novation process in the March/April 1973 issue of *Technology Review*. He points out that during the first sixty years of the twentieth century, students of the innovation process almost universally assumed that basic scientific research would lead automatically to technical progress, that development of research results would lead directly to new products and processes, and that economic growth would follow. Unfortunately, several studies designed to show a correlation between the results of basic research and the number of innovations in a given industry indicated that a major impetus for industrial progress comes from inventions which are not a result of basic research.

While scientific research increases knowledge and provides an essential base from which new ideas and inventions can flow, it is now generally accepted that the major motivating factor in the innovation process is the condition of the marketplace. The existing and expected future economic atmosphere of a given industry largely determines whether inventions are created and developed. A world ready for minicomputers and microcomputers has provided the impetus for innovations in microchip and integrated circuit design, fabrication, and methods of use. An invasion of less expensive, more reliable, and more efficient automobiles from overseas has stimulated domestic manufacturers to emulate and improve on innovative production and quality control techniques used by foreign car manufacturers. Innovations such as these, however, cannot occur unless the scientific information base has already been developed. The market may be ready for an innovative advance but may have to wait for science to produce the required knowledge to develop new products.

Innovation is Dynamic—A further complication arises from the dynamic nature of the innovation process. As scientific knowledge is gained and understanding of market requirements increases, changes in the directions of research, development, production, and marketing are required. The people involved also change their perspectives, mature, lose interest, and are brought in when new problems arise. Every change affects the course of the innovation process in varying ways and somehow must be taken into account.

Dynamism occurs not only in tangible and mechanical areas, but also in the realms of the emotions and spirit. A sudden illness or incompatibility of personalities can cause real disruptions. Personal relations and managerial styles are very important and can change quickly when people are working together on a common problem. Differences of opinion, perceived slights, misunderstandings, and even moral and ethical problems all alter over time and need to be resolved for success to occur.

Logic and Creativity in Innovation—As much as one might like to think the use of rational, scientific logic will produce inventions, innovation in most cases is the result of a creative process in which an invention is made, followed by an often long, tedious, roundabout development which leads to the final product. Rational research frequently is used in the development process to aid in solving problems that arise en route, but such use is secondary to creative thinking, although often financially important.

Creativity in innovations occurs during the attempt to cope with many factors not normally considered important by scientists and other technically trained individuals. Chance contacts, serendipitous events, and unpremeditated discoveries can change drastically the effectiveness of the innovation process and the speed with which it is accomplished.

The Role of Communication—Communication plays a major role in the innovation process. For optimum and timely success all the players need to understand each other's roles and coordinate their efforts just as in a theatrical production. Here is where the art comes in. The innovator has the task of melding both intellectual ability and facts to produce new and coherent concepts and marketable products. If members of the team will not or cannot communicate their knowledge and ideas to one another, a common goal can be reached only with difficulty, in an untimely fashion, or not at all.

The Management of Innovation

Innovation starts with an idea. The idea is ultimately embodied in a device, a substantive material, or a process for accomplishing a purpose. The embodiment of the idea requires an interdependence of skilled people—inventors, engineers, mechanics, production experts, financial managers, marketing experts, and salespeople. Thus, innovation requires managing ideas, material, machines, and people.

Good management is even more important in the innovation process than it is in an established corporation. The well-known authority on business management Peter F. Drucker has predicted that the very heart of management involves entrepreneurial innovation and that social and technological frontiers will challenge the manager of the future. Instead of operating in a closed system, as has often been the norm in the past, managers today must cope with constant change while still maintaining continuity with the past—a situation which exists in any innovative atmosphere. Managers of innovation must rely primarily on subjective judgments; a science of innovation management has yet to be developed, and the management standards and procedures developed in the past are not adequate to the present-day requirements of new ventures.

QUALITIES OF INNOVATION MANAGERS

Leaders with special talents, capabilities, and knowledge are required to manage the innovation process. Such leaders are rare, and successful ones stand out from other managers. Why they are successful has been the subject of hundreds of studies over the years, but their secrets still remain hidden even to successful entrepreneurs themselves.

Successful innovation managers combine the talents of inventors, entrepreneurs, and businessmen and women; it is the rare individual who can adequately fill all these roles alone. Therefore, a number of individuals are normally involved in any specific innovation. But each of them resembles each other in certain general ways. Among other things, each must be intelligent, creative, energetic, and have a high degree of integrity with focused goals. Determination, persistence, and singleness of purpose, combined with flexibility, are also key characteristics. Innovation managers must have all of these and, in addition, an acute sense of time. They must know instinctively when to take risks and when to pull back, when to be aggressive and when to compromise, when to be tough and when to be tolerant, how to motivate colleagues and associates, what customers want and how to satisfy their desires, and how realistic but imaginative financing can be obtained and utilized; they must also be able to accomplish all these things within legal, ethical, and societal bounds.

Innovation managers start small and build; they may even be inventors. But in any event, they think they know about inventing, developing an idea, and building a business. They know that it is not enough to organize an effective team of scientists and engineers and expect markets to materialize like magic. They also know that even though a market may be there, the creative people who conceive of a product initially may not be able to undertake its commercialization successfully.

THE INVENTION

The innovation process starts with the inventor. While another person may have better knowledge of market needs and may communicate these to the inventor, it is inventors who originate specific new products or processes with detailed, qualitative functions. Inventors must be insulated from negative influences while they are inventing intensively, and they must have adequate and patient financial support. Risk of failure is substantial.

THE DEVELOPMENT STAGE

When inventors begin to develop a product or process idea, and often even earlier, they need the help of an enthusiastic champion, a person who cannot only give encouragement but also can be realistic about the next steps to be taken—and often actually undertake these steps on behalf of the inventor. Usually this is where innovation managers first enter the picture; they must provide patience, faith, and utter confidence in the worth of the inventor's findings and their own ability to carry through to the marketplace. They must know how to accomplish things through other people. Together, the inventor and the innovation manager can carry the innovation through its developmental phases and into small-scale production. Once this is accomplished, risk of failure has been greatly reduced.

THE GROWTH STAGE

As long as the market is small and the operations remain relatively simple and straightforward, these two individuals can handle almost any situation. However, with company growth, complexities develop requiring a higher degree of organizational ability, and knowledge of finance, manufacturing, marketing, sales, and personal relations usually not found in people who are inventive or have strong entrepreneurial bent. While creative thinking is an asset, creativity itself is less important at this point, since, now, organizational procedures based on sound business principles become essential. Here is where business experience is needed to decide whether or not market needs require expansion and how to develop the organizational capability to accomplish such an expansion. Innovation managers must find financing, obtain other managers, control operations, and deal with governmental and societal influences. Risk of failure at this time is minimized. During this stage inventors and scientists generally have great difficulty in managing their innovation. They are too involved in their brainchildren—trying for perfection beyond consumer needs, attempting to run all areas of the business themselves, being unable to bring in additional people with specialized expertise, or having difficulty delegating authority to others as the business expands.

THE MATURE BUSINESS

As the innovation process enters the mature stage, it usually provides only one or perhaps only a few products or services. Favorable customer response requires organized expansion—sometimes very rapidly, as has happened recently in the home computer field. Successful managers of innovation must be able to anticipate expansion or changes in production facilities and marketing capabilities, needs for financial support, personnel, and raw materials. And they must be ready to modify the organizational structure as necessary to maintain control of all aspects of the operation.

Manufacturing and Production—Manufacturing and production concern the manipulation of materials and devices using human intercession. Managers of manufacturing and production must have a good historical perspective not only on the specific industry and its markets, but also on how new products and processes must be made to satisfy new market needs in the industry. Engineering know-how, together with the ability to listen to and adjust to relevant feedback from marketing and sales experts, is essential. In new ventures, creativity and flexibility tempered by in-depth knowledge of science and technology are needed in order to produce cost-competitive new products.

Marketing Products of Innovation—Marketing and selling new venture products require time, much patience, and knowledge of the right people to approach. Early awareness by potential users of new products usually depends on external sources, such as reports in scientific and technical publications, advertising, and vendor contacts. Evaluation of new products leading to adoption in the market depends to a great extent on personal communication with technical- and management-level people within the users' firms. At each stage in the marketing process the availability, the quality, and the cost of the new products have a great impact on acceptability. The market for which new products are designed requires close and detailed study to determine the role of competitive products, how firmly established these may be, and how long it will take to obtain a profitable return after marketing begins.

Innovation Depends on Optimum Financing—Knowing how much financing is needed and where to obtain it for each phase of the innovation process is crucial. Too much or too little financial support can kill a venture even with good prospects of commercial success. Obtaining the wrong kind of financing from the wrong source is also deadly. Loss of control of a new venture can easily occur unless care is taken to deal with sympathetic financiers with a genuine interest in the overall success of the innovation.

Organizational Structure and Innovation—Within the organization itself the managers must decide whether the optimum results will be obtained under a hierarchical structure, a decentralized organization, some combination of both, or an entirely different organizational structure. The extent to which a bureaucratic system is used must be decided as opposed to a looser managerial procedure which might enhance creativity and productivity. After a study of successfully managed businesses, Thomas Peters and Robert Waterman, Jr., in their book *In Search of Excellence,* feel that the coming epoch of organizational thought will emphasize informality, individual entrepreneurship, and evolution. Recently, successful companies seem to emphasize flexibility in management, sometimes using entrepreneurs as product champions and, at other times, using a tough, autocratic approach, whichever seems appropriate under the circumstances. Past managerial wisdom, on the other hand, has emphasized the rise of military-like organizations which allow only limited ways to organize and solve problems.

GOOD PLANNING IS ESSENTIAL FOR A SUCCESSFUL INNOVATION

Planning is essential for the success of the innovation process. Even the creative acts of the inventor should be planned to some degree, being careful, however, not to go so far as to extinguish the creative spark. Planning reduces uncertainties in the risks; helps to reduce the effect of or eliminate competitive or externally generated surprises; enables one to distinguish among alternatives in the use of time, effort, and resources; and defines and redefines market potential. Planning also has a dynamic component; it should be done frequently as the venture matures.

Intellectual Aspect of Innovation—Successful management of innovation by innovation managers requires that they grow with the business. They must understand and take into account new and important factors related to expansion of plant and personnel and to the plant's managerial and financial requirements. They must turn their attention to optimizing resources and profits. They must develop strategic plans for the future and need to understand, manage, and control interrelations among these factors.

Societal and Political Content of Innovation—Management of innovation has a large societal and political content. Factors in these areas bring the need for applying ethical, moral, and legal judgments to the management of an enterprise. Successful management takes into account consumer needs; customer satisfaction; environmental impact, both favorable and unfavorable; and relations with competitors, community, and, in some cases, international entities. All legal restrictions, regulatory agency requirements, and health and safety regulations have to be understood and managed.

Enhancing Innovation

INCREASING SCIENTIFIC KNOWLEDGE

Practically all technological innovations rest on a scientific base. Even innovations in service industries ultimately are dependent on scientific principles. The advance of cable television rests on functioning space satellites; electronic banking requires computers; automobiles are built at lower cost by using robots. But until a basic knowledge of scientific principles has been acquired, innovation in a given industrial area is not possible. With such a base, however, innovative ideas proliferate.

Continual scientific research is essential to increase this fund of knowledge; both fundamental and applied research must be supported. Fundamental research is best performed primarily in an academic setting and is primarily supported by government agencies and public and private philanthropies. Debates take place annually relating to the magnitude of expenditures of tax generated public funds to be expended in support of fundamental research. Major support from this source in 1982 amounted to $4.6 billion, about 50 percent of which was provided by the National Institutes of Health (NIH) and 15 percent of which was provided by the National Science Foundation (NSF). Most of the total funding was for mission oriented research in the Department of Defense, the Department of Energy, the Department of Agriculture, and similar agencies. Funding of fundamental research by philanthropic organizations and industry is currently only a fraction of public funding, perhaps 10 to 12 percent. Industry research funding is mostly for applied research to develop or improve specific new products or processes.

Increasing the funds available for scientific research would be expected to enhance innovation. Such funding should come from all sources, not solely from public coffers. Since support of basic research is a long-range, high-risk activity, results may be decades in coming to fruition. This presents hard choices for these funding decisions relative to the financing of other important commercial societal needs.

DEVELOPING TECHNOLOGICAL EXPERTISE

The mere availability of scientific information is not itself adequate to ensure the design of marketable products or processes. The scientific information must be analyzed, dissected, rearranged, and resynthesized into forms that can be marketed profitably. The transformation of scientific information into useful products involves people with technological engineering, marketing, economic, and financial expertise and is generally referred to as "development."

Any program to enhance the rate of innovation and increase productivity thus requires a systems approach, one that integrates the whole gamut of activity involved in bringing ideas from initial concept to valuable products. The innovation process is much more complicated than a simple step-by-step evolution from the base of scientific knowledge. Scientific knowledge and technological development must proceed concurrently. They must interact with each other through feedback loops, information-gathering, and dissemination centers. Fueling such interactions is market demand and the likelihood that profits can be made from the sale of new and useful products and processes. However, it is important to recognize that completion of the innovation process will differ in a number of ways, depending on whether or not market needs, technologically, are being filled and/or scientific advances are being developed.

DEVELOPING AN INNOVATION MANAGEMENT TEAM

Many students of the innovation process rate highly the freedom of action encouraged in the American democratic atmosphere. They feel the inquiring mind and inventive spirit of the American citizenry coupled with the ready availability of venture capital and the presence of many entrepreneurially minded technologists, make it easier, compared with other countries, to start new companies in the United States. Bringing together the right combination of people to realize the inherent potential in this favorable situation is still an art and often depends on fortuitous circumstances rather than detailed planning based on scientific principles.

Better understanding of the innovation process and its interacting factors cannot but help to increase the likelihood of ultimate success. Inventors not only must understand available scientific knowledge, where to find it, and how to use it, but they must also understand what technology exists and is needed to develop their invention, where to obtain it, and how to use it. A dedicated champion with the proper understanding of both the market and the product to be marketed and an adequate source of capital which can be relied upon for years of scant return are absolutely essential to success. Financial investors need to understand the needs of both inventors and business managers to tap the scientific data base and to acquire and use needed technological resources in order to provide marketable products. If these individuals find difficulty in working together for common ends, the enterprise will fail regardless of how sound the base of scientific knowledge or how substantial the market may be.

UNDERSTANDING THE MARKETPLACE

Innovation managers must have a thorough understanding of the position of their products in the marketplace. Too often this understanding is limited or based on insufficient data. Avoidance of this seemingly obvious, fundamental error would greatly enhance the success of innovative ventures.

Innovative products and processes almost invariably push older ones out of the marketplace. The size, complexity, and pricing structure of the existing market must be analyzed, and some idea of where in the market the new products or processes fit must be determined. Timing of market entry, obsolescence of both old and new products, and geographical factors need to be taken into consideration. Knowledge of the nature, strength, and possible response to competition of competing companies is helpful, but it can only be obtained through speculative judgments based on best estimates and intuitive thinking. Early market testing is essential to help prevent gross mistakes, but these tests must not be relied on as an absolute gauge of consumer demand or acceptability. In those industries where patent protection is important, competitors' basic patent positions are necessary to discover and keep in mind.

Understanding the product life cycle concept is essential; a business built on a single product or process may follow the conventional profit life cycle and decline as the product matures, eventually expiring as market acceptance disappears. Successful businesses have a number of products or processes which continuously grow mature, and are replaced by new ones, producing an averaging of profits over extended periods of time.

PATENTS AND COPYRIGHTS

Patent rights ownership is very important in the chemical and pharmaceutical industries to protect newly marketed products from competitive pressures so that the costs of research and development can be recouped. Small businesses also benefit from patent rights ownership as a protection against large, predatory companies. Patents are less important for large companies and the mechanical, electrical, electronic, and service industries. Where patent coverage is essential, obtaining strong claims that can be enforced effectively against unlicensed competitors enhances the innovation process.

Copyrights ownership can play a major role for companies directing their efforts primarily toward marketing and other services. For example, recent court decisions have provided copyrights with a major role in the protection of computer programs from misuse by unauthorized parties.

