidy and difficult to deal with.

Research scientists work immersed in a sea of ideas generated by themselves and those around them, as well as perceived by them in the scientific and other literature. Relatively little appears to be known about the sources of perceived problems and ideas. It is an extremely individual creative process.

An aspect which is frequently disturbing to systematic management is the problem of irrelevance. It is easy to define those possible topics of research that are clearly relevant to any particular subject. It is much more difficult to decide what areas, apparently irrelevant to the subject at hand, will later turn out to be extremely important. For example, in the 1950s it would have been clear to many people that improved glass was important to the future of better optical devices, but it was not apparent to anyone that consideration of the statistical distribution of energy levels and a phenomenon originally called "negative temperature" was of great interest for the improvement of optics. Nevertheless, the latter set of preoccupations led to the laser.

The importance of the seemingly irrelevant is one of the most difficult aspects of the management of industrial research. The most important innovations, insofar as they depend upon new knowledge, frequently depend upon knowledge that arrives from a direction not previously perceived as having much to do with the problem. The best we seem to know how to do is to choose general subject areas that have something to do with the products that may eventually be of interest, to use excellent research people, to give them reasonably free rein, and to expose them to a multitude of ideas about the kinds of eventual products and subjects of interest to the innovator.

This type of discussion of the nature of the research process is not very helpful to managers of industrial research who do not have research backgrounds, but it makes clear why a number of dilemmas surround the problem of how much internal research a corporation should do, how much, if any, contract research, and how much it should depend upon totally external sources for the knowledge and research ideas to be used in innovation.

There are, however, some useful things that can be said. It seems from the prescription above that it is nearly impossible, except perhaps for the federal government or for the largest corporations, to maintain sufficient internal research capability to be able to investigate the obvious relevant subjects and a reasonable population or the unobvious ("irrelevant") research subjects to be sure that they are covering enough bets in their early research areas. At the same time, an industrial operation with no research people is unlikely to have sufficient antennae merely to study research produced by others in order to find precisely those ideas that will be important to its next generation of products.

Thus, there is a kind of minimum research "intelligence sensitizing" operation that innovative corporations require. People capable of recognizing what is going on in a subject are unlikely to keep their edge if they are not somehow engaged in the research process themselves. As the late Alfred P. Sloan, Jr., has pointed out, this implies that to have an adequate research operation, there must be within the organization a group of people who are honed and interested in a variety of subjects that may be important to the corporation.

Their work can then be supplemented by a continuing knowledge of the published and openly available work of other industrial research organizations, of universities, and of the worldwide knowledge-producing organizations. Thus a judicious combination of internal work, external communication, and "R&D watching" is important to understanding the nature of the knowledge that may be used for innovation.

The external connections must be more than mere reading of the published literature. They must include some participation in meetings and organized research activities of the communication kind. This is because the delay between new ideas, their informal circulation in scientific communities, and their eventual publication can be sufficiently long so that, if one only reads, he is always significantly late in learning of new, continually emerging research and ideas. This difficulty becomes more acute as time passes since the process of change in science and engineering accelerates, possibly as a consequence of improved technological means for communication. If so, this will continue to accelerate as means of communication become more and more mediated through computers, permitting large networks of people to exchange data and ideas conveniently and inexpensively.

An important way in which an industrial research organization can extend its scope and reach is found in a variety of relationships with other research organizations. Since it is generally not possible for it to have close relationships with competitors, or frequently even with those in related industries, it is logical for the organization to extend its possibilities by relationships with university and government laboratories.

INDUSTRY COLLABORATION WITH GOVERNMENT LABORATORIES

Although there are increasing relationships of collaboration and of use of each other's facilities, which can be developed beneficially for the advantage of both government and industrial groups, there are complications in the case of government laboratories. The principal complication has to do with intellectual property and general government insistence that, when government money is involved, the public right in the intellectual property that results must be captured by the government. This area is changing, but so far this attitude means that industry and government are somewhat at arm's length in relationships where the corporation is interested in keeping all the rights in the intellectual property. There are notable exceptions, especially in those industries where the government is a major customer or where government sponsored industrial research has become extremely important. This is particularly true in aerospace and Department of Defense related industries.

INDUSTRY COLLABORATION WITH UNIVERSITIES

A variety of mechanisms have been developed for useful industry-university relationships in research, and there is a great deal of current activity in the invention of new arrangements. A traditional arrangement is for university faculty engaged in research in subjects of interest to corporations to be retained as consultants by the corporations. While employed as a consultant, the faculty member is an employee of the corporation. This arrangement is used to protect the proprietary rights, if any, of the corporation with regard to things that the consultant might learn from the corporation.

