condoms or pills and the other half take intrauterine devices or vasectomies, over a 5-year period the direct acceptor-year cost is less than $4.
5. A "contraceptor" is a person who voluntarily accepts (uses) contraceptives.
6. The above numerical example was the basis for President Johnson's statement to the United Nations General Assembly in San Francisco that $5 spent on birth control was worth $100 used for economic development.
7. The original precursor of the model used here was described by S. Enke [*Raising Per Capita Income Through Fewer Births*, General Electric-TEMPO, Santa Barbara, Calif., 1968)].
8. The gross rate of reproduction is the number of female live births a representative woman would be expected to have if she survived to age 50.
9. In these calculations t is 0.015, n is 0.5, and k is 0.35. That n and k sum to less than unity implies diminishing returns to workers and capital because of land-resource scarcity. Annual savings for investment equal 0.25 V minus $35 P approximately.
10. Income per head of population slightly exaggerates improvements in economic welfare when it rises because of shifts in age distribution from children to work-age adults. In equivalent consumer units a child is here 0.75 of a work-age adult. In the low-fertility case the increase in income per equivalent consumer is from $171 in 1970 to $394 in A.D. 2000.
11. S. Enke, *Quart. J. Econ.* **77**, 55 (1963).
12. Suppose the birth decrement is X and the fertility rate is y. Then a first crude approximation of the number of "contraceptors" is X/y. However, there may have to be three fewer conceptions for each two births, because of abortions and miscarriages. And of every three women of fertile age, only two may be at risk of pregnancy, with the other one being either not exposed to intercourse, sterile, or already pregnant at the time. Given these ratios, these two effects cancel, leaving the X/y relation. Few contraceptive methods are perfectly reliable in practice, and this may raise X/y by 1.1 times. Thus, if y is 0.2, for every one birth less there must be 5.5 women attempting contraception. At $5 per contraceptor a year, the cost of preventing a birth is then $27.50.
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Scientific Research and the Innovative Process

The dialogue between science and technology plays an important, but usually nonlinear, role in innovation.

William J. Price and Lawrence W. Bass

The process of change is a central feature of the individual and organizational environments of modern man. The creating of new attitudes, new ways of doing things, new forms of social relationships, new products, new industrial practices—in short, innovation in the broad sense of the word—demands our attention, not only because of the results of change but also because of the extent to which the process of change is becoming a way of life.

Understanding the innovative process is therefore of paramount importance. The part played by technology—and we use this term to include product- or process-directed applied science—is generally understood and accepted, but what about basic research which has as its principal goal the discovery and organization of knowledge? Does scientific research play a central role in the innovative process, and, if so, how?

The conventional views based on the idea that innovation usually starts from new understanding give the answer "yes." We also believe that the answer is certainly "yes." It has become increasingly clear, however, especially through several recent studies, that the demonstration of the role of science in innovation requires focus on the nature and intensity of the dialogue between the scientific and technological communities, rather than on a preoccupation with the role of new scientific knowledge as the fountainhead from which innovation springs.

Innovation, Invention, and Research

The innovative process includes invention. Invention is the creation of an idea and its reduction to practice; innovation is the bringing of the invention into widespread use.

Scientific research is characterized by the continuous accumulation and ordering of new knowledge. Each research contribution generally builds on what has gone before. Concurrently, ordering takes place through laws and theories evolving within the scientific disciplines.

The process of sophisticated invention is related to orderly arrangement in the continuum of knowledge, because such invention requires the existence of a body of relevant information before ideas can come to fruition. Since the process of invention requires, however, a simultaneous connection of the knowledge with an external situation for potential utilization of the invention, it is a special case of ordering. Nevertheless, the dependence of invention on the relevant body of science means that innovation can be related to the search for new understanding, particularly in radically new technologies, such as the transistor and nuclear-energy technologies.

World War II undoubtedly had a profound influence on conventional views concerning the relationship of science and technology. Many persons who were engaged in scientific research when the war broke out helped exploit scientific knowledge, thus bringing about many important innovations in a short time. Unfortunately, from the standpoint of understanding the role of science in innovation, the fact is often overlooked that, during the war emergency, the vast majority of the scientists involved were working not as basic researchers but as technologists.

It is not surprising, therefore, that innovation is often viewed as an orderly process, starting with the discovery of new knowledge, moving through various stages of development, and eventually emerging in final, viable form.

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According to this "linear" model, innovation seems to be a rational process, essentially similar to the other, more systematic functions of an organization. The assumption is that it can be analyzed into component parts and controlled rationally—that is to say, planned, programmed, and managed much as other, more routine activities are.

The studies reviewed here indicate that the "linear" model is not typical. One appreciates the nonrational nature of the innovative process when one notes that the more novel the invention is, the less orderly and predictable is the process. The introduction of a new cake flour may be managed rationally. On the other hand, radical innovations often require that the organizations which adopt them undergo major internal changes, many of which cannot be programmed in advance.