GOOD COMMUNICATIONS ENHANCE INNOVATION

The success of the innovation process depends on good communications among people at all stages from the initial conceptualization through the life cycle of the commercialized products and processes. The means used to communicate and the people involved in it vary appreciably from stage to stage and change almost constantly.

At the outset, inventors obtain their innovative ideas from almost any source—the published scientific and technical literature, unpublished reports, personal contact, the media, or even daydreams. Their personal experiences are their frame of reference; they ask themselves the question, "What would happen if I did this or that?" Communication with others may be limited or nonexistent at this point; nor is it usually necessary until after their ideas have been tested in a laboratory or, perhaps, in a limited way in the marketplace.

As the innovation process develops, additional people become associated with the inventor and his or her early colleagues. One of these may play the role of an innovation manager. Communication now takes on a different, more complex aspect. New, broader sources of information are needed; communication lines are lengthened; a number of people, rather than just two or three, must be kept informed. Time becomes very important; analyses of available information must be made; bits and pieces of information must be integrated. Innovation managers and their associates communicate with outsiders—financial supporters, marketing analysts, legal counsel, and tax experts. Each of these outsider experts speaks a different language, and the inventors and/or entrepreneurs must learn, if they do not already have the facility, how to speak the same language. While some communication will be through written literature, as in earlier stages, most will be by personal contact in private meetings, both internal and external conferences, and at professional society gatherings. As more and different groups contribute to the activity, technology-interface problems arise, and personality conflicts begin to surface. These unfavorable situations must be resolved as soon as they are perceived in order to conserve momentum and minimize lost time.

Coordination of all efforts now becomes very important. Successful innovation projects involve much more communication, both internally among project personnel and externally with colleagues outside the project, than less successful projects. Outside communication of the successful groups includes contacts within their own specific discipline and others as well. Any action which promotes frequent contact within and among disciplinary groups improves research and development effectiveness.

As the communication network grows and expands, individuals who possess a special facility for communications emerge. Others naturally turn to these individuals for help in arranging contacts and obtaining information. These key people become "technological gatekeepers" channeling information flow in and out of the organization; they are especially important in large, geographically separated organizations. Generally speaking, such gatekeepers are high-technical performers and busy first-line supervisors, interested in a wide variety of outside activities. Management, entrepreneurial management especially, is well advised to identify these individuals and encourage and develop their capabilities.

When an innovation enters the commercial stage, good communication in all its aspects must be developed in all facets of the operation. This is particularly important at the time of first marketing. Customer reaction and its timely and accurate feedback to manufacturing and internal marketing departments are essential to make sure the products fill real market needs and produce satisfied customers. While communication needs change drastically in mature organizations from what they were in the early stages, sensitivity to these needs must be present throughout the innovation process.

The Role of Venture Capital

Adequate financing is essential throughout the entire innovation process. Unless financially sponsored by their firm or another interested party, inventors have great difficulty in accomplishing initial experimentation and testing of their ideas. Without sufficient funds, months and even years may be required just to produce a prototype or the first successful test. This situation is not all bad, however, since time, as well as money, is required for inventors to become aware of problems to be solved and means to be devised for their solutions. Backtracking and rethinking are normal and necessary to avoid falling into unforeseen traps. The availability of funding cannot substitute entirely for time during the early stages of innovation.

The nature, type, and amount of capital, as well as the philosophical and motivational attitude of the person or group furnishing it, change as the innovation process matures. In the initial stages minimal capital is required, prospects of eventual return are low, and the length of time before any return is received may be quite extensive. During this period opportunistic venture capitalists may find that it is expedient to loan money, with or without interest charges, in return for a stake in the enterprise. They must be patient and be prepared to endure disappointments, as well as be willing to provide additional funds occasionally.

When products are developed and marketing begins, additional operating capital is required more frequently and in larger amounts. It is necessary to support manufacturing and marketing efforts of sufficient size over a period of time that is long enough to indicate acceptability of the new products. The risk to capitalists is reduced, but the amount of money at risk is substantially increased, perhaps as much as ten times that required during the initial research, development, and testing stages. In addition to loans, public sale of bonds, debentures, or stocks, it is frequently necessary to raise adequate capital to carry a new venture through this phase of growth. Raising capital in this manner, however, entails dilution of ownership since purchasers of stocks or bonds own equity in the company.

AVAILABILITY OF VENTURE CAPITAL

Until the 1960s and 1970s the use of venture capital was considered a black art surrounded by an incomprehensible mystique, and the venture capitalist was perceived as something of a high-stakes gambler. This situation has changed greatly in the last two or three decades, and today's venture capitalist is regarded as a rational businessman or businesswoman with a well-studied understanding of the venture capital process and an organized approach to funding new venture.

While venture capital appeared to dry up in the early 1970s, in actuality there has always been more than an ample supply for small businesses and new enterprises backed by talented people with good business ideas with only modest funding requirements. The apparent lack during the 1970s occurred primarily in financing the expansion of already existing businesses whose marketing of products was adversely affected by depressed economic conditions. In the 1980s this situation reversed as the general economy became more favorable. Venture capital is now being perceived as plentiful, especially for those companies in high technologies—computers, electronics, and bioengineering, for example.

FINDING VENTURE CAPITALISTS

A major problem inventors and entrepreneurs face is finding compatible venture capitalists with sufficient means to support a new venture for the necessary length of time. Venture capital may come from investment bankers, mutual funds, individuals, family trusts, insurance companies, pension funds, commercial banks, corporations, public and private venture capital companies, small-business investment companies, or private partnerships (including research and development tax shelters). Each of these sources has different objectives, motives, and methods of operation. A few are interested primarily in frontier research; others, only in high technology with high return (albeit at high risk); still others, merely in established companies with products already on the market. Some have interests only in certain areas, such as chemicals, petroleum, or heavy industries; and others are involved solely in marketing proven products or services.

In general, venture capitalists search for high-risk, high-payoff situations. They regard the desired return on their investments to be in the range of 500 to 2,000 percent. As a rule of thumb, a 300 percent return in four years or a 400 percent return in five years is acceptable. However, those who were patient enough to be involved at very early stages of an innovative venture expect even higher returns over longer periods of time.

Innovation managers seeking venture capital must evaluate their needs realistically. If they raise more capital than needed at any given time, they are in effect selling more ownership in their venture than needed. On the other hand, insufficient funding leads to potential disaster resulting from underestimating or understating their requirements. The successful innovation manager also knows that financial requirements generally follow a relatively smooth curve, whereas obtaining capital is usually a stepwise operation.

Impediments to Innovation

The innovation process is hindered by any number of unfavorable circumstances. Some arise from internal difficulties, but many more emerge from external sources unconnected with the specific innovation under development.

INTERNAL IMPEDIMENTS TO INNOVATION

Most internal impediments to innovation are unrelated to the technical merit of the invention itself, but, instead, they arise from either the inadequacies of the people involved or unforeseen external circumstances.

Inventor Attitudes—Many inventors are eccentric; they try to beat the laws of nature, have an obsession they cannot or will not drop, and are forever searching for the nonexistent pot of gold. Inventors of this type are doomed to failure, because they do not possess sufficient scientific and technological understanding, knowledge of the marketplace, or adequate financial and economic know-how for them to succeed. They may attract entrepreneurial or even venture capital attention for a brief time, but their inventions (almost invariably without merit) wither and die, taking their backers with them; the innovation process is never completed.

Resistance to Innovation—Innovation resistance is a very real problem, not only within an organization, but in the marketplace as well. Recognition of this fundamental characteristic of human nature and devising means to cope with it are hallmarks of the successful innovator. Overcoming resistance to change has been the subject of much study by sociologists and pragmatic trial-and-error experimentation by managers and marketing experts. Present thinking states that resistance primarily results in regard to social change, not technical change, and from perceived changes in human relationships that involve personal prestige, worth, and interactions. Communicating the need for change beforehand, discussing the possible results of the change with the people who will be affected, and providing examples of benefits from the change are all useful techniques to minimize such resistance.

Poor Management—A Denver Research Institute study of 200 innovations that failed after initial commercialization reports that poor management accounted for 23.5 percent of innovations cancelled, shelved, or inordinately delayed. Many management errors seem preventable. Over 33 percent of the management errors involved market factors which management could have anticipated. For example, one company, at great cost, developed a welding torch for repairing automobile bodies only to find that potential customers viewed the torch as a fire hazard. Almost 10 percent of the failed innovations resulted from lack of a market; approximately 7 percent were blocked by competition; about 5 percent ran into patent infringement problems or antitrust law violations.

General Georges F. Doriot of American Research and Development Corporation has provided an interesting summation of management errors found in that organization's experience with start-up companies. They include:

1. becoming too emotionally involved in an idea or individual;
2. excessive delays in foreseeing problems or applying corrective measures;
3. the inability of entrepreneurs to grow with the business;
4. the inability of technically trained managers to stay knowledgeable in their fields;

5. acquiring a bureaucratic structure too early;
6. a lack of foresight;
7. excessive belief in the product under development;
8. inadequate knowledge of competition and the marketplace;
9. pricing products too low at the start of marketing;
10. poor knowledge of costs, overhead, and inventories;
11. a lack of understanding of the difference between operating profitably and having a profitably growing, competitive enterprise;
12. the premature breakup of the original team or, conversely, too great a loyalty to the original team; and
13. a greater interest in personal return than in building a viable enterprise.

From these limited examples of poor management, it is apparent that managers could save good innovations by asking the right questions at the right times.

EXTERNAL IMPEDIMENTS TO INNOVATION

Innovations undertaken without due regard to economic, environmental, and societal factors are in peril from the start. For the most part, economic influences arise from outside the immediate venture. These include such items as inflation, general economic recession, unforeseen political situations, or public opinion. These factors must be considered at the very beginning of innovations by inventors, entrepreneurs, and investors. As the innovation process proceeds, reevaluation of these factors must be undertaken frequently.

Public Opinion—Currently, public focus is on the contributions science and technology can make in the solution of broader societal problems. Critical changes have recently occurred in the international environment affecting world trade conditions and the availability of energy and raw materials. While some people believe these new focuses are cyclical and that profound changes will not occur in the future, the majority believe that fundamental changes in our society and economy will take place over the next few decades. Extrapolating from the extraordinary changes that have already occurred in the electronics industry (embodied in the swift changes being brought by the proliferation of the use of computers) and from the unpredictable, imminent, and profound effects that the infant industry of biotechnology is beginning to produce, it is safe to predict that the choices made by today's society will determine the society of tomorrow. These choices must be made with as much knowledge and moral integrity as can be brought to bear. The mere marketing of products for profit must be tempered with consideration of the larger and long-range consequences on society as a whole.

Government Involvement in Innovation—New and more restrictive laws and regulations are being promulgated in an effort to maximize benefits to the public. However, much of this activity has been reactionary rather than progressive, costly and inhibitory, and so far often limiting the optimum societal use of science and technology. To ensure a proper balance between risk and benefit will require much more study and discussion, as well as action in broader societal terms. Private sector priorities and judgments must be used as a major element in planning economic growth with the full realization by public figures that use of public funds may create private profit in the process of accomplishing national objectives.

During the 1970s and the 1980s, a piecemeal approach was taken by various public and private sectors directed toward improving conditions or enhancing the motivation in different areas of the innovation process. Many of these efforts have been misdirected or treated symptoms rather than basic problems. For example, Congress has "reformed" the patent laws with the objective of making it easier for research universities and institutes to obtain patent ownership of inventions made with government funding. However, such organizations have no means for developing the patents they own and must either rely on some patent-service agency or independently enlist individuals or industrial companies to recognize market needs and develop products to meet those needs.

Much federal-level discussion has occurred relating to the establishment of cooperative technology centers, centers of academic excellence, and similar institutions to increase the collaborative efforts among universities, industry, and government. Problems immediately arise regarding which party will play the dominant role in program planning, allocation of resources, and management of these centers and as to how the results and benefits arising from the work done at such centers will be utilized. As a consequence of an inability to resolve these problems, substantive action to implement these suggested activities has not yet occurred. The government-industry-academic interface has been and is continuing to be an area of intense discussion and study. While it is conceded that more effective cooperation among these sectors would enhance innovation, appropriate means for accomplishing this purpose have so far eluded definition, except in a few special cases.

Recognizing the desirability of transferring government owned technology to the private sector, the National Technical Information Service (NTIS) has been charged with disseminating scientific information and patented inventions developed in government research laboratories. However, only a small budget has been allowed and a staff of less than a dozen people provided. The scientific concepts disseminated, for the most part, have essentially no relations to civilian market needs since they were developed primarily for government purposes such as defense and space exploration. The NTIS program has been limited to writing and publishing a huge volume of descriptive material which is made available only at a few selected locations. While its availability is made known through listings in journals such as the *Federal Register* and government procurement notices, such methods of information dissemination are almost totally ineffective even though accomplished at substantial cost.

EFFECT OF LEGAL CONSTRAINTS ON INNOVATION

A surfeit of international, national, state, and local laws and regulations impinges on the innovation process beginning at its earliest stages—even while accumulation of scientific and technological information is occurring. Awareness and observance of these statutes are essential, since they are designed ostensibly to aid innovation, to regulate how innovation is accomplished, or to inhibit or prevent abuses—all done in the name of the common good. Observance of these laws and regulations inevitably leads to bureaucratic procedures and large amounts of paperwork that entail extensive clerical and bookkeeping activities. Such peripheral consequences must be kept in mind and taken into account throughout the innovation process.

In the late 1970s and early 1980s, the federal government sought to ease the inhibitory nature of a number of these laws and regulations and to provide further incentives to innovation through new laws. Reform of the patent laws, favorable provisions in authorization and appropriation acts for public-grant agencies, and favorable tax treatment for research and development expenditures were put into effect. However, these are all of a piecemeal and relatively timid nature and, while helpful, a long way from having any major favorable influence on the innovation process. Innovative leaders take into account these legal aids, but they do not depend on them to help reach their goals.

Food and Drug and Similar Regulations—A special case of restraint on innovation in the chemical and pharmaceutical industries is posed by the Food and Drug Administration's regulations and those promulgated by other environment, health, and safety agencies. The need for such regulations is not questioned, but the excessively restrictive nature of some of the regulations, as well as the inappropriate way in which some regulators apply them, have increased the cost and lengthened the time necessary to introduce new and useful drugs. In addition, they have inhibited the scientific research directed toward the discovery of new chemical entities of therapeutic value.

Science and Technological Policy

Innovation is a major source of economic growth; it can help control inflation, create jobs, and achieve a more satisfactory balance of trade. It is the single most important contributor to productivity improvement. Properly managed, it can contribute significantly to the improvement of living standards. In this broad sense innovation embraces not only technological changes but also includes new methods of management, financing, marketing, and distribution.

The complex and dynamic process of innovation involves a number of main elements, universities and their scientific information base, inventors, entrepreneurs, businessmen and businesswomen, the public, and the government. Accordingly, it would seem desirable to find ways to improve and enhance the interrelationships among these elements for the benefit of all. Throughout the innovation process, large investments of time, effort, skill, and money are required. Such investment, although highly risky, must be applied at every stage with an inventor-entrepreneur-businessperson as the driving force.

Innovation is accelerated when businesses invest in new plants and equipment; conversely, new and advanced technologies create a large demand for capital investment. When demand for improved products occurs at the same time as innovative research produces new technologies, economic growth occurs. Thus general trends in the rate of capital investment relative to gross national product reflect the vigor of economic activity. In the United States in past years, changes in the national cash flow and investment in plant and equipment have moved closely together, but since the early 1970s, cash flow has exceeded capital spending by a much larger and continually widening margin, suggesting an accumulation of cash by American businesses.

A *Business Week* survey found that industrial leaders were reluctant to invest their cash reserves because of uncertainties about the course of inflation and federal wage, price, regulatory, and energy policies. In addition, stringent conflict-of-interest rules have kept the best people out of government and inhibited access to industry experts. Most meaningful of all has been the reduction of potential rewards that are perceived to result from undertaking high-risk capital investment.

Many people believe development of a comprehensive formal policy at the federal government level is necessary to combat or alleviate uncertainties and to encourage an increased flow of innovation. However, most thoughtful experts in both industry and the private sector believe that an overall government policy would be too rigid and too difficult to enforce meaningfully in view of constantly changing economic and societal requirements.