In many cases these relationships go beyond consulting (in the usual sense of advice) into corporate sponsorship of university research. This is normally totally open, with publishable research having no proprietary rights for either party. This relationship with the university can be used to expand greatly the industrial organization's direct access to excellent research upon a wide variety of subjects and topics. In some cases this has resulted in collaborative research where both parties are finally the authors. These arrangements provide a means for the industrial organization to widen and extend its contact with university research and, by judicious sponsorship, to find specialists or professionals with similar interests. It thereby, in effect, extends the actual research on subjects which are either of interest to it or which may fall in that class of potentially important "irrelevant" research.

An additional useful consequence of these relationships is the contact that they provide with students, especially graduate students, with consequent recruiting advantages for the corporation.

These relationships are of a traditional kind and are well understood by most universities and corporations. They do not generally have any but positive effects on both the mission of the universities and the mission of the industrial research laboratories.

Counter Flow from Industry—There has been much less flow of industrial research personnel into university work, except in some instances upon retirement. Not infrequently industrial people teach part-time at local universities or, in rare instances, take "sabbaticals" to work in university teaching and research. This is much less common than consulting and summer work for industry by faculty and students, and it seems to present a number of difficulties from the industrial side, particularly with regard to the continuity of jobs and career patterns in industry.

UNIVERSITY RESEARCH CENTERS AND RESEARCH PARKS

Recently a number of new arrangements have been tried to bring industrial and university research closer together. Many universities have organized research centers around particular subjects they believe to be of industrial interest. These subjects have included large-scale digital circuit integration, robotics and computer aided design and manufacturing (CADCAM), and genetic engineering and related fields of research.

In a number of cases the pattern has been for the university to organize a center and invite a number of industrial sponsors to participate in supporting it. As a return for their sponsorship in money, in kind, and possibly in the direct provision of people and ideas, the industrial sponsors get frequent, early, and somewhat special access to what is going on in the research center. There are no legal proprietary rights in the results, and the research center does not sequester its research for only its sponsors; research results are published in the normal way. However, the intimacy of access, the possibility of general intellectual influence, and perhaps direct influence upon the problems chosen for research (by presenting those of possible interest, which may be different than would otherwise have arisen) seem to constitute a sufficient lure to make the best of such arrangements successful.

In another arrangement, there are several cases, particularly in the digital electronics industry, where a group of industrial firms amounting to a trade association collects funds which are used to sponsor relevant research at a number of universities. Presumably there will be less of the special access relationship in this kind of sponsorship; rather it is a means for a number of industrial firms, which might not individually have the capability to do all the research they would like to do or sponsor, to stimulate that research in the university laboratories. Thus is increased the availability of a pool of ideas and knowledge upon which business may draw for the development and innovation of products.

Another device is the development of an industrial or research park in conjunction with one or more universities. In this situation the university acts as developer of an R&D oriented industrial situation close to itself or as stimulator of that development by others. The desired result is the establishment of a community of innovative firms with which the university may work, both in terms of corporate sponsorship of university research and of interchange of personnel and ideas.

In all of these cases there is an exchange of benefits: the university benefits from financial support and by stimulation for its research from questions relating to innovation posed by industry; the corporation benefits from the stimulation of university research, the availability of knowledge and concepts to which it may have special or intimate access, and, hence, the contribution of research ideas required for product development.

Applied Research and Development

The early stages of development constitute an area that is frequently called "advanced development." In the Department of Defense it is referred to as "exploratory development," with the term "advanced development" being reserved for a slightly later part of the process. In any case, this is the time when a new idea has emerged as a phenomenon, a material, or a process which clearly has relevance to either the corporate product or to the manufacturing processes for that product. The problem is how to turn the idea from a laboratory event or curiosity into some kind of useful engineering or product result—how to develop it technologically.

This aspect of the problem is frequently regarded as "routine engineering," but is far from that. The process of developing a technology from research knowledge is a creative process in itself, because it involves the development of totally new designs and ways for making things based on knowledge not previously in existence or use. Development involves a different kind of process from the basic research process. Because the new knowledge will not be of particular use all by itself, it must be fitted into a matrix of other materials, other mechanisms, and other portions of what will finally be a working technology.

At this stage there is likely to be little constraint regarding product design or cost; as will be seen, that comes later. The concern now is to turn the knowledge into something that can be made to work in a reasonable way, not yet in a way which is refined enough to be product. Because this process involves imbedding the new possibilities in a matrix of older systems and ideas, there is less free play and far more constraint than in the research context, although the process still involves experimentation and inspiration; creative idea generation continues to be extremely important—more important than being systematic.

It is during these early attempts to use new phenomena, materials, or knowledge to develop new technologies and working systems that gaps, errors, and difficulties in the research product (knowledge) are frequently detected. It is here that the things not measured or noticed in earlier research can become important. Frequently there is strong feedback from this early development which leads to refinement and improvement of the original research.