The Industry Advisory Committee to the Federal Domestic Policy Review on Industrial Innovation has recommended that the areas of highest priority for policy change lie in regulatory reform and provision of tax incentives. The regulatory reforms are recommended to include better assessment of cost-risk factors and to provide guidelines for taking optimum advantage of industry's capacity to satisfy the environmental health and safety needs of the public through innovation.

The committee feels a specific preplanned policy may be helpful in devising tax reductions designed to strengthen investment incentives for plant and equipment. However, any reduction in tax revenue poses a dilemma: such a reduction could cause federal deficit increases that lead to higher inflation rates. Congressional action in the early 1980s provided a few minor revisions in the tax laws designed to favor additional investment in innovation, but more creative thinking is still needed on this issue.

Improvement in the theoretical assumptions made by economic planners in calculating revenue impacts of alternative tax policies is greatly needed. Economic planners and forecasters are hindered by a lack of understanding of the interplay between the numerous factors affecting their theories and the results of their predictions. Present-day models of the economic structure are simply not appropriate, in the opinion of many experts.

The United States is such a large and diversified country and so indoctrinated in democratic principles that central planning of a science and technology policy by a small, albeit possibly representative, group of either elected or appointed officials does not seem appropriate. Such an approach may be desirable for small countries with limited resources or for underdeveloped countries, but the examples of central planning in the large socialist countries do not inspire confidence that this mechanism will provide adequate guidance for the future.

SOME GENERAL FACTORS IN INNOVATION SUCCESS

Reports resulting from international conferences held in the late 1960s and during the 1970s by the United Nations Office of Economic and Commercial Development summarized the factors believed to be pertinent to innovation successes in the United States. These include:

1. the presence of technologically oriented universities geographically located so that a business climate encourages the cooperative generation of new ventures;
2. entrepreneurs who have previously successful entrepreneurs as examples to follow;
3. the existence of institutions and venture capital sources comfortable with technologically oriented innovators and possessing the rare business appraisal capabilities needed to translate inventions into profits; and
4. good communication networks provided by close proximity to and frequent consultation among all essential personnel in the innovation process.

EXAMPLES OF SUCCESSFUL INNOVATIONS

So many factors are involved that pinpointing any single one or even several major ones responsible for a particular successful innovation is next to impossible. Similarly, it would be foolish to follow slavishly in the footsteps of a successful venture since the rules of the game change, and the players and markets are different the second time around. However, a few examples of successful innovations may illustrate some of the reasons they prevailed.

3M Company—An article in *Innovation* (September 1969) states that 3M is considered one of the best-managed industrial companies in the United States, compiling a remarkable growth over the thirty-year period from 1940 to 1970. Sales increased 120 times, earnings increased at an annual rate of over 13 percent, and market value rose at an annual rate of 18 percent. These results reflected 3M's market philosophy of "look for the uninhabited markets." By 1969 approximately 25 percent of its sales were from products developed in the previous five years. In large part its success came from an exceptional ability to find and develop entrepreneurs from within the company. Market analysis at 3M goes hand in hand with the evolution of product ideas. Entrepreneurs from 3M evolve to be, perhaps, 25 percent technical expert and 75 percent entrepreneur.

Masers and Lasers—Working on a grant from the Department of Defense, Charles H. Townes in 1951 conceived of a means for amplifying electromagnetic radiation that produces coherent beams of microwaves and light—now known as masers and lasers. A patent covering the initial invention was issued in 1959, to be followed over the next two decades by a large number of succeeding patents to cover modifications and improvements. Over 100 companies became involved in developing the technology, which, at first, was devoted to military uses. Nonmilitary products did not appear for some ten years after the initial patent was published. Today, the many uses of these devices have become a multibillion-dollar industry whose greatest impact caused a revolution in both land based and satellite communications—to say nothing of check-out counters in supermarkets!

Platinum Based Antitumor Drugs—Supported by both federal and industrial grants, Barnett Rosenberg in the late 1960s discovered that certain chemical complexes of platinum suppressed reproduction, but not growth, of mammalian tumor cells. Patents were obtained covering these materials and their use, and they were subjected to extensive toxicity, teratogenetic, and clinical testing under both government and industrial auspices. A way was found to overcome their initial high toxicity, and they were finally brought to market late in 1978 by Bristol Laboratories after the long and expensive development period required to obtain Food and Drug Administration clearance. Today these products have a commanding position in the worldwide treatment of many intractable cancers. In addition, great scientific and industrial interest has been spawned in the search for therapeutically active analogs based on platinum or other precious metals.

Mushroom Nutrient—As a result of an intensive study of the nutritional requirements of mushrooms, L. C. Schisler developed a feeding formulation and procedure for its use which greatly improved the quality and yield of commercially produced mushrooms. The patent covering this invention was licensed to a partnership that formed a new venture to manufacture and market the nutrient formulation. The product enjoyed almost immediate acceptance and is currently used extensively by the mushroom industry in the United States and Canada, and good prospects for foreign sales are also evident. The venture is now developing additional related products and services that are expected to form a solid basis for future growth and long-term viability.

EXAMPLES OF INNOVATION FAILURES

There are uncountable reasons why promising ideas never reach the marketplace or are withdrawn after initial market penetration. It would be fruitless to make a comprehensive listing, but a few examples of failed innovations may be illustrative and illuminating.

The New World Computer Company—This company went public in 1978 and, additionally, raised $3.4 million. It is now short of cash for a reason not uncommon among pioneering technology companies—constant dissatisfaction with its products. After developing an excellent computer drive, the cofounding partners decided the drive had insufficient capacity; so, instead of going into manufacturing, they went back to the development laboratory; later they decided to miniaturize their product; next, they entered into an unfruitful joint venture with an overseas company; and now they have acquired another company and its entrepreneurial president. While there is still hope for the future, the company currently has no products on the market, and its credibility has been seriously damaged.

Prestressed Concrete for Highways—In July of 1983, the *New York Times* carried a news item describing the possible use of prestressed concrete for highway construction. The procedure uses about 33 percent less cement, 50 percent less steel, and results in lowered maintenance, fewer cracks, and fewer potholes compared with current methods for the construction of concrete highways. The Federal Highway Administration is preparing a design and construction manual which will authorize the concrete's use for highways. Although test results in the United States and Europe have demonstrated its effectiveness, neither the cement nor the steel industries have shown any interest in commercializing the process. Neither industry perceives increased profits nor other benefits to individual companies. Prestressed concrete experts summarize the situation by commenting that new ideas need a group to promote them, and this idea has no such group nor any other driving force behind it. Furthermore, state and federal highway officials, who should be expected to use the idea as a major cost saver, are ultraconservative and unwilling to take the risk of using anything new when they know the old ways so well. This idea obviously needs an entrepreneur with a knack for convincing die-hard suppliers and customers of the substantial societal benefits of the idea, as well as to assemble a new venture that can become profitable marketing this process.

Synthetic Perfume Bases—The inventor of a useful chemical procedure to produce synthetic base materials for the perfumery and flavoring industries formed a new venture to develop and market these chemicals. Lacking management and marketing expertise, he formed a cooperative undertaking with an experienced entrepreneur, purchased production facilities, and formed a relationship with an experienced marketing organization. These moves overextended his financial capabilities, and a market for his products could not be developed quickly enough to produce an adequate cash flow that could sustain production. As a result the company was forced into bankruptcy.

Ion-Exchange Strengthening of Glass—This process was envisioned as a means for strengthening glass for automobile windshields and architectural use. Although extensive development was performed, the expense of the final product was not competitive with the plastic-laminated glass commonly used for these same purposes. A ruling by the Food and Drug Administration in the early 1970s that mandated the use of shatterproof material in eyeglass lenses revived the technology. However, subsequent development of moldable crack-resistant plastic lenses has limited drastically the market for the strengthened glass. Prospects for development of new uses for this process in the future remain dim.

Summary and Conclusions

A firm base of scientific information and a deep understanding of the marketplace are the essential requirements for a successful innovation. Inventors, entrepreneurs, and businesspeople—each with their special talents and expertise—are needed to put the process into motion and to bring it to a successful conclusion. The innovation process is complex and dynamic, full of pitfalls and opportunities, and subject to many influences—internal and external, predictable and unpredictable. To negotiate a successful outcome requires unusual ideas and outstanding people working together with dedication and goodwill for a common benefit.

Niels Reimers

5

The Government-Industry-University Interface:

Improving the Innovative Process

Introduction

As a society moves from an agrarian to an industrial to an informational economy, the interest in innovation quickens. Specific factors that increase our concern about innovation abound in the United States. Basic major industries, such as steel and automobiles, falter, and increasing quantities of foreign goods appear in our marketplace. We observe a year-by-year continuation of a negative balance of payments and high unemployment.

This concern about innovation is evident in other industrialized countries as well. While Japan might be considered to be an exception to this worldwide concern, it is redoubling its efforts to encourage innovation. In addition, Third World countries are making efforts to enhance their ability to compete in world trade through innovation. Their comparatively low wage scales become competitively advantageous for fewer products

NIELS REIMERS *is the founder and director of the Office of Technology Licensing at Stanford University. Mr. Reimers is the past president of the Licensing Executive Society, U.S.A. and Canada. Previously, he was with Ampex Corporation and Philco-Ford Corporation. Mr. Reimers has lectured and written numerous papers on the licensing of basic technology.*

as automated production reduces the labor component of the end product.

Even those countries which, because of their high level of natural resources in comparison to population (such as the U.S.) have been able to enjoy a comfortable standard of living must also look toward innovation as a means to compete in future world trade as their resource-to-population ratio diminishes.

Countries are seeking to leverage their intellectual capacity through innovation and production of high-technology products. In this search for innovation, the linkage between the basic research discovery and the commercial product or process is of particular interest. This chapter intends to review some factors that affect innovation in the United States at the three-way interface between the university, industry, and government.

Overview

There are changes to be made to improve U.S. innovation at the interfaces between government, industry, and universities, even though, on the whole, the system works well enough to be the envy of other countries which seek to find their own formulas for innovation. The government's primary contributions to U.S. innovation are indirect, such as tax policy and support of research programs at American universities. The government's direct involvements, for example, the synfuel program, are, by and large, unsuccessful and divert resources better used elsewhere.

Spin-off innovation from present military and space programs, as well as national laboratories, appears modest; justification for these programs must be based on rationale other than contribution to U.S. commercial competitiveness. Diversion of national, human, and financial resources to the world's largest military program appears the greatest governmental influence on U.S. commerce. That the growing concern for military security may have a more subtle effect, the eroding of our national optimism, and hence innovative spirit, is a thesis briefly explored.

Technology and information controls in the United States seem to be increasing. Much debate ensues as to whether such controls, often confusing and subject to frequent change, are or are not helpful to national security. There is little debate on another effect of rigid controls; scientific research, the underpinning of innovation, does not flourish under secrecy.

A number of university-industry linkages are reviewed. Much public attention has been given to initiatives such as university research parks, patent licensing, and research collaborations with industry. But the greatest contributions to U.S. innovative capacity come in two forms. First, and most significant, is the university graduate who brings to industry the fruits of training in university research programs, overwhelmingly funded by federal and state governments. The research findings of the faculty and students are the second major contribution of universities to U.S. innovation. These findings are promptly and openly disseminated through various forms such as journals, conferences, seminars, industry affiliate programs, and, yes, through the graduated student.

Industry, the central participant in the process of innovation, delivers the end result, making use of the welcome resources (such as the graduated student) that society provides and overcoming the unwelcome impediments (such as technology export controls) that society imposes. On balance, those resources have been positive; however, though U.S. industry has led the world in innovation, signs suggest that this lead is slipping.

Overspecification, overregulation, and rigid planning produce corporate environments not helpful to innovation. Innovation appears to flourish more in less-structured ("skunkwork") operations, as will be discussed later.

The Historical Role of the U.S. Government in Innovation

The Magna Carta of innovation was certainly the Statute of Monopolies passed in 1624 by the English Parliament. This law prohibited all monopolies and restraints of trade. But it recognized patent monopolies were important both to reward the inventors and to promote technical progress and innovation in society. Other countries desiring to enhance economic freedom and growth adopted similar statutes. Except for this legislation, governments in most free-market economies appear to have had little direct influence on innovation and industrial growth.

As America entered the twentieth century, "trust-busting" antitrust legislation was enacted to curb monopolies which constrained competition, controlled prices, and had a deadening effect on innovation. Otherwise, the government was relatively quiescent with respect to innovation until the Great Depression of the 1930s, when regulatory creep began. This changed dramatically with the advent of World War II when the federal government realized the value of research and development, and corporate contracts and basic research grants in universities became dominant support factors.

GOVERNMENT SUPPORT OF RESEARCH

Following the war, the Office of Naval Research developed an efficient and effective program of grants to university scientists. This program, extended by other government agencies, produced the scientific and technical manpower necessary for "high-technology" industries, as well as many of the scientific discoveries that underlay the important innovations made in mid-century.

Today government is such a pervasive factor in research and development that its *overdirected* involvement could harm innovation. Countries with planned economies (such as the Soviet Union) have lagged far behind market oriented economies in commercial innovation. With few exceptions (such as the space program), the attempts that the U.S. government has made in "directed" innovation have been notably unsuccessful also (e.g., the synfuels program). Frederick-Carl Beier, director of West Germany's Max Planck Institute for Foreign and International Patent, Copyright, and Competition Law, has suggested that a motto for the appropriate balance should be: "only as much government as absolutely necessary and as much private industry as possible."

Current worldwide competition requires continued government involvement in support of university research to produce scientific and technical manpower, as well as to enable the breakthrough innovations resulting from the research that allow the U.S. to compete successfully in world trade. Government can assist innovation in a free-market system through the direct support of research, support of graduate education, and indirect market incentives. An example is the establishment of needs that results in a market "pull" toward technological solutions, rather than a government planned "push."

Major innovations or "breakthroughs" often arise from undirected research. But, as Ralph Gomory, vice president and director of research at IBM Corporation, noted (in a May 6, 1983, article in *Science* magazine): "Real breakthroughs do occur; they are rare and stunning events. The more common course of technological evolution is steady year-to-year improvement, and when that is rapid and persistent, the results are just as revolutionary."