It is important to note that development of this kind is frequently done by somewhat different kinds of persons than those engaged in research. Research people characteristically are interested in carrying through the more constrained process of producing a designated end result from their research results. Development, on the other hand, is frequently more an engineering skill than a scientific one, or even a research engineering pursuit.

There is a particularly interesting process going on in much engineering research today which bears upon the nature of the process of development of research ideas into technology. Many of the traditional engineering technologies, metal casting and sheet metal forming being good examples, can best be described as well-formulated traditional crafts. There is a body of phenomenal, logical, and empirical knowledge, with bits and pieces of theoretical understanding, which forms a well-understood art that can be learned. Skilled engineers in these areas carry a body of knowledge which can be applied not only in product design and development, but also in the integration of new research knowledge into new technological possibilities. However, the process is inherently difficult and limited since the basis of understanding any of these crafts in a broad scientific sense does not exist, and thus the knowledge is not there to extend the processes and techniques into areas that are very different from those in which they have been previously tested and applied. Hence, the process of using new knowledge to expand into new possibilities with these technologies can be very slow and partakes of the character of tinkering, rather than of systematic design and development. Consequently, an important line of engineering research at the present time is the process of putting many of these traditional crafts on a sound basis of scientific and theoretical engineering understanding.

By itself this process does not necessarily provide new technology, but it lays a foundation for rational extension of known technology into new areas of development. Much of this work has been made possible by recent advances in computer technology which allow the application of theoretical and fundamental physical and chemical ideas to areas where sheer mathematical manipulation and computation difficulties would have been a major barrier a few years ago. This is not the development of new scientific knowledge in a fundamental sense, but rather the ability to apply scientific knowledge to rather complex engineering problems in entirely new ways.

This brings us to the point in the innovation process at which a piece of new knowledge has been turned into an actual capability; the idea has been made flesh. Although this is not yet a product, a first step has been taken that may make an innovation possible.

Returning to the laser example, we have arrived at the stage where an understanding of stimulated emission from an inverted-state population has been turned into a laboratory microwave amplifier and then into a radiating light-emitting population of molecules in the laboratory. This is now a demonstration that the understanding can be made to work as a device, but not yet anything that could be used as a marketable product. There are other examples in materials and many other developments where a device can be produced, but it is not yet anything that could be made to be bought or sold.

PRODUCT DEVELOPMENT AND THE INNOVATIVE PROCESS

> *This little piggy went to market,*
> *This little piggy stayed home.*
> Mother Goose

A Digression—At this point I must digress to point out that, for purposes of providing this chapter with a reasonable flow, I have used a traditional model of the innovation process, one which proceeds systematically from research and scientific ideas through their development into working technology and continues their development into salable products, the development of manufacturing technology to make them, the construction of the necessary machines and plants, etc. The reader should keep in mind that this linear time sequence is a grossly simplifying artifice. In the real world this is a kind of technology-push model of the process in which it is the new ideas that lead to the creation of products. It is frequently the case—sometimes it is argued, for no good reason that I can see, that it should always be the case—that it is the product idea which comes first, followed by a development constructed to produce the product; sometimes research is initiated to provide the knowledge that might make the product idea possible. It is clear that ideas for product, ideas for knowledge, and ideas for development can originate in many places and at different times in the process, and all of them stimulate and guide the others.

It is particularly true in the industrial context that knowledge of the aspirations and plans of the firm and what it intends to do in a general, future-product way can be important, if not essential, to the proper guidance and conduct of the internal research and development of the firm. The managers of industrial research in the firm should be knowledgeable of, and sensitive to, the product interests of the firm, but by no means should they allow themselves to be overwhelmed and entirely channeled by those interests, or else they will surely miss the most important "irrelevant" research and even some of the obvious relevant research and development that can lead to really new and interesting products. More will be said about this later when the subject is treated in terms of internal and external technology transfer.

The whole process can be viewed as a sequential line from research to product introduction with a set of nested feedback loops which connect the various parts of the process to each other. This model makes it seem nearly as complex as it really is.

With this in mind, the question of development is approached again, but now explicitly as part of a process intended to lead to something which can be sold as a product in the market. This step is the central portion of the innovative process—the conversion of a working development into a real product. This may conveniently be referred to as product development.

A product is different in many ways from an idea that has been shown to work. In the development of a product, major aspects of the product as a system and as part of a system arise. What previously was only a working device must now be imbedded in an environment somewhere out in society. New requirements arise, including requirements for reliable and safe operation, perhaps for the ability of the eventual product to be maintained in its operating environment, and for servicing when and if it fails.

The question of what it will finally cost to produce the product as eventually designed and manufactured is frequently dominant in product development. Indeed, the question of *when* to worry about cost can be a dominating problem in the innovative process. In many cases the worry about cost of eventual production has become so dominating a question that perfectly promising research and advanced development possibilities are destroyed because of too early a set of assumptions about the cost effects of their later development.

It is frequently assumed that if something is difficult and complex in the laboratory, it will also be difficult and complex and costly even after its eventual development. As stated, often this kind of business attention too early in the development process can be a destroyer of useful results. This is true in spite of the fact that there is abundant historical evidence that predictions of cost, and even of market, for brand new devices were not only wrong, but wildly wrong when made early in the process. The past twenty years of history of costs of computer hardware and software need only be suggested to make this point. (The same needs to be said about the nature of the market, and that point will be picked up somewhat later.)

Nevertheless, it is necessary to have some concern about cost in a number of stages in the process. For example, if a new material being developed in the research laboratory depends in some essential way (and one had better be sure that it is essential and not merely a curiosity of the current stage of the research) on some other material of intrinsically limited quantity, a rare element, for example, then it is worth discussing cost before going too far with the research. However, it may be cautioned that early estimates of required quantities have a bad habit of being incorrect. What is more difficult to remember or predict is that learning how to do something and understanding what one has done using a rare and difficult material may turn out to be a guide to how to do the same trick using a common and cheap material. This is not invariably so, but the possibility must be kept in mind before an estimate of atrocious cost is used to stop an otherwise promising research or product development project.

At this stage it is also important to consider the question of how the product can be manufactured; indeed, the process of product development may be as much or more of a process of manufacturing system development as of development of the product itself.

For these reasons, product development has to be seen as a rather systematic and systematically planned procedure. In the earlier stages of research and exploratory development, producing the result is the key question. The question of replication of that result in large numbers and how one would go about it may be interesting, but it is certainly secondary to making the basic thing happen in the first place. In product development, however, the nature of the product, how to produce it, what it costs, and who will buy it become the essence of the matter. This is the stage in which business requirements and questions enter in a full-blown way.

Determination of Risk—The question of risk now becomes important. There are both technical and business risks to be considered.

One must consider the risk that the product envisioned may, in fact, not be technologically realistic. Even though all the facts and knowledge are believed to be known and there has already been an engineering demonstration of the feasibility of the concept, it may still turn out that there is missing knowledge that may or may not be available from further research, the demonstration of feasibility cannot be translated into a really reliable product, or the product can be produced only by manufacturing techniques that are not feasible, either for the required volume production or within the necessary cost range.

This is a stage in which testing, redevelopment, further testing, and further redevelopment become important, and where even the costs of this rigorous process begin to be significant in terms of the effect of their amortization on final product costs. The technological problem of testing may be significant, not only in terms of the dollar costs to accomplish it and the risks and uncertainties of actually getting the product, but also in terms of the time that must be allocated for the necessary testing for reasonable certainty of the result in terms of knowing product characteristics correctly.

At this point in the process the costs are sufficient and the product planning must be far enough advanced so that one begins to think in terms of firm schedules for bringing a product to market. This kind of "schedule thinking" is required even before the certainty of testing has demonstrated the availability of a real product, certainly before mass production has begun and has demonstrated the feasibility of the product and the process to produce it. Accordingly, at this point there is a significant gambling risk for any investment, recognizing an uncertain possibility of success.

At this stage there must be introduced significant investment risk capital or venture capital, either from within the firm, by borrowing from money or other markets, or by borrowing from venture capitalists who are in the business of placing such bets. The mere virtue of an idea at this point is not likely to be sufficient to convince everyone that a sensible investment should be made. There are complicated problems of estimating whether there indeed will be a market for the magic product, if it is indeed possible to produce it, along with estimates of detailed costs, and how long one can manage to carry on development and testing before passing beyond the right moment for market introduction.

This is the part of the process that tests the fundamental attitudes of the firm and the money markets upon which it depends. It is clear that some American innovation has been destroyed at this phase, because short-term possibilities of turning money over in other than product development and marketing are competing with the possibility of long-term, and perhaps larger but riskier, gains to be made by building a business and a market on a new product. While it is certainly necessary for a business to do well enough in the short term to survive into the longer future, it is not always clear that the long-term profitability is to be maximized by taking the short-term gains.

Current business practices of fancifully pessimistic discounting sometimes have led to a short circuiting of the innovative process and a concentration on money manipulation rather than product creation. There seems to have developed a general habit of considering only short-term payoffs to be worthwhile while discounting all long-term future possibilities, in spite of a strong track record of innovative companies which have spent as long as decades building product possibilities which then became major market opportunities.