A Path of Innovation

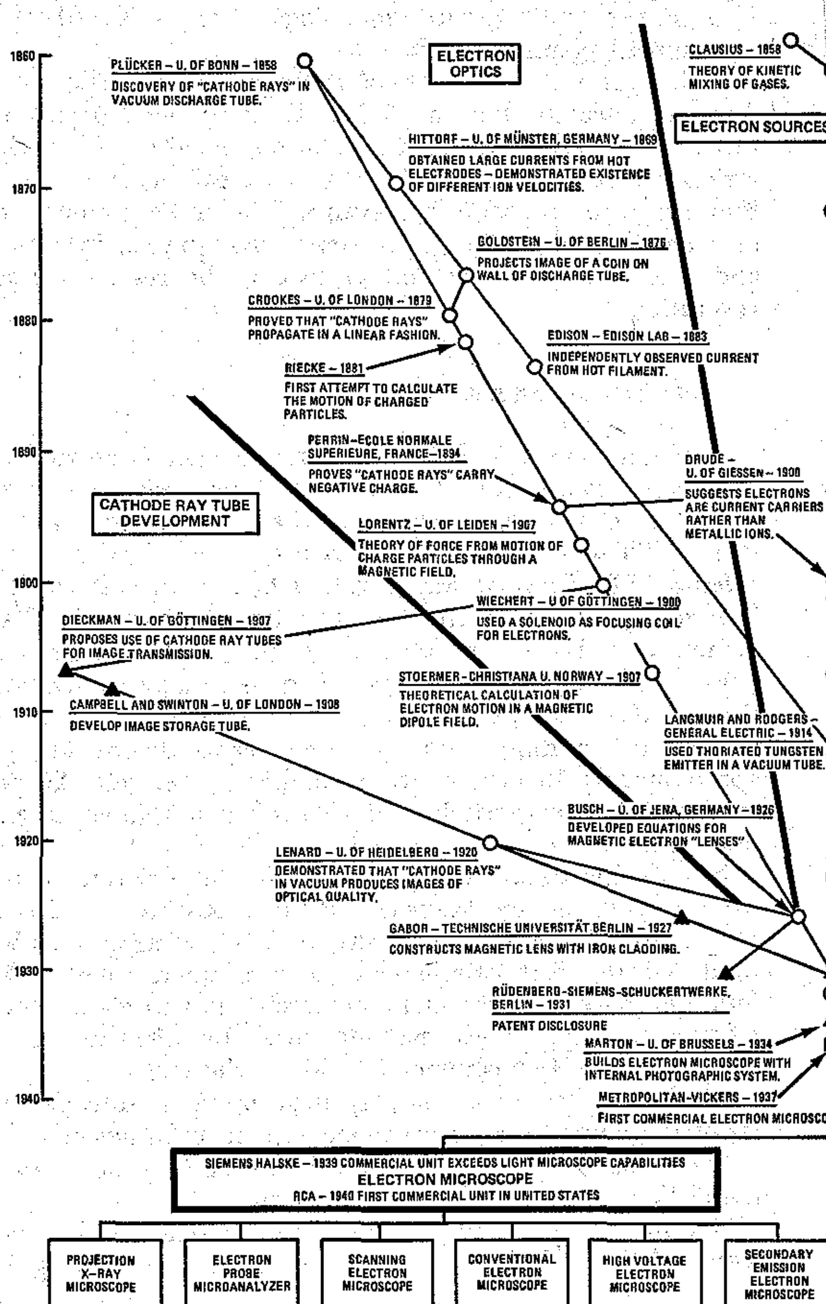
As long ago as 1968, the National Science Foundation sponsored a systematic study of the role of research findings in the overall process leading eventually to a major technological innovation. Titled *Technology in Retrospect and Critical Events in Science* (TRACES), it was prepared by the Illinois Institute of Technology Research Institute and later extended by Battelle-Columbus Laboratories. This study retrospectively examined the key technological events which led toward major innovations. In the TRACES cases, the average time from conception to demonstration of an innovation was nine years. Of the key events, approximately 70 percent were nonmission research, 20 percent mission oriented research, and 10 percent development and application.

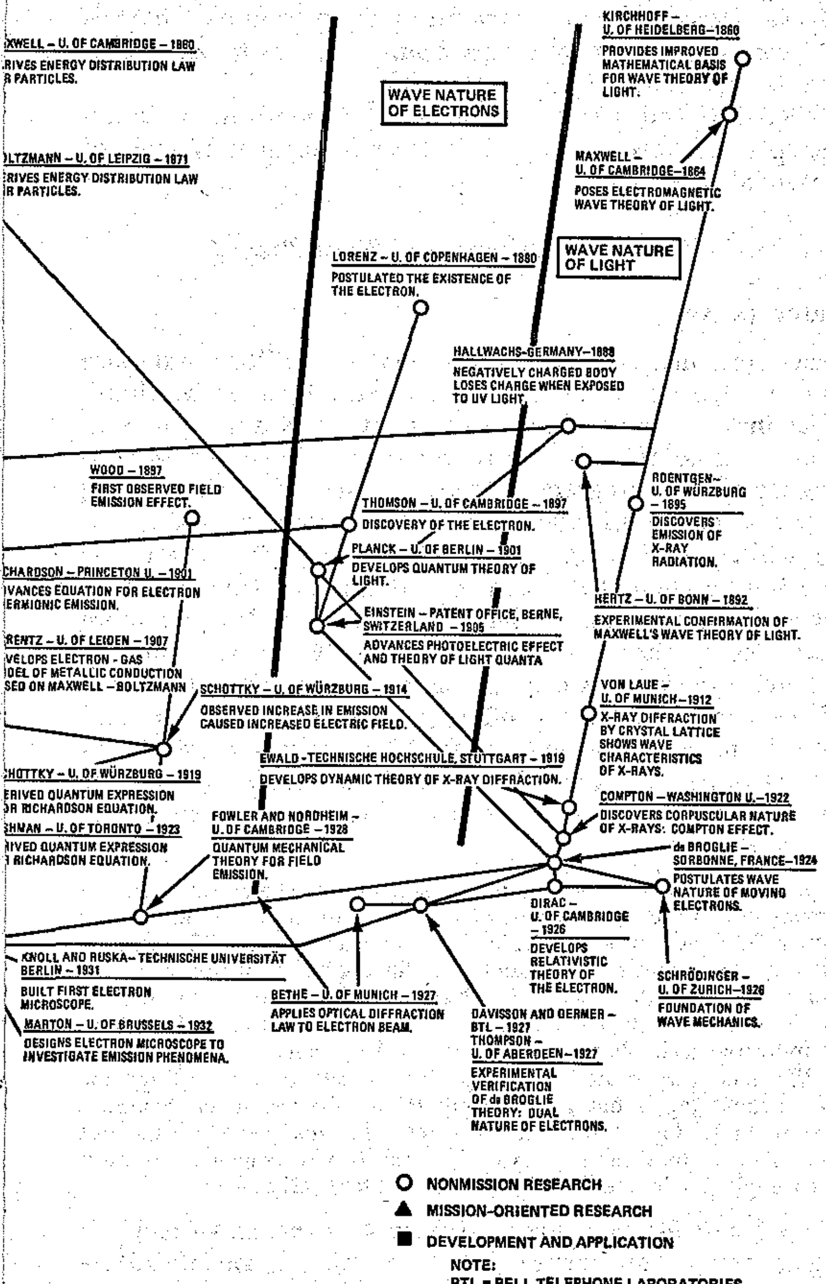
Nonmission events along the path to the electron microscope were discoveries by Maxwell, Planck, Roentgen, Hertz, and others (see Figure 1). Ultimately, in 1937, Metropolitan-Vickers produced the first commercial electron microscope. This was followed in 1939 by the first commercial unit to exceed the light microscope capabilities, manufactured by Siemens. In 1940, RCA made the first commercial unit in the U.S.

While the key events largely took place in universities and industrial laboratories, government support of universities, as well as tax and other policies, contributed to the innovation and commercialization of the electron microscope.

Recent experience in U.S. universities indicates that the majority of the technological developments now occurring have a

Fig. 1. The Electron Microscope




WAVE NATURE OF ELECTRONS
WAVE NATURE OF LIGHT
KIRCHHOFF – U. OF HEIDELBERG–1860
PROVIDES IMPROVED MATHEMATICAL BASIS FOR WAVE THEORY OF LIGHT.
MAXWELL – U. OF CAMBRIDGE–1864
POSES ELECTROMAGNETIC WAVE THEORY OF LIGHT.
XWELL – U. OF CAMBRIDGE – 1860
RIVES ENERGY DISTRIBUTION LAW R PARTICLES.
LTZMANN – U. OF LEIPZIG – 1871
RIVES ENERGY DISTRIBUTION LAW R PARTICLES.
LORENZ – U. OF COPENHAGEN – 1880
POSTULATED THE EXISTENCE OF THE ELECTRON.
HALLWACHS-GERMANY–1888
NEGATIVELY CHARGED BODY LOSES CHARGE WHEN EXPOSED TO UV LIGHT.
WOOD – 1897
FIRST OBSERVED FIELD EMISSION EFFECT.
THOMSON – U. OF CAMBRIDGE – 1897
DISCOVERY OF THE ELECTRON.
ROENTGEN– U. OF WÜRZBURG – 1895
DISCOVERS EMISSION OF X-RAY RADIATION.
PLANCK – U. OF BERLIN – 1901
DEVELOPS QUANTUM THEORY OF LIGHT.
CHARDSON – PRINCETON U. – 1901
VANCES EQUATION FOR ELECTRON ERMIONIC EMISSION.
HERTZ – U. OF BONN – 1892
EXPERIMENTAL CONFIRMATION OF MAXWELL'S WAVE THEORY OF LIGHT.
EINSTEIN – PATENT OFFICE, BERNE, SWITZERLAND – 1905
ADVANCES PHOTOELECTRIC EFFECT AND THEORY OF LIGHT QUANTA
RENTZ – U. OF LEIDEN – 1907
VELOPS ELECTRON - GAS DEL OF METALLIC CONDUCTION SED ON MAXWELL – BOLTZMANN
SCHOTTKY – U. OF WÜRZBURG – 1914
OBSERVED INCREASE IN EMISSION CAUSED INCREASED ELECTRIC FIELD.
VON LAUE – U. OF MUNICH–1912
X-RAY DIFFRACTION BY CRYSTAL LATTICE SHOWS WAVE CHARACTERISTICS OF X-RAYS.
EWALD - TECHNISCHE HOCHSCHULE, STUTTGART – 1919
DEVELOPS DYNAMIC THEORY OF X-RAY DIFFRACTION.
HOTTKY – U. OF WÜRZBURG – 1919
ERIVED QUANTUM EXPRESSION OR RICHARDSON EQUATION.
COMPTON – WASHINGTON U.–1922
DISCOVERS CORPUSCULAR NATURE OF X-RAYS: COMPTON EFFECT.
SHMAN – U. OF TORONTO – 1923
RIVED QUANTUM EXPRESSION R RICHARDSON EQUATION.
FOWLER AND NORDHEIM – U. OF CAMBRIDGE – 1928
QUANTUM MECHANICAL THEORY FOR FIELD EMISSION.
de BROGLIE – SORBONNE, FRANCE–1924
POSTULATES WAVE NATURE OF MOVING ELECTRONS.
DIRAC – U. OF CAMBRIDGE – 1926
DEVELOPS RELATIVISTIC THEORY OF THE ELECTRON.
KNOLL AND RUSKA– TECHNISCHE UNIVERSITÄT BERLIN – 1931
BUILT FIRST ELECTRON MICROSCOPE.
MARTON – U. OF BRUSSELS – 1932
DESIGNS ELECTRON MICROSCOPE TO INVESTIGATE EMISSION PHENOMENA.
BETHE – U. OF MUNICH – 1927
APPLIES OPTICAL DIFFRACTION LAW TO ELECTRON BEAM.
DAVISSON AND GERMER – BTL – 1927
THOMPSON – U. OF ABERDEEN–1927
EXPERIMENTAL VERIFICATION OF de BROGLIE THEORY: DUAL NATURE OF ELECTRONS.
SCHRÖDINGER – U. OF ZURICH–1926
FOUNDATION OF WAVE MECHANICS.
NONMISSION RESEARCH
MISSION-ORIENTED RESEARCH
DEVELOPMENT AND APPLICATION
NOTE:
BTL = BELL TELEPHONE LABORATORIES

significantly shorter transition time from conception to commercial use. However, *major* breakthroughs continue to experience a seven- to ten-year gestation from discovery to significant commercial application.

The TRACES study provides evidence of the continuing significant interplay of basic and applied research, ultimately realized in commercial products.

Innovation from U.S. Military and Space Programs

VIEW FROM JAPAN

Benefits from the spin-off of innovations from military and space programs are frequently asserted. However, Masanori Moritani, at the Japanese Nomura Research Institute, was unable to confirm the existence of a significant number of such innovations resulting from these programs, except for those occurring during a short period at the initiation of the U.S. space program. In his book, *Japanese Technology,* Moritani claims that concerns by Japanese businessmen that technological spin-offs from the U.S. military and space programs make U.S. private industry a more formidable competitor are "unwarranted." He argues instead that the military and space programs were a detriment to U.S. competitiveness by siphoning off most talented researchers and engineers from corporate enterprise. "The stagnant steel, consumer electronics, and general machinery industries are unable to compete for top-caliber researchers," Moritani declares. Continuing, he states:

> In Japan, in sharp contrast, the top Japanese researchers and engineers are committed to the development of civilian technology, not just in the computer field, but in VTRs [video tape recorders] and VTR cameras, televisions, automobiles, steel, and the like. The competence of researchers at the top does not differ that much from country to country. Even China has developed a hydrogen bomb despite the backwardness of its industrial technology, and has launched as many as eight satellites. The difference lies in how this top class is put to use. Perhaps the greatest benefit Japan has gained from taking shelter under America's nuclear umbrella for a "free ride" in defense has not been financial but human. Thanks to America, Japan has not had to squander its most talented engineers in the development of military technology.

Military Demands May Erode Ability to Innovate—America's growing concern for military security (beginning in the late 1940s) may well be debilitating to the basic optimism necessary for innovation. Professor David Kennedy, in a *Stanford Magazine* article, "War and the American Character," suggests that this continuing intrusion of military preparations into American life accounts for the steady erosion of our exuberant optimism as a people. By historic and international standards, the U.S. flourished for 175 years in a setting relatively free of war and military preparation. Kennedy perceives that, while history is catching up with us, we are still distinctive among most nations in never having experienced the terror, demoralization, and destruction of modern war in our heartland.

> In this important aspect, we are still innocent in a way that sets us apart from nearly all peoples in Europe or Asia. It is not pleasant to ask what would happen if America one day became the battleground. . . . Given the long lines of internal transportation and communication, the concentration of our population in vulnerable metropolitan areas, the generally comfortable lives to which so many have become accustomed, the racial and economic conflicts that only relative peace and prosperity have made manageable, and the deep American hostility to authority and coercion that necessary martial law would entail, it is especially frightening to contemplate the circumstances in which America would lose this last item of innocence about modern warfare.

Kennedy further suggests that the fact that the U.S. has not felt the "direct pain of war" in its heartland may explain the "long-deep acquiescence" of the country to the war in Southeast Asia.

Even our most deadly conflict, the Civil War, reinforced popular attitudes in the North that war was waged in remote areas, accelerated economic growth, and strengthened social elites. The North's victory confirmed an attitude of "righteousness and omnipotence" toward others, providing "a huge repository of self-congratulation on which the nation has drawn ever since." These attitudes, continues Kennedy, were reflected in Woodrow Wilson's call for the U.S. to make the world "safe for democracy" in World War I and in Franklin Roosevelt's demand for unconditional surrender in World War II.

These global conflicts erased a long-held, romantic notion of battle for millions of Americans. But our casualties were only 1 percent of Europe's, our industrial output soared, and wealth poured into America "on a scale that invited comparison with the oil exporting nations today," Kennedy says. But the sense of buoyance and optimism that characterized earlier epochs was noticeably missing. "Books like *The Naked and the Dead, The Caine Mutiny,* and *From Here to Eternity* were almost shot through with a sense of futility, absurdity, and resignation." These views reflect "deep anxieties about security in an age in which the U.S. has suddenly become intricately involved in a volatile, unstable world order—an experience for which 175 years of 'free security' left the American psyche peculiarly unprepared."

"So, too, with the economic abundance and economic status of America," he continues. Military expenditures averaged less than 1 percent of our gross national product well into the start of the twentieth century, but

> . . . since 1950 [that fraction has increased, and] we now spend more than any other nation on military items. . . . [Vietnam alone cost $330 to $350 billion.] We now know the constraints on individual freedom, the dark uncertainties of the spirit, the poisonous effect on our political life that war and preparation for war has long made familiar in other societies, but from which we were for so long spared.

This relentless pressure on the American psyche stemming from fears necessary to accept preparation for war, the possibility of a nuclear Armageddon, and the very presence of war erodes the national self-confidence. If Kennedy's assertion is correct (that there is an erosion of national self-confidence) and if we accept that creativity and innovation are characteristic of a confident and optimistic people, we should be concerned that our ability to innovate may also be quietly eroding.

National Security and Export Controls

The national security restrictions on transfers of technology and information are many and varied. There are several major laws under which our government may act to restrict technology exports and many other influences which affect implementation of those laws and future technology controls. These controls in general do not enhance innovative activity.

Atomic Energy Act—One of the oldest statutory authorities is the Atomic Energy Act (42 U.S.C. 2011–2296). Originally adopted in 1946 and significantly overhauled in 1954, this law controls exports of restricted data concerning the design, manufacture, or utilization of atomic weapons; the production of special nuclear material; or the use of special nuclear material in the production of energy. The law has been invoked against private parties who independently developed information of this type.