These problems of risk are further complicated by the changing time scales for market development and competition. In previous eras, U.S. business operated with the confidence that it was sufficiently technologically advanced with respect to other parts of the world so that it could work out its technology at leisure in the belief that others did not have the fundamental capability to catch up even when they saw the product. The entire process was then considerably more relaxed. In the past twenty years, however, the ability of many parts of the world to develop high-technology products, based upon their own fundamental technological understanding and ability to either copy or independently develop what they have seen, has added considerable pressure to shorten the time required for product development.

Currently, rather complex difficulties, previously much simpler, surround even questions of proprietary rights, secrecy, and the ability to protect ideas with patents. Not only is it the case that many aspects of modern technology development are difficult or impossible to patent or copyright, e.g., software, genetic change, and many computer related ideas, it is also the case that patent protection, when achieved, is likely to be so specific that a sophisticated outsider, seeing the result and examining the patent, can invent a new way to do the task which totally by-passes the patent.

First to Market or Second—It is necessary to consider the entire question of whether one wants to be first to market, paying for the research and development that leads to the product, or whether one might benefit by lagging slightly and putting the effort into developing a second generation when it has become clear that the first generation of products is a market success. There appear to be cases in which the ability to come second to market very rapidly may have short-term business advantages for particular products. However, an understanding of the knowledge and technology is still essential.

From the point of view of the overall capability of the firm, or, in the long term, the nation, such decisions can result in the loss of innovative and technological capability. It is difficult to believe that one can repeatedly be second to market over a long period of time—never be a primary innovator—and still retain the necessary edge to succeed in high-technology innovation, or even "back-engineering" or "redevelopment" innovation.

It must be noted, however, that it is sometimes the first development that contains the bulk of the mistakes, and the second developer can perhaps profit by avoiding some of the first difficulties. Even so, it does appear that in the long run the knowledge necessary to have the capability to make the choice between being first innovator or first copier needs to be maintained if the innovative process in the firm or the nation is to be healthy. This aspect of the matter deserves considerable further study.

One area of this question that needs examination is the effect on the reputation of the firm and its products achieved by innovation or by copying, both on the firm's position in the market when it brings a new product into public view and on the motivations and morale of people within the firm who are responsible for the innovative processes that take place. Certainly a reputation for newness, advanced product concept, and technology is bound up with a reputation for quality and reliability and thus with the whole matter of what price the public will pay for whose product.

Indeed, the whole matter of what product the public perceives coming to market (and perceives itself buying) is bound up with the question of the innovative process in an important way and is not really well understood. For example, when the Polaroid camera and film were introduced, the original market intention apparently was for snapshots and personal photography. However, the product appears to have been carried through its initial years by the fact that it was the best available technique at the time for recording what happened on an oscilloscope face; the early film market was dominated by electrical and electronic engineers taking data. As other means improved and the public market became established, this product innovation peculiarity changed. Similarly, the original market for microcomputers was an engineering market, shifted to a device-control market, and is shifting now to a public consumer goods market. It is probably difficult to plan these shifts; a certain amount of luck may be required.

THE OVERALL PROCESS OF INNOVATION

It is clear that what has been described as the innovative process—beginning with research, proceeding into exploratory or advanced development, and continuing into product development, manufacture, and marketing—is a complex process with a variety of aspects. The numerous feedback loops have been mentioned above, but it is important to emphasize that the social nature of the various parts of the process may be very different. The untidy, artistic, inspirational nature of research and early development has been referred to, but it must be noted equally that, while "creative intuition" is important in the management of manufacturing and in the problems of risk-taking and business analysis, a good deal more tidiness is required in these aspects. Systematic methods and tidiness are also important to the technical areas of careful reliability testing and quality analysis and assurance. While there are artistic aspects to all parts of the innovation process, the systematic aspects are much more emphasized at the product manufacturing and marketing end, and the inspirational aspects emphasized more at the research and development end.

TECHNOLOGY TRANSFER AND INNOVATION

The problem of technology transfer, matching different kinds of technological and business cultures as one proceeds through the innovative process, is complex. Basic scientific knowledge must be transferred by the research people to the development engineers, who differ somewhat from them and also from the product engineers who are next in line; the manufacturing engineers differ from all the preceding in their interests and responsibilities. Finally, business and financial people come from a still different culture and are likely to look for hard demonstrations in areas where scientists and engineers are accustomed to considerable ambiguity in terms of analytical and experimental proof of results.