Another law restricting technological information was enacted in 1981 as an amendment to the Atomic Energy Act (42 U.S.C. 2168). It permits the secretary of energy, in certain cases, to prohibit the dissemination of unclassified information pertaining to the design of production facilities, security measures for the protection of production facilities and nuclear material, and the design of any atomic weapon or component even if such information has been declassified.

Gerald Lieberman, Vice Provost at Stanford University, commented to the Department of Energy (DOE) in April 1983 that, contrary to the intent of Congress, proposed DOE rules on unclassified nuclear information have "unlimited potential to chill research, teaching, and the general interchange of information." He observes the traditional freedom to publish the results of university research and, further, that the Atomic Energy Act of 1952 provides "the dissemination of scientific and technical information relating to atomic energy should be permitted and encouraged." The proposed regulation "is so vague, ambiguous, inconsistent, and couched in such general categorical terms as to be capable of interpretation [which would give] the Secretary [of Energy] maximum flexibility to prohibit dissemination of anything and everything he chooses. . . ."

Invention Secrecy Act—Another statute which the government may use to control information developed independently by the private sector is the Invention Secrecy Act of 1951 (35 U.S.C. 181–188). The law dates back to America's entry into World War I, but the present statute was enacted in 1952. This act provides that the patent commissioner shall make a patent application available to U.S. defense agencies for review whenever, in his opinion, the publication or disclosure of an invention might be detrimental to the national security, even if the government does not have a property interest in the patent. If a defense agency determines that the publication or disclosure of the invention would be detrimental to national security, the commissioner shall order that the invention be kept secret and shall withhold the grant of the patent for not more than one year, subject to renewal of his order.

Arms Export Control and Export Administration Acts—Two sets of major laws control the export of technical information. One of these is the Arms Export Control Act (22 U.S.C. 2751–2794), and the other is the Export Administration Act (50 U.S.C. App. 2401–2420). These laws not only govern the export of data and goods from the U.S., but they also limit the access of foreign nationals to such information and materials within the United States. Agency regulations implementing these statutes embrace scientific information and define exports broadly enough to include the domestic publication or release of information.

The Arms Export Control Act governs the sale of U.S. defense articles, services, and technology abroad. The Export Administration Act controls the export of goods and technology which would make a significant contribution to the military potential of any country or combination of countries and which could prove detrimental to national security of the United States. The Department of Commerce administers the Export Administration Regulations and the Department of State administers the International Traffic in Arms Regulations under these laws. These departments and the Department of Defense consult each other on sensitive license applications under either set of regulations, but while the Department of Commerce has expediting procedures, the Department of State does not. The Department of Defense uses its "Military Critical Technologies List" as a reference for making recommendations to either the Department of Commerce or State. The 1983 list covers about 700 pages, and part of it is classified.

More than 90 percent of U.S. exports, in terms of dollar value, are shipped under general license authorization without the need to obtain a validated export license in advance. However, most experienced exporters know which items raise national security concerns, and they do not attempt to procure validated export licenses for them.

International Exchange and Proscriptions—The Coordinating Committee on Export Controls (CoCom) consists of fourteen of the fifteen countries in the North Atlantic Treaty Organization (Iceland is not a member), plus Japan. The body has no official power to prohibit sales by its member countries, but its recommendations are often, though not always, followed. The United States controls some items that other CoCom members do not.

CoCom has routinely granted approximately 1,700 exceptions to its rules each year.

Congressional Jurisdiction—In the Senate alone, numerous committees have overlapping jurisdictions on technology transfer. The Senate Committee on Banking, Housing, and Urban Affairs has jurisdiction over criminal sanctions to enforce export controls. The Committee on Foreign Relations has jurisdiction of the Arms Control Act. The Committee on Governmental Affairs reviews the ability of the executive branch to enforce export controls. The Senate Committee on Intelligence is often consulted in the preparation of hearings by other committees on these subjects and the Committee on Armed Services has an obvious interest in Department of Defense matters.

Freedom of Information Act—Further legislation upon the flow of technological information is the sunshine laws, whose intended purpose is to open government files to public scrutiny. The Freedom of Information Act (FOIA) provides a number of exceptions for certain classes of information that need not be released under an FOIA request. For example, in some cases, release of information may be delayed in order to allow patents to be filed when premature public release would bar patenting.

Legislation to amend the FOIA has been proposed that will allow agencies to withhold "technical data" that may not be exported lawfully outside of the U.S. until the appropriate approval or license has been granted. Other proposed legislation would deny foreign entities the right to obtain, under an FOIA request, documents from government agencies.

Restrictions on Information Flow: "The CIA Report"—Much debate over the transfer of technology surrounds a published report of the U.S. Central Intelligence Agency (CIA) entitled *Soviet Acquisition of Western Technology* (1982). The thrust of the report is that the success of Soviet and East European intelligence services in acquiring U.S. technology has resulted in a significant threat to American security. Although the report states that the "overwhelming majority" of militarily significant technology was acquired by intelligence organizations, the CIA believes open and legal acquisitions are still important because "it is often the combination of legally and illegally acquired technologies that gives the Soviets the complete military or industrial capability they need."

One example the CIA gives of legal channels used by the Soviets is the Dressler project, which supplied three foundries for the Soviets' Kama River truck plant. The CIA asserts that large numbers of trucks produced there in 1981 are now being used by Soviet forces in Afghanistan and by Soviet military units in Eastern Europe opposite NATO forces. Another example of legal acquisitions discussed is the Soviet purchase of 168 grinding machines for the production of small, high-precision bearings. The CIA claims these purchases provided the Soviets with the capability to manufacture precision bearings in large volume sooner than they could have on their own. Defense officials argue this sale enabled the Soviets to speed construction of more stable and accurate missiles having a multiple-warhead capability.

A third example is the legal acquisition by the Soviet Union of two huge, floating dry docks purchased from the West for civilian use and diverted to military purposes. When the Soviets took possession of one of the dry docks in 1978, they used it for their Pacific Naval Fleet. The other was sent to the Northern Fleet in 1981. According to the CIA, these are the only dry dock facilities in either of the two major Soviet fleet areas, northern or Pacific, capable of servicing the new Kiev-class aircraft carriers. Their importance will be greater when the Soviets construct the still larger carriers for high-performance aircraft projected for the 1990s.

National Academy of Sciences Report—On September 30, 1982, a special panel of the National Academy of Sciences issued its own findings on the transfer of U.S. technology. The Panel on Scientific Communication and National Security concludes: "There has been a substantial transfer of U.S. technology—much of it directly relevant to military systems—to the Soviet Union from diverse sources." However, "there is a strong consensus . . . that universities and open scientific communication have been the source of very little of this technology-transfer problem." The panel emphasizes that national security is more apt to be enhanced by a policy of open scientific exchange that promotes scientific accomplishment than by a policy of secrecy controls.

Proponents of selective national security restrictions on technological information offer a counter to the National Academy of Sciences report. They argue that advances in technological innovation and economic productivity occurred during the very years in which rather strict controls have been in effect. They further claim that many of the most successful and innovative corporations are those that deal extensively in areas of national security information restrictions and themselves engage in additional industrial security practices. They maintain that there is little persuasive evidence of economic damage or innovation chill due to selective applications of national security controls.

"Secrecy: The Road to Nowhere"—Edward Teller, who played a major role in development of the hydrogen bomb, claimed in M.I.T.'s *Technology Review:*

> In the last third of the century, the United States has lost its position in all military fields, most specifically in those where we practice secrecy. . . . We now have millions of classified technical documents; we also have falling productivity. Rapid progress cannot be reconciled with central control and secrecy. The limitations we impose on ourselves by restricting information are far greater than any advantage others could gain by copying our ideas.

Teller, a consultant to Lawrence Livermore Laboratory, has fought to open up the classification system for government research laboratories. He points out that technical fields where the U.S. leads, such as electronics, are those "where we practice the most openness."

The San Diego Incident—In August of 1982, four Soviet scientists were to attend the annual meeting of the Society of Photo-Optical Instrumentation Engineers in San Diego. Their attendance triggered actions by the Departments of Commerce, State, and Defense and ultimately led to withdrawal of some 150 papers by U.S. scientists from the meeting. Penalties for an individual's knowingly violating technology export laws include up to ten years in prison and fines up to $250,000.

Cryptography and the NSA—A voluntary and self-policing system for university researchers in cryptology evolved in the late 1970s as a result of concern by the NSA and CIA of sensitive cryptographic technology being transferred to the Soviet Union. While recognizing the importance of unfettered scientific communication, Admiral Bobby Inman, then speaking for the CIA, expressed his belief that the problem of leakage from academics, while then small in comparison to industry and espionage related leakage, would be a growing problem.

University–DOD Forum—Five university presidents (Stanford, Cal Tech, Cornell, M.I.T., and UC–Berkeley), concerned about the evolving constraints upon international scientific communication, wrote a letter which led to establishment of a joint university –DOD forum to study the question of science and technology transfers at universities. Their letter stated, "Restricting the free flow of information among scientists and engineers would alter fundamentally the system that produced the scientific and technological lead that the government is now trying to protect and leave us with nothing to protect in the very near future." The letter goes on to say that the significant practical difficulties of enforcing export restrictions are "virtually impossible" for universities to administer. It is difficult to imagine guards at classroom doors of U.S. universities, enforcing security by checking students who would be required to wear badges indicating their clearance to attend certain lectures.

Technology Hemorrhage—Concerned officials have described Soviet access to sophisticated U.S. devices as a "hemorrhage of technology." Democratic Senator Sam Nunn of Georgia suggests that the United States is funding two military research programs —our own and the Soviets'. Democratic Senator Paul Tsongas of Massachusetts considers certain technology controls absurd. "We lose the technology, the foreign business, and become known as an unreliable supplier," he notes. Boeing was denied approval to sell to Ethiopia a 767 aircraft with a laser gyro. Ethiopia then bought a French Airbus with the same laser gyro, which could be sold to France, an ally, by the American manufacturer.

President's Office of Science and Technology Policy (OSTP) Report—A government-wide study group headed by OSTP is expected to soon release its report of a study of national security and technology transfer issues. The study focuses on government organizational structure concerned with technology transfer matters, U.S. policies on controls or lack of controls or technology transfers to various nations, and issues associated with unclassified but militarily sensitive data. Louis T. Montulli of OSTP, in describing the government's view of the issues, has reported that "right now, forty-four separate groups in ten or more U.S. departments are either studying this subject or actually executing the present policy."

Federal Acquisition Regulations (FAR)—The FAR are new, uniform regulations to be used by government agencies for procurement. The final section, covering copyrights and technical data, was offered for public comment in May 1983. According to one of the reviewers, "Not only are there unacceptable controls of freedom of publication, inappropriate 'backdoor' enforcement of export controls, but, through the copyright and data clauses, the tenets of PL 96–517 [the University and Small Business Innovation Act] are violated."

New Technology Control Laws—Legislation to replace the Export Administration Act of 1979 was introduced in the Ninety-eighth Congress. In S. 434 (the Garn Bill) "technology" is defined broadly enough to include virtually any information or goods as being subject to government control. Senate Bill 407, introduced by Senator Nunn, gives criminal enforcement power to the Customs Service as well as statutory authority for warrantless arrest and search and seizure. A second bill by Senator Nunn, S. 408, entitled the Technology Securities Enforcement Act of 1983, stretches racketeering laws to cover violations of the Export Administration Act and Arms Export Control Act, exposing violators to a twenty-year prison term. S. 408 also amends electronic surveillance statutes to permit court-authorized surveillance where there is probable cause to believe that a violation of the Export Administration Act, the Arms Export Control Act, or the new technology theft statute is being committed.

INNOVATION, SECRECY, NATIONAL SECURITY, AND TECHNOLOGY CONTROLS

One can debate whether or not broad controls of technology and information enhance American security. There is little debate, however, that scientific research and innovation do not flourish under secrecy. Recall that the patent system in England was established by Parliament in 1624 because the practice of secrecy was inhibiting technical progress and innovation. Further, Article I, Section 8 of the U.S. Constitution provides for a patent system for the same reasons.

Regulations, Specifications, and Special Interests

Regulation vs. Innovation—"Regulation creep" is a disease that can have deleterious effects on innovation. It is progressive in nature, appearing to attack older societies more severely than younger ones. Rigid regulations and specifications for government and industry procurement can serve to dampen innovation and increase costs. Creativity is unlikely to flourish in such an environment. However, there may be a limited number of situations where regulation can spur innovation. For example, tightening automobile exhaust emission standards acts as a regulatory "pull" for new and improved methods and devices for lowering exhaust emissions.

Skunkwork vs. Specification—Thomas Peters, of the Stanford Graduate School of Business, has reported numerous anecdotal cases to justify his assertion that small skunkwork operations in a company will time and again provide more successful results than project teams operating under detailed specifications. While noting the word *skunkwork* may have originated with L'il Abner, Peters believes *skunkwork* apparently was used first as a business term to identify a group of Lockheed mavericks who produced the U-2 aircraft. "When a practical innovation occurs, a skunkwork, usually with a nucleus of six to twenty-five, was at the heart of it. The skunkwork seldom reinvents the wheel," claims Peters. Some general sense of direction may help, such as "Northwest." "What's not sensible," he argues, "is trying to prespecify the difference between a course of 343 degrees and a course of 346 degrees."

In their bestseller, *In Search of Excellence: Lessons from America's Best Run Companies,* Peters and Robert Waterman point out that the "best run" companies have provided the environments that stimulate skunkwork teams. Even giant IBM turned to a collection of no less than seven parallel skunkwork teams to develop its enormously successful computer.

Strategic and Product Planning—James Utterback at M.I.T., from his studies of many successful products, concludes that "the initial use and vision for a new product is virtually never the one that is of the greatest of importance commercially." There is an apparently inherent organizational tendency to do the wrong thing vis-à-vis stimulating innovation. "In 32 of 34 companies, the current product leaders reduced the investment in the new technology in order to pour even more money into buffering the old," he observes. Neither Utterback nor Peters suggests doing away with strategic or other technology planning. But in Peters's words, a company desiring to encourage innovation needs to allow "maximum play" to the "substantially sloppy process" that produces successful innovations.

Special Interest Coalitions—It is not only governments that are responsible for rules which act to constrain innovation. Mancur Olson, University of Maryland economist, in *The Rise and Decline of Nations: Economic Growth, Stagflation, and Social Rigidities,* theorizes that the special interest coalitions endemic to free societies become more and more influential as a stable and affluent democracy matures, giving rise to a form of national "economic sclerosis." As analyzed by Eliot Marshal, in his 1983 review in *Science,* Olson's theory works as follows:

> In societies that permit free trade and free organization, coalitions will form around marketable goods and services. Groups of producers, like those who grow wheat or own oil, will organize to protect their assets and, if possible, will boost profits by raising prices. Physicians and lawyers do much the same in joining professional societies. Labor unions organize workers to bargain for wages.
>
> In the early stages of this coalition building process, there are relatively few interest groups, and their memberships are small compared to the society in which they operate. As they develop, they try to impose a variety of specialized rules on the economy that supports them. By law or collusive contracts, they make penalties for those who would market the same goods or services outside the group. They also offer selective advantages to those who join and cooperate. Because these groups are small (Olson says they typically include no more than one percent of the people in their state), they have no incentive to boost members' welfare by boosting the state's welfare. Instead, they concentrate on promoting their own narrow interest, even at the cost of retarding the general economy. A modest effort at self-aggrandizement may bring great rewards.
>
> As time goes by, tariffs, price supports, monopoly prices, wage guarantees, and business codes grow more numerous. All are intended to channel commerce for them. *The combined effect is to create obstacles to trade and to prevent innovation.* The economy suffers.

In the past, nations suffering from this affliction have enjoyed renewed growth after a cataclysm has intervened to wipe out existing trade barriers, or when new territory has been opened for development. Sometimes, the power of a domestic group is undercut by low-cost imports, if the imports are not blocked. Rarely has any nation abolished special interest codes voluntarily.