Technology transfer, in any case, cannot be achieved merely by passing specifications, patents, or research reports to other people. Consenting adults must be engaged in the process, and a great deal of communication and mutual accommodation between the various parties must take place before a real understanding of both possibilities and requirements can be achieved. It is characteristic of the process that neither the product engineering nor marketing people have a very clear perception of what the technology can really do for a possible product. They, as the customers for technology, are always wrong. The research and early development people, on the other hand, have a tendency to see good products in every technological triumph and to try to convert each laboratory success into a business result. The mismatches in communication arising from these different attitudes and expectations can easily destroy the possibility of bringing the technology and product ideas together to a successful conclusion.

The transfer process from laboratory to market appears to work satisfactorily only when rather intimate dialogues among the various parties can be achieved. Frequently a period in which individuals actually transfer from one part of the process to assist in establishing another part on a firm basis may be necessary. For example, research people and engineers from early development may need to participate, or at least be available for detailed discussion, in portions of the product engineering process.

The rigid application of cost-accounting methods that were designed for different kinds of products and other situations can be death to a successful development, in that it may prevent easy communication (travel is expensive), misallocate costs and distort incentives, and hamper or prevent the development and technology transfer process since accountants do not fully understand this process. (This problem will be discussed further below.)

Because of the necessity for dialogue and feedback, a rather complicated process, we must turn our attention to the question of the organization of the firm for innovation.

The Organization

> *. . . the life of man, solitary, poor, nasty, brutish, and short.*
> Hobbes, *Leviathan*
>
> *Experts should be "on tap but not on top."*
> Attributed to A. E. by L. Gulick

The principal point to be made about organization for innovation is that bureaucratic matrices cannot be diagonalized; that is to say, there is no perfect organization for any particular purpose. Any hierarchical system will raise divisions between activities that need to communicate. Functional organizations tend to make tight development projects difficult, while project organizations tend to stifle the development of long-range deep technological competence in fields that may later be needed for other projects. This inherent difficulty frequently leads to cycles of reorganization, as one organizational system after another is tried and proved inefficient. It leads also to various kinds of matrix organization in which individual development or business centers may simultaneously be partly answerable to a project and partly answerable to a functional leader responsible for maintaining a basic technical competence and capability.

This may be one reason why small business units, and commonly small firms, can proceed most rapidly and effectively on many new innovations: they are small enough so that organizational requirements are minimized, and they can operate with fairly complete informal communication among all parties. When the organization grows beyond a certain size, this rather simple and unorganized arrangement becomes too unwieldy since the number of communication links grows in a combinatorial and, hence, exponential way.

The introduction of hierarchical organization to maintain a sorting of roles, tasks, and organizational control ruptures many of the seminal communication links that operate in simpler organizations and poses the problem of how to keep intact and healthy the communication lines required for the all-important technology transfer of innovation. Matters of centralization and decentralization of research and development in the firm (the establishment of central laboratories as opposed to laboratories and development organizations spread among manufacturing divisions but linked to the central research and development organization) should not be seen as solutions to a universal problem. Rather they should be viewed as attempts to introduce organizational devices that produce a good compromise for the preservation of the various communication links between research and early development and with product development and business aspects. Because what is to be preserved is a set of communication links which pass information and transfer technology in various ways, not any particular set of organizational niceties, frequently bureaucratic arrangements in the firm or in government, proceeding from standard hierarchical or organizational models, are more destructive than facilitating of the basic innovative process.

The problem has been made chronically worse over the past twenty years as firms are increasingly organized in terms of financial and accounting arrangements rather than product, marketing, or innovation arrangements. This is often true even when the parent organization is structured by product or R&D and manufacturing lines.

The problem arises because the details of accounting and bureaucratic systems may result in communication difficulties, as well as in assignment of incentives which interfere with the communications important to the innovative process. For example, the establishment of separate cost centers may make it difficult to have the adjustment of engineering and business requirements and the communications needed in an innovative development; this is particularly true if these are also profit incentive centers. Such difficulty results, for example, if it is necessary for one party to increase costs while another party can decrease costs, even though the sum of the two is lowered, and the result is to the benefit of the total corporation.

The problem also arises because of organizational rules for communication, the styles of various executives, and sometimes questions of legal arrangements among various parts of a firm which are intended to satisfy other kinds of rules and criteria.

Thus the question of business, accounting, and organizational systems in innovation must be seen from the point of view of their effects on communications and the ability to take a large-scale system design attitude to the product, the process for producing it, and its eventual marketing. Systems that systematize and segregate the various parts too well may distort the incentives for, and destroy the possibility of, real innovation.

This situation is complicated by the fact that recent attitudes have emphasized financial results to the point that there has been a loss of interest in the product itself. It has become a symbol of profitability rather than the essential element. Thus the operation of the firm can be seen increasingly in terms of cash flow, cost control, and accounting procedures, along with the systems of organizational control, as means by which there is control of a financial empire—a situation in which the idea of innovation gets lost along with the idea of the primacy of the product and its marketing.