Government Patent Ownership

PUBLIC LAW 96–517

Culminating over ten years of effort toward development of policies that would best encourage the exploitation of the fruits of government funded research, the University and Small Business Innovation Act was implemented in Public Law 96–517 (effective July 1, 1981). This gives nonprofit organizations and small business firms first option to acquire title to inventions conceived by them under federal research funding. As was brought out during congressional hearings, when the government took title to inventions from federally funded research, only 3 to 5 percent of the patented inventions would eventually be commercialized. In contrast, when title was in the name of a university, approximately 50 percent of the patented inventions were eventually licensed to industry for commercialization. Close to 30,000 unlicensed patents had been accumulated by the government at the time the bill was passed. PL 96–517 allows a federal agency to exempt university operated laboratories from the law. The Department of Energy, which administers eight such university laboratories, has chosen to exempt them.

Background Policy for PL 96–517—One of the motives behind the legislation which led to the passage of the University and Small Business Innovation Act was to encourage industry involvement in university research. This required the reduction of the prospect for "contamination" of rights to research results in a laboratory which was funded in part by a government agency. A common occurrence in a laboratory with such mixed funding would be attribution of an invention *both* to a sponsoring company *and* a sponsoring government agency. While the company would have rights to an invention through its sponsorship, the government could assert rights in its independent share of the invention and then make rights in that invention available to the company's competitors who had not participated in any of the costs of the research. This "contamination" was removed by PL 96–517, which provided (with certain exceptions) first option to rights in inventions under government supported research to the universities.

Changes Following Enactment of PL 96–517—In order to ascertain the possible effects of PL 96–517 on university-industry interaction, the author conducted a survey of about twenty universities known to interact actively with industry. Sixteen responses were received. All respondents indicated that university-industry interactions were increasing, although not attributable solely to PL 96–517. Data on the number of invention disclosures during 1978–82 showed a steady increase in the annual rate of invention disclosures made; the largest increase was in 1982—up approximately 20 percent from 1981.

Universities were asked about the change in industry support of 1982 compared to 1978. In all cases, the percentage of the total university research budget supported by industry increased significantly, and several predicted that 1983 would show an even larger increase. Even so, the average share of industry research support at universities is well below 6 percent, and even a larger percentage increase will not provide a substantial addition to or substitute for federal funds.

The Federal Laboratories

FEDERAL LABORATORY BUDGETS

Often overlooked in analysis of factors in research, development, and commercialization in the United States are the national laboratories. The 1979 budget of $794 million for the Sandia and Livermore laboratories alone was greater than the combined 1979 research funding of the top six (in terms of funding) U.S. research universities: The Johns Hopkins University, Massachusetts Institute of Technology, Stanford University, University of Washington, the University of California at San Diego, and the University of California at Los Angeles. Moreover, the 1983 budget of those two laboratories was $1,630 million—double that of 1979 and equivalent to the 1983 federal funding of the research programs of not only the above six universities, but also the estimated funding of the next six as well.

Overall, the federal laboratory system incorporates some 755 laboratories and consumes more than 33 percent of the federal research and development budget. It has been charged that the flow of dollars into the laboratories has been at the expense of industry and university research laboratories, which, ironically, have comparatively superior track records of contributions to U.S. innovation.

WHITE HOUSE SCIENCE COUNCIL REPORT ON THE LABORATORIES

Based on a 1983 report of the White House Science Council, the *New York Times* reported, "The federal laboratory system has 'serious deficiencies' that limit the quality of its work and the nation's ability to compete against foreign technological research." Only three laboratories were praised: The Fermi National Laboratory in Illinois, the Stanford Linear Accelerator Center in California, and the China Lake California Naval Ordnance Laboratory.

ENERGY ADVISORY BOARD REPORT ON FEDERAL LABORATORIES

In a late 1982 report, the Energy Advisory Board criticizes the "floundering" system of support, management, and oversight of those federal laboratories administered by the Department of Energy. On the other hand, in a 1982 article in *Chemical and Engineering News,* a Los Alamos laboratory official is quoted as saying:

> One of our problems is that there are too many industrial concerns at the federal trough, and they are competing with each other and the labs. And in many projects it isn't clear that what they do is any different than what the national labs do. If we are going to be assessing the role of labs, we ought to be assessing the whole issue of federal funding, rather than industrial relationships. Many contractors are producing useless gold-plated widgets for the Department of Defense or the Department of Energy, and we ought to take a look at who those guys are.

THE FUTURE OF THE LABORATORIES

The Energy Advisory Board and White House Science Council reports do not recommend closing the national laboratories, but rather they note their potential as important centers of research on national problems. David Packard, chairman of the prestigious White House Science Council panel on the federal laboratories, warns, however, that unless corrective action is taken with regard to the laboratories, the nation will face "serious problems" that will threaten its scientific and technological leadership.

Industrial and University Research

BEFORE WORLD WAR II

In the United States, university based research developed toward the end of the nineteenth century, which is about the same time the modern industrial corporation was emerging. Industrial research laboratories became a feature of prominent U.S. corporations after 1910, reaching a peak in the early 1930s. In 1927, it was estimated that total national research and development expenditures were $212 million. Over 90 percent of these funds was estimated to represent work by industrial concerns in their own research laboratories. A 1982 National Science Board (NSB) report on university-industry research relationships considers the importance of these industrial research laboratories to be that of "having created a locale for advanced research and development, and required staffing by scientists and engineers with advanced training and degrees."

In the early part of the century, very wealthy individuals and large, general purpose foundations, such as The Rockefeller Foundation and the Carnegie Institution of Washington, were sources in aiding research in American universities. More important for the support of research in the basic sciences were the smaller, specialized foundations, such as the Dreyfus Foundation, the Petroleum Research Fund, Research Corporation, and the Alfred P. Sloan, Jr., Foundation.

Through the land-grant system, agriculture related research was encouraged by both federal and state governments. U.S. university enrollments doubled every twenty years from 1900 to 1960, providing a steadily growing, well-educated work force for science and engineering teaching and research.

In the mid–1920s, Herbert Hoover, then secretary of commerce, sought to raise $1 million from American industry to support basic research in the nation's universities. He told industry leaders they would lose a form of intellectual capital if they did not make it possible for able researchers in universities to be relieved of some of their teaching obligations and to be equipped to do first-rate scientific research. This effort failed because of corporate reluctance to contribute to openly published research that could give advantage to competitors. The Hoover campaign did, however, create support for the National Research Council and for a program that kept science alive during the Great Depression.

EARLY UNIVERSITY-INDUSTRY COOPERATION

In the period prior to World War II, the NSB report notes several university programs that were distinguished in their vital approach to university-industry cooperation. Particularly noteworthy was the effort led by William M. Walker, Warren K. Lewis, and Arthur D. Little to develop a chemical engineering curriculum at M.I.T. closely suited to the needs of the chemical industry. Considerable financial support was received from companies through Walker's Research Laboratory for Applied Chemistry. Research support was also received for the aeronautics program established at Cal Tech by Theodore Von Karman. This contributed significantly to the growth of the aeronautical industry.

At the University of Illinois, the chemistry and chemical engineering program of Roger Adams made their chemistry and chemical engineering departments into the world's largest producers of doctorates in any discipline. While this program did not include a major component of direct industrial support for academic research, it provided considerable support for student fellowships and encouraged the flow and exchange of people between the university and industries.

POSTWAR ENHANCEMENT OF RESEARCH SUPPORT

World War II brought together unprecedented numbers of industrial, academic, and government scientists and engineers in collaboration on wartime projects. Notable innovations included radar, penicillin, synthetic rubber, and nuclear energy. These collaborations are enthusiastically described in the NSB report:

> The scientists themselves found the process exhilarating and intellectually exciting. This excitement was also communicated to their graduate students, who learned that product-oriented work can give high intellec-

tual stimulation. In addition, the contacts made and the process broadened student perspectives on their work and career options.

After the cessation of hostilities, the Office of Naval Research in particular became an important factor in developing the research base at universities. Its support enabled leading scientists to reestablish and enlarge research programs earlier sacrificed to the war effort. This support also illustrated the value of relationships of industry and university scientists that lead to many consulting arrangements, as well as direct employment of academics in corporate research laboratories.

Perhaps the most productive of any corporate research laboratories, in terms of scientific discoveries, are the Bell Laboratories. For example, their 1947 discovery of the transistor by William Shockley and others led to a new industry. Bell Laboratories encouraged their scientists to spend sabbaticals at universities and, likewise, enabled university scientists to work at Bell. In addition many science professors encouraged their brightest students to work for a few years in Bell Laboratories' well-equipped facilities before seeking an academic appointment.

IMPACT OF FEDERAL FUNDING

A fundamental shift in emphasis for university research arose in the 1950s and 1960s due to the ever-increasing growth in federal funds for academic science from the National Science Foundation, the National Institutes of Health, and other agencies and departments. This decreased the need for industrial support of university research, gradually led to barriers between university and industry, and sparked negative attitudes on both sides. These differences widened during the period of the Vietnam War. Though by no means universal to all campuses or in all companies, this apparent deterioration of university-industry ties was reversed in the 1970s. Efforts of "bridge building" began, and recognition of the value of interaction between universities and industries increased.

The Sequence of Innovation

Stanford President Donald Kennedy, former head of the Food and Drug Administration, observes that there appears to be a fairly standardized historical sequence of innovation following

World War II and the rise of the modern research university. He explains:

> The first phase is publicly funded and oriented toward the discovery and explanation of basic phenomena. It is characterized by loose informal organization, very open communication, including quick publication of all details of an experiment. Typical institutions where this study of phenomena occurs include departments of biology, chemistry, or physics, a laboratory in the NIH institute, or a special industrial organization like Bell Telephone Laboratories.
>
> The second phase is best called application. It is focused upon processes, and takes place in various settings: applied institutes, some university departments (of engineering, for example), nonprofits (like SRI International or Battelle), and industrial laboratories. There is a mix of public and private funding and environments that are variable with respect to proprietary secrecy.
>
> In the third stage, development, attention is given to practical application, including such matters as scale, rates and means of economical production. The innovative emphasis is on products; funding is by private risk capital; and the environment tends to be close for proprietary reasons and tightly managed. Essentially all such work takes place in commercial laboratories.

Kennedy perceives that this three-stage process of innovation is now being compressed in a revolutionary way. He describes this compression as resulting from a fundamental rearrangement of the social sponsorship of discovery to which several forces contribute:

> First, a number of scientific disciplines are now being recognized as "ready" for accelerated application. As a discipline matures in power and confidence, leaps from the laboratory to applications that once seemed intimidating become commonplace. This now appears to be the case, for example, in immunology and genetic engineering, as well as microelectronics.
>
> Second, there is a growing social awareness of the importance of scientific discovery to national productivity, and a consequent impatience with the traditional time requirements for diffusing technology to the public. In the past decade, various studies—particularly for biomedical research—have demonstrated that the typical time lag between the initial research discovery and practical application is ten years or more.
>
> Third, there is increasing concern in research universities, where more than two-thirds of the nation's basic science is done, about the retreat in public support for research. Federal funds for non-defense research have shrunk by 38% in real dollar value since 1968. Half of this decline took place in the first two years of this decade [the 1980s].
>
> Fourth, and perhaps most unexpected of all, the venture capital financing

of small, research intensive firms and fields like biotechnology and microelectronics has been transformed. Since major changes were made in the capital gains tax, the investment funds available for such ventures have jumped from an estimated $70,000,000 in the mid-1970s to about $1.5 billion in 1982.

The result is an entirely novel mixture of influences upon university scientists and their institutions. For the University itself, there are new and challenging pressures on investment policy (Does the institution go into business with its own faculty?), on technology licensing (Should the University license inventions to faculty-led ventures? to their competitors? and if yes, under what terms? And should there be full disclosure of terms?), and on policies related to consulting faculty conflict of interest, and the protection of graduate student interest.

Many of the problems are simply not solvable by the institution alone. For the scientists themselves, and the "invisible colleges" that hold them together in national and international networks, there are other questions such as: How much can or should they guard against the withholding of information and exchange for proprietary reasons? How much involvement outside of faculty members' primary institutional affiliation is appropriate?

In general, this new climate offers more opportunities than it does problems. What we must try to do is involve industry more productively and creatively with university research in a way that leaves the latter intact, instead of risking fractionation of the training and research components and the division of faculty time between on- and off-campus ventures.

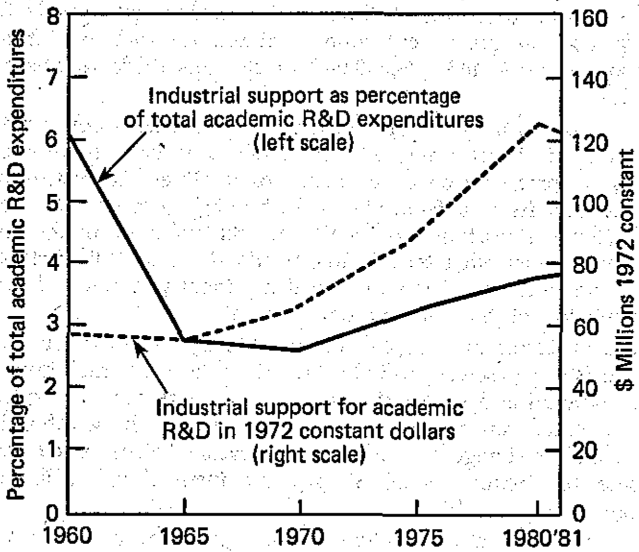
The University-Industry Connection

INDUSTRIAL SUPPORT OF UNIVERSITY RESEARCH

Data developed by the National Science Foundation (Figure 2) show that industrial support of academic research has been modest. In terms of the percentage of industrial research support in relation to total academic research expenditures, there is a sharp decline from 6 percent in 1960 to 3 percent in 1970, resulting from the rapid increase in federal support of university research and the relatively low amount of corporate support. An informal 1983 survey of major research universities shows that the percentage of industrial support of academic research for fiscal year 1980 was estimated at $235 million.

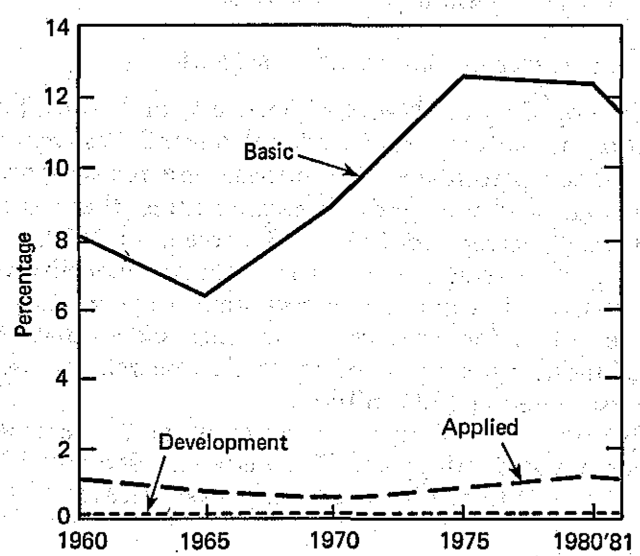
Overall, industry performs a fairly constant 70 percent of all U.S. research and development. But between 1960 and 1970, the percentage of this total directed toward basic research by and in

Fig. 2. Two Ways of Looking at the University-Industry Connection



industrial laboratories shrank significantly, dropping from nearly one-third to about one-sixth of total basic research activity in the U.S.

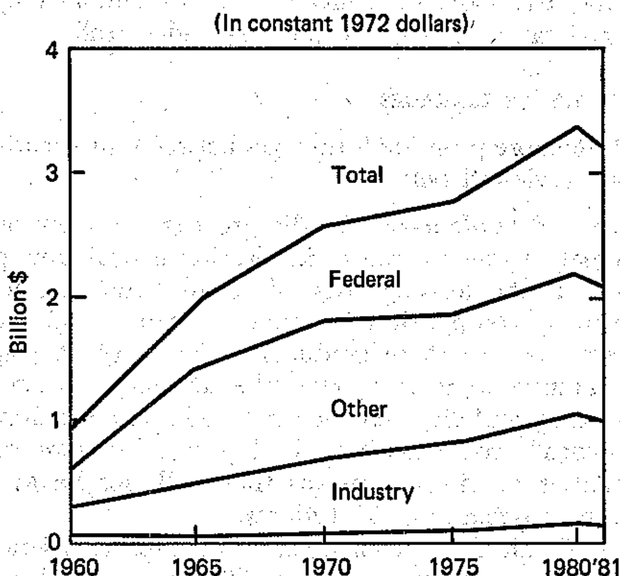
Fig. 3. Industrially Supported Academic Research as a Percentage of Industrially Supported In-House Research—by Character of Work, 1960–81



The portion of industry budgets allocated for support of university basic research increased from a low of about 6 percent in 1965, to a level of about 12 percent in 1974, where it essentially has remained (Figure 3). News media reports suggest industry sponsored research in universities tends to focus on a few fields. In 1979, nearly half of all industry sponsored research was within engineering, the largest percentage in chemical engineering. But industry does not interact with universities in innovation solely through contractual research.

Even a large percentage increase in the industry support (3.8 percent in 1981) would not have great effect on dependence by universities on federal research support (Figure 4). The overwhelming significance of federal support is even greater for universities without state funding, which includes many of the major U.S. research universities.

Fig. 4. Sources of Support for Academic Research and Development, 1960–81



STAGES OF UNIVERSITY-INDUSTRY INTERACTION

Ties between a university and a company progress through several stages. At first a company may become aware of university technology and expertise useful to its business interests through an academic consultant or the university's technology licensing office.

The second, or "research" stage, derives from the interaction with the academic consultant or the person who provided the technology to the company from the university licensing office. In this stage, the academic, having gained a better understanding of the technology needs of the company, suggests a line of research to be conducted at the university.

The third, or the "application" stage, occurs when the company uses the research results (in some cases under license from the university), hires students, and engages the academic as a consultant to assist in adaptation of research results to their products and processes.

The fourth, or "philanthropy" stage, occurs when the company makes unrestricted gift support available to the university. This recognizes that alternative costs of research might have been substantially higher. Companies often support those areas of the university from which they draw most of their employees, including the liberal arts. Corporate matching of individual employee gifts to their alma maters has become very widespread.

UNIVERSITY-INDUSTRY LINKAGES

Eleven of the more prominent linkages between universities and industries are reviewed below.

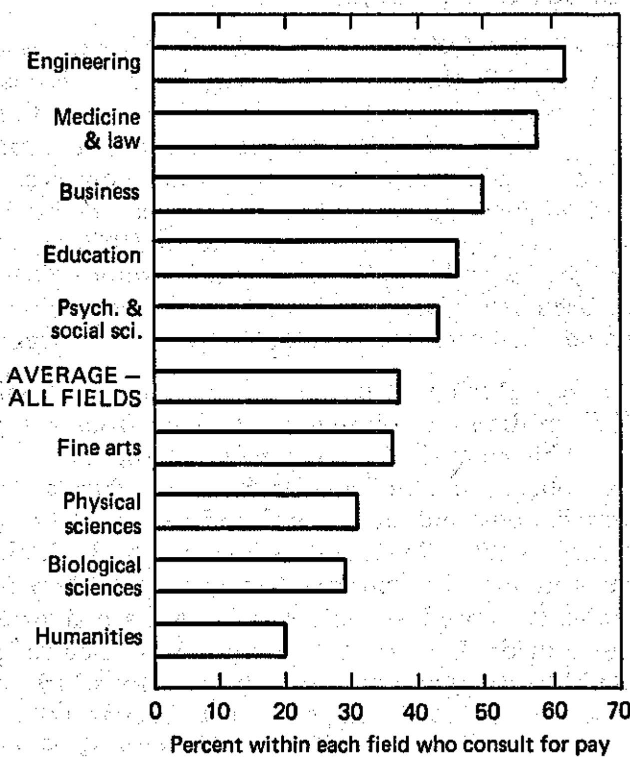
The Graduated Student—By far the greatest contribution that universities make to the process of innovation is providing graduates qualified at the leading edge of science and engineering. There is growing competition between companies and the universities themselves for these graduates. Both have shortages of doctoral researchers in certain fields like computer science, electrical engineering, and plant biochemistry. This competition leads to the "seed corn" problem, where the loss of the best researchers from universities to industry means they will not be available to teach the next generation of students.

In some academic departments, such as computer science and electrical engineering, as many as 30 to 50 percent of all doctoral candidates are foreign students. In these fields, many American students go into industry after receiving a master's degree, which leaves foreigners comprising half of the doctoral recipients in the U.S. Most of them remain in the U.S., both to teach and to join industry; the U.S. is eating the "seed corn" of other countries. Such students from developing countries are sorely needed back in their homelands after they complete their training in the U.S.

Another effect is realized in high-technology academic departments with large proportions of foreign graduate students. Graduate students typically teach undergraduate sections, and American-born students complain of great difficulty in understanding or communicating with many of their instructors.

Academic Consulting—Opportunities for consulting differ considerably by academic field (Figure 5). In 1969 nearly 66 percent of academic engineers reported paid consulting activities, as compared to less than 33 percent of their physical and biological

Fig. 5. Faculty Participation in Consulting for Pay, by Academic Subject Field, 1969



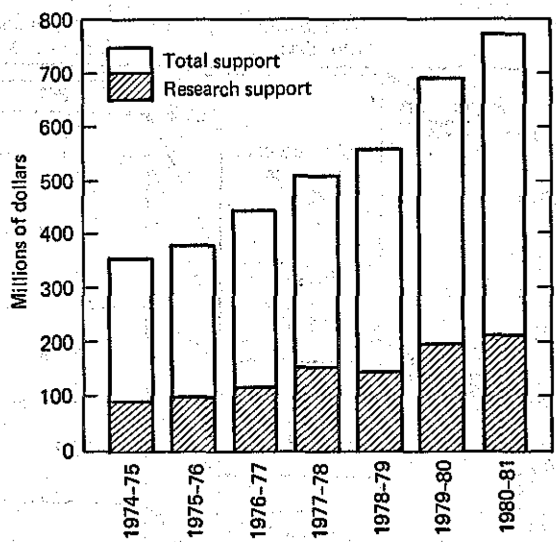
science colleagues. While about 50 percent of the faculty in the professional schools reported paid consulting, only 20 percent of the humanities professors were so engaged. While recent data are not available, it can be perceived that the percentage of faculty in the biological sciences engaged in consulting will have increased substantially.

The president of Genex Corporation has pointed out that in 1978 there were only 4 companies worldwide that specialized in recombinant DNA technology, with a total capitalization of roughly $20 million. By late 1981 there were 110 recombinant technology firms with about $700 million capitalization. In addition perhaps 120 companies worldwide are currently in recombinant DNA technology. Since there is insufficient in-house expertise, these companies are strongly dependent upon close collaboration with academic scientists. In time, the growing competence of biotechnology research in these companies will lessen the need for much of this collaboration.

University and Industry Research Collaborations—As the TRACES study illustrates, collaboration between industry and universities may be required to produce those revolutionary innovations that will enable the U.S. to maintain its competitive posture in commerce. Important changes are now occurring in science and engineering which have enormous potential payoffs in industrial use. These include recombinant DNA research and solid state physics as it applies to microelectronics. Other areas that have been less glamorous and perhaps less visible to the public include materials research and artificial intelligence.

Philanthropy—During 1980–81, colleges and universities reported $778 million in voluntary donations from corporations (Figure 6). This comprised 18.4 percent of the total voluntary support to colleges and universities from all sources, including alumni foundations and nonalumni individuals. Contributions from industry to educational institutions can be both charitable and for self-interest. U.S. industry benefits significantly from the trained students, as well as the research results that educational institutions provide. Industry is in a uniquely competent position to evaluate institutions and university projects for which contributions are sought, generally in areas that directly relate to the commercial interests of a company. This may skew corporate

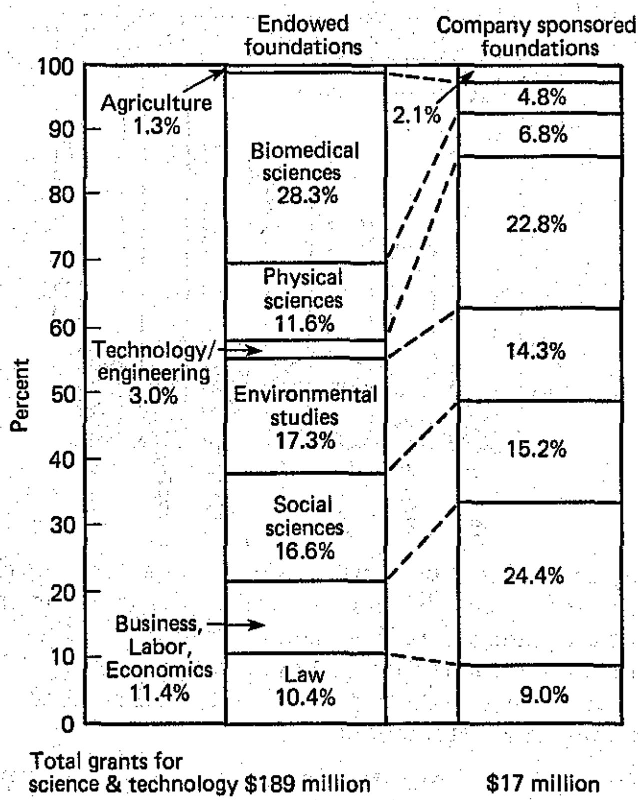
Fig. 6. National Estimate of Corporate Voluntary Support of Colleges and Universities, 1974–75 to 1980–81



gifts away from the humanities, but it does free unrestricted university funds from the more technical departments in order to support the humanities. The data in Figure 7 exclude some of the largest donors of corporate philanthropy such as IBM and DuPont, which make their gifts directly rather than through company sponsored foundations.

Industry Affiliates Programs—Industry affiliates programs provide a channel of convenient and direct communication between university faculty and graduate students and member company scientists and engineers. Access to students is considered one of the prime reasons that companies, through an annual membership fee, join affiliate programs. Annual symposia on campus give company representatives an opportunity to both learn of current research and gain first-hand knowledge of the nature of research conducted by graduate students. Affiliate programs also encourage campus participation by scientists and engineers from member companies in seminars, colloquiums, and other campus activities. Visits by faculty members to affiliate companies may give both a chance to learn more of each other's research concerns. Industry affiliates are encouraged to bring technical problems of a nonproprietary nature to the attention of faculty members. This

Fig. 7. 1979 Grants of Endowed and Company Sponsored Foundations for Science and Technology, by Field



may influence research directions at the university. Affiliate companies are usually provided early access to reports and publications in their area of interest, as well as the resumes of students.

Research Consortia—Research consortia, in contrast to industrial affiliate programs, are created to address specific mission oriented research when economies of scale are such that fragmented industry and university research is less likely to enable national industry to meet organized foreign competition. In fact, the U.S. Department of Justice has issued guidelines relaxing antitrust strictures, thereby enabling and encouraging collaborations involving many competing companies.

Financing for such consortia generally is a mix of corporate philanthropy, corporate research support, and federal research support. An example would be the Stanford University Center for Integrated Systems project that explores microelectronics (in particular, very large-scale integration [VLSI] microelectronic circuits). Such consortia may be stimulated by the highly publicized collaboration of Japanese government and industry in "target" technologies. These Japanese efforts both trained people for industry and provided the critical mass for new scientific and technical developments in the targeted technology.

Publications and Conferences—A free and open flow of ideas from universities to industry results from the swift publication in journals, scientific meetings, and conferences of the most current research results.

Scientist Exchanges—Definitive data are not available as to the nature and quantity of temporary appointments of company scientists to universities and of university scientists to companies. Judging from a 1983 discussion of university-industry interactions between the author and a group of German university presidents, this practice is much more prevalent in Germany than in the U.S.

Shared Equipment Use—Opportunities for collaborative use of expensive research equipment are often underexploited. There are several reasons for this. One is the proprietary nature of industry research. Another is the owner's priority for access to the equipment. In addition, universities seeking to make their research equipment available to industry and to share the equipment maintenance costs by charging for such access may be in jeopardy of violation of their nonprofit status.

The university can find itself in unfair competition with private companies that do not operate in a tax-free mode and are in the business of renting or leasing specialized research equipment. The NSF has certain guidelines for determining which NSF funded specialized research equipment at universities can be made available to industry in order to avoid such unfair competition. Clearly, if the research equipment is unique, there would not be a question of unfair competition.

A common organizational arrangement for access by industry to equipment, as well as to consulting services, is utilized by universities in the United Kingdom. An entity, separately incorporated, is established either on university grounds or conveniently adjacent to university grounds. This legal entity acquires the specialized research equipment and makes access available to industry. These entities often also act as agents for faculty consulting, typically adding a surcharge on the order of 10 percent to cover their effort in arranging such consultantships. Such entities also provide a locus for more applied research which may not be appropriate for academic departments.

Industrial Parks—To encourage close interaction of industry and universities and to facilitate local innovation, many universities or communities seek to establish research parks in close proximity to the university, such as Research Triangle in North Carolina. While there is considerable momentum in the U.S. to establish such industrial parks, only a few universities have been able to achieve any success. In summarizing its study of three forms of university-industry collaboration (research parks, cooperative research centers, and industrial extension services), the General Accounting Office claims ". . . the most dramatic contribution to innovation appears to be made by research parks."

Technology Licensing—Since the mid–1970s there has been a significant growth of on-campus university technology licensing departments. This is illustrated by the membership of the Society of University Patent Administrators (SUPA). At the end of 1975, the year of its first annual meeting, SUPA had 51 members; at its 1983 annual meeting, 226 individuals attended, and membership growth continues to increase. This development reflects desire of universities to establish their own technology licensing programs in contrast to using separate patent management organizations. It often is more economical for a university to use a patent management organization until its research volume reaches a stage where an on-campus organization can be justified.

Research Corporation, a nonprofit patent management organization, was established in 1912 based upon patents governing the electrostatic precipitator donated by Frederick Gardner Cottrell, then professor of chemistry at the University of California at Berkeley. Research Corporation retains a percentage of gross royalty income and utilizes such revenues in a program of research grants which total more than $60 million to date. Such "seed money" grants, usually to beginning scientific investigators, have been of great value, often leading to the establishment of major academic research programs for which continuing funding of larger amounts is obtained from federal research agencies such as the National Science Foundation.

Universities typically share between 15 percent and 50 percent of royalty income with inventors. At many universities all inventions of university staff, faculty, and students are required to be assigned to the university; at other universities, only those inventions which occur under sponsored grants and contracts are assigned to the university. However, because university inventions normally are undeveloped, requiring significant risk capital to develop a marketable product or process, a university typically must grant an exclusive license (for a limited exclusive period) to a company in order to encourage such investment. After this exclusive period, the intellectual property under the license is made available on a nonexclusive basis to all companies. Public Law 96–517 provides that first option to an exclusive license to a U.S. patent arising from federally funded research must be for U.S. manufacture.

The oldest university technology licensing program appears to be that of the Wisconsin Alumni Research Foundation (WARF) established in 1925 to exploit the patents of Professor Harry Steenbock for the benefit of the university. Through both royalty revenues and shrewd investment of them, WARF has given over $100 million to the University of Wisconsin. Annual donations have averaged about 5 percent of the university's research budget, and it has been suggested that this research funding has been a significant factor in the eminence of its research program, providing the important leverage of "free" research dollars without the extensive administration involved in proposal preparation, reporting, and other "strings" of federal and industrial research support.

The amount of direct license income (excepting any income from investments derived from such royalty revenues) has not been large at U.S. universities. During 1981–82, less than ten universities received more than $1 million in royalty revenues; the largest amount received was $2.5 million. Although greatly increased emphasis on technology licensing and university-industry interactions may cause royalty revenues to grow substantially in future years, technology licensing programs tend to have a greater influence on universities through establishment of industrial linkages than in direct royalty revenues.

FOSTERING UNIVERSITY-INDUSTRY INTERACTIONS

In general, the ease of university and industry interactions in the United States is looked at with envy by other countries, often singled out as a model for their own future growth. The interaction has stemmed more from the initiatives by the universities and industries than from the government. But the sustained, indirect involvement of government through its support of basic research at universities has enabled them to train students and foster innovation by industry. Increased university-industry research collaboration has been widely forecast for the 1980s. As the NSB report notes:

> Questions are raised about whether industry has sufficient resources available to increase allotments to university research; whether academic research can really benefit industry; whether academic freedom and openness of scientific communications can be preserved in the face of the constraints and temptations of commercial enterprises. But the new arrangements highlighted here reflect an optimistic mood that is grounded in an awareness that the problems and opportunities in technologically based industrial production are substantially different from those in the past.