It has been the conventional practice in recent years for accounting and business people to be on top, while the innovators are merely on tap and judged by financial criteria which may or may not be appropriate to the system characterizing the innovation under discussion. It is not clear that if the innovators were always on top, the result would not be a complete distortion of the cost of the financial possibilities of the innovation. The point really is that the purpose of a business is to make a profit by producing and selling products of some sort, and recent business practices seem frequently to have lost the central impetus of this idea. Because so many of the recent accounting and business practices are hedged about by external requirements of government, legal standards of accounting, business practice, and law, it is necessary to consider these external factors by themselves.

External Factors and Sectoral Relationships

> *My object all sublime*
> *I shall achieve in time—*
> *To let the punishment fit the crime—*
> *The punishment fit the crime. . . .*
> *On a cloth untrue,*
> *With a twisted cue*
> *And elliptical billiard balls!*
> W. S. Gilbert, *The Mikado*

Several aspects of the social responsibility and the ethics of the firm in bringing innovations to market have become institutionalized in recent years in ways that have probably been deleterious to innovative drives in industry, although in some respects they have succeeded in bringing protection of the public to a new and useful degree of awareness and accomplishment. Whether they have produced this result in a way which had to have the adverse consequences it did, and whether this is essential to producing this result, is open to considerable question.

Already referred to are the questions of accounting standards and the application of a variety of tax standards which produce accounting arrangements that may or may not foster the kinds and nature of internal communications that are important. The computer has made multiple accounting systems within a firm possible, accounting legally and correctly for tax purposes, while also accounting for costs in such a way that incentives can be established that have the right impetus toward innovation. However, few if any firms appear to have seized the opportunity to treat internal matters of incentive and understanding of costs on a rational in-house basis while having separate accounting systems for fulfilling tax and other accounting standards established to do somewhat different things. The two are no more than mathematical transformations of each other.

An example of this is the extreme artificiality of depreciation and amortization systems in tax and accounting standards. It appears that just at the time when it might be possible to account for depreciation using the actual life of various pieces of equipment as a sensible way of dealing with the problem, we have moved even further into artificial standards for depreciation and have tied tax incentives to depreciation periods which may not have much to do with the actual use of hardware. The same has to be said about the basis for taxing inventory gains, as in the introduction of first-in-first-out (FIFO) and last-in-first-out (LIFO), just at the time when real accounting is simultaneously possible, cheap, and very likely the best management control system.

The point is not whether these have useful aspects as incentives for action by the firm, it is merely that their mindless translation into internal accounting standards and financial incentives may destroy many of the things that they were intended to foster. It appears that broader analysis and greater thought about this problem might be advantageous for the improvement of U.S. innovation. The question is less one of subsidy and tax burdens by sectors than it is one of the internal technology of translation for the firm's own self-understanding and the proper construction of its internal and external incentives.

PRODUCT LIABILITY

A second important problem is the growing body of product liability law and practice and its increasing form as a legal adversary system which has become more gladiatorial than judicial.

There is no question that a reasonable liability to the public of an innovator and manufacturer for the consequences of a product is sensible. However, this is increasingly being translated into the assumption that everything which was produced must be always safe and risk free under all circumstances, no matter how used and no matter whether the unanticipated harm may be of insignificant frequency.

It is extremely difficult even to deduce what the standards are for regulating estimation of the existence of a product defect, whether systematic or random, in either manufacture or design. The criteria are unclear. Increasingly the establishment of safety and environmental regulations proceeds on an assumption that it is possible to deal with the natural world without any risk of random events or human failure, and in a situation in which complete safety is always preserved with no untoward or unexpected consequences from any cause.

The fact that this assumption is almost certainly a violation of natural law and the way in which the universe is constructed seems of little interest to those asserting such views. This seems to occur because the basic facts about probability and the manner by which things are really designed and manufactured are quite unknown to those who have not been educated in any way in engineering and science. The legal profession, regulatory and judicial, appears not only to be proceeding in considerable ignorance of science, but is, in fact, developing a set of rules of evidence that is quite independent of, and in contradiction to, what is known about natural events. Legislation is frequently even further from any scientific relevance.

Unfortunately the counterbattle of industry against this difficulty, as well as some of the problems of regulation to be mentioned below, has not always been rational or entirely honest throughout. The legal defenses of corporations have frequently been based on countering irrationality with irrationality; the whole process becomes a jousting contest rather than a proceeding seeking justice. A battle of foolishness has ensued.