The NSB report suggests three factors that characterize the present situation.

The first factor is that product and process improvement in innovation in some industries has evolved to levels of complexity that demand understanding of fundamental physical and biological phenomena, thereby requiring much higher levels of training in and use of basic science in engineering than the "cut-and-try" inventor of yore.

The second factor considers that incremental advances in narrow technical areas, which may have been characteristic of much industrial development in the past, are giving way to use of a broad range of science and engineering disciplines on complex, often ill-defined, problems or exploitations of new analytical capabilities. Hence, it is becoming increasingly difficult for any single industrial laboratory to fully encompass the required expertise. The

NSB report suggests that a partial remedy may be for industry to seek out "the pertinent skills" in the nation's universities.

The third factor notes that the rapid expansion of the nation's research and development system following World War II "has diffused research capabilities over a much broader range of institutions—academic and industrial—than before." This suggests the future unlikeliness that any single company can hold and maintain a leading edge on technical advance in a given area, such as DuPont's experience in polymer fibers.

The Challenges Ahead

In general, while there are certainly areas for improvement, the linkages between government, universities, and industry work extremely well, but there is no basis for complacency as competition is rapidly closing the gap. This is evidenced by the declining competitiveness of the United States in many market areas.

Productivity has been dropping in the U.S. since 1978, and our share of the world's market declined by 23 percent in the 1970s. In high-technology goods, the United States' share of the world market declined from 30 percent in the 1960s to about 20 percent by 1982. Selected industries in high technology showed even sharper percentage drops: telecommunications fell from 30 percent to 19 percent, scientific instruments declined from 30 percent to 15 percent, and pharmaceutical drugs decreased from 28 percent to 15 percent.

Egils Milbergs, director of the Office of Productivity, Technology, and Innovation of the U.S. Department of Commerce, perceives the following five basic "forces" where government policy is needed to accommodate the challenge of international competitiveness.

Industrial Targeting Strategies—This is illustrated by the Japanese, whose industrial targeting strategies have brought new products to the market much faster and with a much higher quality and reliability than U.S. firms have been able to do. Governmental actions to counter this competition include direct funding of research and development projects, preferential access to procurement, import protection, and other such measures.

Newly Industrializing Countries—Countries such as Mexico, Brazil, Saudi Arabia, Korea, and Singapore are expected to join in the competition for new markets in a large way. Competition from these countries is already beginning to affect Japan in areas such as steel and automobiles where U.S. competitiveness had been significantly eroded earlier.

Increased Rate of Technology Change—The rate of technology change acts to accelerate the obsolescence of plants and equipment. For example, the lifetime of research equipment twenty years ago was fifteen years, whereas in the 1980s, the lifetime is four years.

Changing Demographics—This fourth force for change is U.S. human resources. Milbergs notes that the new labor force has a higher expectation from the work environment, desiring to share more in management decisions and profits. Emphasis is being placed on more benefits and fewer hours. Dislocations are anticipated because of shortages of technically skilled individuals in key technology areas and pools of displaced workers in other technology areas. Milbergs observes:

> It is possible that by the year 2000, over half of the labor force in the manufacturing sector will be replaced because of automation, rationalization, foreign outsourcing, or the fact that we no longer have a comparative advantage in a particular manufacturing sector.

Change in Management Philosophy—Present U.S. industrial management is under sharp criticism for the emphasis of short-term results rather than long-term, more strategic investment. Another manifestation of this management system is the plethora of adversarial proceedings, one aspect of our society that other countries do not desire to emulate. To be a Master of Business Administration, Doctor of Medicine, or Bachelor of Laws has long been more prestigious among youth in our society than to be a chemist or engineer, yet these latter professions produce the products and services on which industry is based and which positively influence innovation.

Cecily Cannan Selby

6

Current Trends in Mathematics, Science, and Technology Education:

Implications for Technological Innovation

Introduction

Identification and encouragement of innovative thinking and practice and of technological understanding as educational objectives are notable omissions in all but a very few of the plethora of articles, studies, reports, and recommendations about elementary, secondary, and college education which mark our current time. At a time when our leaders of government, industry, and academe are extolling the crucial value of innovation in scientific and technological endeavors and when vast improvement is being called for throughout all of education in these areas, this is a puzzling omission. In the watershed of interest in and concern about schooling in general, especially precollege education in mathematics, science, and technology, the case is repeatedly made

---

CECILY C. SELBY *was a cochair of the National Science Board Commission on Precollege Education in Science, Mathematics, and Technology. Her broad professional career has encompassed the fields of science, education, management, and communications. A member of the board of RCA Corporation, the National Broadcasting Corporation, Avon Products, and until recently, Loehmann's Inc., as well as a trustee of Radcliffe College and the Brooklyn Law School, Dr. Selby is, in addition, a member of the Rockefeller University Council, the Corporation of the Woods Hole Oceanographic Institution, and formerly of the Corporation of the Massachusetts Institute of Technology.*

that technological advances require scientific and technological literacy in the total population, new skills in the work force, and an expanding pool of future scientists, engineers, and technologists. Students in this pool must be capable of both the solid achievement and the innovations that can lead the country's technological (and thus economic) advances.

Beyond one valuable report (*Learning Environments for Innovation,* U.S. Department of Commerce, 1980), little is said about preparing students at either the elementary, secondary, or college level for *innovative thinking and working*. This may reflect a resistance to teaching toward an objective that cannot be measured or one of several other assumptions: that such talent is too rare to be worth a concerted effort to develop, that we do not know how to develop it, or that it is really not that important. Alternatively, it could mean that the problems faced in moving our entire school population a giant step ahead are so monumental that issues of individual creativity appear to decision makers to be of much lower priority. These assumptions must now be seriously challenged.

NEEDS OF A TECHNOLOGICALLY DRIVEN SOCIETY

Responsible leaders in all sectors recognize that a technologically driven society requires some degree of scientific and technological literacy for all who would live productively within it. Education for appropriate understanding and skill in mathematics, science, and technology must thus move to share center stage with the other liberal arts throughout all of schooling. What instructional objectives should be included in mathematics and sciences and be available to all students? What do we mean by technological literacy? Objectives usually mentioned include the ability to solve problems, to master appropriate subject matter, and to approach issues with rigor and the ability to quantify and analyze. Should they also include encouragement, or even legitimization, of some students' interest in and ability to deal with ambiguity, to take risks in thinking or in extrapolation from observations, or to explore radical, extreme alternative hypotheses for problems that are posed?

That such objectives are not addressed in most current educational planning, particularly at the precollege level, is understandable when one considers the historical trends which led to the educational policies and practices of today. Neither innovation nor technology has yet been considered within overall goals for educational planning, for teacher training, for school organization, or for precollege curriculum development. With respect to innovation, is it that we consider the role of public education primarily one of socialization which should reward conformity in thinking and behavior, encourage allegiance to hierarchical organizations (such as the traditional student government), and take satisfaction with the body of knowledge being communicated? Have we assumed that we need only the few "elite" innovative and creative thinkers who would emerge or would be cultivated by the more privileged educational system or opportunities such as science fairs and talent searches outside formal education? With respect to technology, have we considered it primarily an issue of job training or vocational education? Is it again a subject for out-of-school learning up to the level of preprofessional education?

It will be instructive to ask these questions in the light of the historical and politico-sociological trends that brought us to today and then to consider changes in educational objectives required by current conditions and future needs—particularly those related to technological development and innovation.

Historical Review: How Did We Get to Where We Are?

Before Thomas Jefferson's leadership in committing the United States to free public education, privately funded institutions for education (such as William and Mary [1693], Harvard [1636], and the various academies of New England, including the Boston Latin School [1635]) were established in the colonies. These schools and colleges were direct descendants of the aristocratic "liberal education" of England and Europe, stressing the classics, literature, mathematics, and natural philosophy (science). In the U.S. the Ordinance of 1785 set aside public lands for the support of schools in every township, proclaiming that "schools and the means of education shall forever be encouraged." Initially the program at public secondary and elementary schools followed the classical tradition but included some practical skills following Benjamin Franklin's recommendations regarding "useful learning."

During the late 1820s in England, a reaction arose to discrepancies between the quality of most elite private grammar ("public") schools and those available to others for lower fees. The leadership of this movement came from the middle class, whose income was derived largely from commerce and industry. They sought more utilitarian ends for their students and founded schools managed by a committee, proprietors, or a managing board (in today's language) with an emphasis not so much on producing gentlemen, but rather individuals for industry, commerce, and the services. While the curriculum remained classically based, it included more "modern" subjects and much greater emphasis on mathematics. Often schools were organized for students over the age of fourteen into classical and modern divisions. According to Geoffrey Howson *(A History of Mathematics Education)*, this movement led to considerable interest in and attention to the methods and rationale for the teaching of mathematics in the United Kingdom which influenced developments elsewhere.

Particular problems of teaching and learning mathematics gradually became more explicitly and professionally scrutinized. For example, in 1836 Augustus De Morgan, writing on the goals of mathematics, stated that it was not sufficient to justify mathematics a place in the school curriculum because it is useful. He argued that law, medicine, and architecture are also useful but are specialized subjects to be embarked upon only once a general education has been completed. He, and most educators following him, saw the principal contribution of mathematics to general education as a vehicle for the enhancement of the faculty of reasoning. De Morgan addressed the dual aspects of mathematics —the practical and the contemplative (an important continuing consideration as one deals with this subject):

> The actual quantity of mathematics acquired . . . is . . . of little importance, when compared to the manner in which it has been studied, at least as far as the great end, the improvement of the reasoning powers, is concerned. We might be tempted to say, let everyone learn much and

> well; well in order that the habits of mind acquired may be such as to act beneficially on other pursuits; much in order to apply the results to mechanics, astronomy, optics [etc.] which can never be completely understood without them.

In U.S. developments of about the same era, the initial concept of the liberal arts on which the early institutions were founded was picked up within the Jeffersonian education philosophy: the principle of free higher education for those who have the talent and motivation to benefit from it. This became accepted political philosophy with the Ordinance of 1785 for schools and the founding of the University of Virginia (1819) as a public state funded college.

UTILITY AND EDUCATION

The next trend in U.S. education, unique in its pervasiveness in the Western tradition, was the Jacksonian emphasis on utilitarian ends. Such objectives for education became reality with the founding of land-grant colleges for agriculture and the mechanical arts under the Morrill Act of 1862. Elementary and secondary schools participated in this utilitarian vocational thrust by means of the Smith-Hughes Act of 1917 and, later, The Vocational Education Act of 1963.

During the latter part of the nineteenth century, the primary obligation of educational institutions was perceived to be to provide students with the skills and attitudes that would allow them to perform the tasks the society needed. When Justin Morrill, Republican representative from Vermont, introduced his legislation in 1856, his intent was for students from each congressional district to receive a scientific and practical education at public expense. He believed the nation needed this new expertise to increase its productivity and found that existing colleges were little interested in providing instruction in subjects such as science, agriculture, and mechanics. Apparently Morrill recognized the potential benefits to *individuals* of state supported, low-tuition colleges, but these advantages were inadequate to persuade his colleagues to pass his original bill. His bill had considerable opposition, taking six years from introduction to passage. By this time, amendments to the legislation provided for federal land grants to each state to establish universities providing instruction in agriculture, the mechanical arts, and training for military officers. Morrill's argument, although unsuccessful in the late nineteenth century, would prove to be successful in gaining adherents in the twentieth century when equal education opportunity became a profound educational goal.

According to reviews by Patricia Albjerg Graham, the variously inspired efforts from 1862 to 1914 to provide federal aid to higher education had one unifying theme—that the product of that education, whether it be research, demonstrations, or instructed students, would be valuable to the United States in terms of improved industry and agriculture. In 1870 Calvin Woodward, a Harvard mathematician, complained that schools were training students to be "gentlemen" rather than preparing them for work.

The parallel development of the land-grant colleges of the nineteenth century and the new emphasis on research in U.S. universities later in that century (e.g., at Johns Hopkins and Clark) continued the side-by-side development of utilitarian and intellectual liberal arts approaches and was successful in strengthening both the intellectual and technological base of the American economy and society. Indeed, for the most part, the nation retained its confidence in the overall system until after World War II.

Harvard had instituted the Bachelor of Science degree in 1851 to distinguish between completion of a program focused on modern scientific subjects (by omitting classical studies) and completion of a traditional liberal arts program grounded in the classics. At Bowdoin a comparable distinction was made by whether or not Greek and Latin were offered for entrance. By the beginning of this century at Harvard and elsewhere, an elective system of courses was introduced, pushing out the old classical model. Distribution requirements were then added and organized by departments to try to maintain some sense of a required core and a stable program. Leadership in redefining what such a core should be was provided by Columbia University. Based upon its World War I experience in educating officer candidates on the background of the conflict, Columbia College, in

1923, developed and introduced its two-year sequence called "Contemporary Civilization," which served as a model for programs in general education later introduced in the 1930s and 1940s (e.g., Harvard's "Report on General Education" in the late 1940s).

CREATIVITY AND EDUCATION

Starting in Europe and England with Comenius, Rousseau, Spencer, and Froebel and continuing in America with the leadership of John Dewey, questions about how people learn—and, therefore, how to teach them—gave birth to the progressive movement in education of the 1930s. The major educational trend developed several significant independent schools and affected teacher training, individual teacher initiatives, and movements such as that of the "open classroom." Emphasis on the individual needs of and the creativity inherent in each child led to discovery-and-inquiry methods of teaching, individualized instruction, and independent study.

At the beginning of the twentieth century, individual educational outcomes were beginning to take precedence over societal ones, initially for the children of the well-to-do. Partly owing to the influence of the progressive movement, some educators were beginning to believe—and to argue—that their primary obligation was to the child and not to society. Perhaps another reason why many educators in the first half of the twentieth century were willing to shift focus from the society to the child was, as Graham suggests, because of their changing view of American society. If one believed that America had accomplished the massive initial tasks it faced as a nation—conquering frontiers, assimilating immigrants, and becoming accepted as a world power—then perhaps it could afford to concentrate on the needs of its children and on unleashing their creativity.

The attempt to enhance creativity and the effort to increase educational opportunity were luxuries that many saw the nation could not afford when the energies of its citizens were required for the more pressing tasks of gaining preeminence in the world. This point will be important to remember as we look at the thrust of most educational recommendations being made in the late twentieth century with emergent concern about U.S. preeminence as a world power.

The educational issues we are facing today thus arise from a tension among the four educational approaches that brought us to this point: liberal arts intellectualism, Jeffersonian egalitarianism, Jacksonian utilitarianism, and the student-centered developmental approach of progressivism. If the inclusion of creative thought and action in educational goals is a luxury for the few, then how can the many have true access to fields such as science, mathematics, and engineering where the introduction of concepts and processes associated with "elite" education at an early age can be shown to be the only true access? How can we do justice to the extraordinary variety of cultural backgrounds of students in our precollege and college systems in an education (including technology) for useful participation in society and also provide access to opportunities for the highest level of intellectual, innovative, and creative endeavor within the fields of mathematics and science? How can we keep children's own interests and talents alive throughout a "basic" education considered necessary to provide them with skills that contribute to society? How can schools help children retain their individuality and integrity and yet prepare them to live in an industrial society requiring conformity without being either alienated or crushed by it?

The Current Status of U.S. Education: Where Are We?

The 1983 report of the National Commission on Excellence summarizes well the depth and breadth of concern about current school and college conditions:

> Our nation is at risk. Our once unchallenged preeminence in commerce, industry, science, and technological innovation is being overtaken by competitors throughout the world. . . . We report to the American people that while we can take justifiable pride in what our schools and colleges have historically accomplished and contributed to the United States and the well-being of its people, the educational foundations of our society are presently being eroded by a rising tide of mediocrity that threatens our very future as a nation and as a people.

Focusing particularly on elementary and secondary education in mathematics, science, and technology, the National Science