Thus the questions are not whether there should be safety and environmental regulations, or even whether these regulations should be both stringent and stimulative of important technical advances for the protection of public and environment. Rather, they are whether it will be possible to establish such regulations on the basis of reasonable understanding of what is known, knowable, and unknowable, and what classes of risks may be acceptable for the public and in accord with nature. The process of assuring minimal risk seems to be proceeding increasingly by a random establishment of things to be controlled, without any particular examination of the hierarchy of dangers to which anyone or anything is exposed. Perhaps it is impossible to do better while preserving everyone's rights in the context of a democratic society, but it does seem that a more reasonable set of approaches should be devised.

The importance of this comment on personal risk and product liability within the context of this chapter is simply that the exposure of innovative possibilities to the fear of random regulation of supposed consequences has what is nowadays called a "chilling effect" on the interest of firms and of individuals within firms to produce innovations. It is already the case that the ability to think through possible safety improvements is hampered by the fact that there are regulations which would make them improper, and, therefore, considerable nervousness exists about either the political or legal possibilities of changing those regulations without getting embroiled in intolerable political and legal situations. We are sometimes telling the goose not to bother with the golden egg because there is a faint suspicion that the shell might possibly be bad for health or environment. It is easy to "pooh-pooh" this possibility and regard its remoteness as a defense of doing things in an unethical or irresponsible way, but that does not make the fact of its effect on innovative people any less real. Innovators are beginning to feel as though the apparent attitude of those who do represent, or claim to represent, the public is something along the lines of "go see what Johnny is doing and tell him to stop."

GOVERNMENT, INDUSTRY, AND INNOVATION

Aside from questions of regulation and the like, the role of the government in sponsoring research and development can be important in its effect on the possibility of industrial innovation. It is particularly important that the government continue to take a long-term view of the sponsorship of long-term research and development. Most firms simply cannot take a very long view of their responsibility for knowledge generation for future innovation; this is a task in which the commonality of interests of the country must engage. The idea that everything undertaken without an immediate market view is unlikely to be worthwhile is merely a piece of foolishness in the face of both history and reasonable economic analysis. Markets choose things in terms of a hierarchy of immediate benefits and are notoriously bad at long-term thinking.

Neither does rigid government planning have a good track record. However, a pluralistic means of letting a large, thoughtful community work on long-term research and technology problems does seem to have been productive in the stimulation of innovation and new production in the U.S. Certainly the world production of new technology owes a great deal to the long-term funding and support by government of basic scientific and engineering research, and it even owes a good deal to the support of the development of that research into technology available for product development. One has only to look at the development of the computer and everything that it is bringing to us, the development of radio and microwave communications, and related items to understand the meaning of this assertion.

It is considerably less certain that government should engage in demonstrating that technologies that are clearly possible in principle can be turned into pilot products. This verges on the subsidization of individual industries or firms and may be so strong a central control of what product is produced as to derail the possibility of broader innovative efforts. Perhaps some means can be found to involve the totality of an industry along with government in contributing to the development of the demonstration of a basic technology and leave the individual firms to construct the means for production. This seems to be closer to the pattern that the Japanese have been employing quite successfully than it is to any U.S. attempts involving government sponsorship of demonstration projects. Before this can be successful, a rethinking of the nature of necessary antitrust protections is in order.

Conclusion

> *When you're lying awake with a dismal headache*
> *and, repose is tabooed by anxiety,*
> W. S. Gilbert, *Iolanthe*

Innovation is a complex and fragile process involving elaborate communication among a variety of cultures and different kinds of people. It can easily be destroyed on a Procrustean bed of bureaucratic arrangements and "management." This involves the paradox of the self-defeating solution: systematic management can in fact prevent the good management of innovation. Innovation must be managed in terms of the requirements of the process and not as an incident of the management of other aspects of the firm. To do otherwise is to mistake the scaffolding for the structure.

In this sense, we need the development of new business and social regulation concepts and technology, for it appears that the means for management, particularly of innovation—public or private—have not progressed as rapidly in the technological sense as our ability to develop new technologies and apply them to both old and new problems. It is not a question of determining whether the business managers or the innovators are to be on top; it is instead a question of constructing new means for all cultures to work together toward common ends.

During World War II and during the explosion of American innovation thereafter, we found those means, but in excess of enthusiasm for formal managerial systems we appear to have forgotten how to use them. Perhaps we need to revisit and relearn our past successes so as to bring new technology, both social and technical, to the future innovative process.

Willard Marcy

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Enhancements and Impediments in the Innovation Process

Innovation

Technological innovation is the transformation of new concepts into needed or desired products or processes not previously available. The transformation is accomplished by a complex process involving complicated organizational structures, a dynamic process subjected to and modified by frequent changes resulting from technological, environmental, and societal influences. Logic and emotion play key roles; science and art are importantly involved.

NATURE OF THE INNOVATION PROCESS

Erik A. Haeffner of the Institut for Innovationstechnik in Sweden presented a detailed and provocative analysis of the in-

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