Recent Studies of Innovation

Several studies of the innovative process have shed considerable light on the role of scientific research. We review three of these briefly and refer to several others.

Materials Advisory Board study. A panel of R & D managers, led by Morris Tanenbaum, director of research and development of the Western Electric Corporation, recently completed a study (*1*) of research-engineering interactions for the Materials Advisory Board of the National Research Council. Each participant selected and documented a case which he believed clearly illustrated productive collaboration between scientific research and engineering. Ten case histories were analyzed. They concerned developments in metals, ceramics, and synthetic polymers. The participants searched the records for patterns of events and circumstances which recurred frequently.

The point which stood out most clearly was that, in nine of the ten cases, explicit recognition of an important need was identified as a major stimulus in bringing about the research-engineering interactions. Basic research by itself rarely produced a technological opportunity which was quickly recognized and developed. Far more frequently, an urgent need initiated a search for a solution from prior basic knowledge. An individual with a well-defined concept of a technological need started the successful research-engineering interaction.

In most of the cases, the science that led to the technological solution was available before the dialogue began. Rarely did the technological need directly stimulate generation of the science used to solve the problem. Also, the fruitful interactions occurred between organizationally independent groups which were often geographically separated.

In only three cases did the majority of the research-engineering interaction events involve in any way individuals whose principal interest was in basic research. However, if consideration was restricted to development of the idea through the invention stage, then in more than half of the events interaction with a basic research finding or a basic researcher was found to be important.

Dow Chemical Company study. A study made by compiling and analyzing the histories of several innovations important to Dow Chemical Company has recently been published by Boyer and his associates (*2*). Members of the company team conducting this investigation found that successful innovations typically involved the complex interplay of concepts and people along a highly branched and unpredictable path. They concluded that "uniqueness cannot be programmed." Their story is concerned with "how different people and different groups interact with each other across substantial barriers (groups, disciplines, geography, etc.) to produce unique results that no individual or no single group is likely to accomplish alone." Important sources of scientific knowledge were research initiated in various parts of Dow because of scientific curiosity, Dow consultants from universities, new employees who had been recently engaged in scholarly research in graduate school, visiting lecturers, technical meetings, journal articles, and input from management.

In summary, the group listed the important sources of uniqueness as access to a large number of original research investigations, however inspired; sustained financial support; means to facilitate communications between groups and disciplines; a creative approach to the marketing of unique concepts and ideas; and a desire for uniqueness on the part of management.

Air Force study. Recently the Air Force Office of Scientific Research (AFOSR) made a study (*3*) of the benefits accruing to this service through the support of basic research, primarily in universities, during the last decade and a half. This study, which included material obtained from a large group of persons with thorough knowledge of these investigations—for example, principal investigators—has provided considerable specific information on how the innovative processes pursued by the Air Force have benefited from this support.

The study shows that AFOSR has helped "colonize" many scientific areas which have turned out to have special relevance to important applications. "Colonizing" may be described as increasing the chance of important discovery in an area by accelerating the world's scientific activity in that field. Air Force programs for the support of scientific research and such other activities as symposia, amplified by funding from other sources, have affected very significantly the rate of development of vital areas—for example, hypersonics, magnetic resonance spectroscopy, control theory, visual perception, mass transfer cooling, information theory, cryogenics, and quantum electronics.

This study also found many specific instances in which AFOSR-supported scientific research had provided important inputs to weapons development at all phases of the research, engineering, and production cycle. Contributions were identified with new or improved manufacturing procedures, design techniques, instrumentation, and weapons-systems-component concepts, to mention a few cases. In addition, many of the scientists supported by AFOSR have been helped to achieve and maintain their expertise, and this in turn has made it possible for them to consult and make other direct contributions to the innovative process.

Finally, both in the AFOSR study and in the Department of Defense's Project Hindsight (*4*), the importance of Department of Defense research support of postgraduate education was underlined. For example, at any one time the AFOSR is providing at least partially for the research of more than a thousand doctoral candidates and of many more candidates at the master's level. The overall impact is apparent from the observation that these graduate students rank at the top of the nation's younger generation of scientists and are developing their expertise in areas particularly relevant to Department of Defense interests.

Additional studies. Sumner Myers (*5*), in a survey of 567 innovations in the housing, computer, and railroad industries, placed particular emphasis on the source of externally generated scientific data and on the impact of these data in stimulating technological developments. He concluded that new scientific knowledge seldom starts the process but, rather, that successful innovation comes from the synergistic combination of several ideas, many derived from unrelated R & D.

The Illinois Institute of Technology Research Institute, in collaboration with the National Science Foundation, reported (*6*) a historical tracing of events leading to five major technological innovations (magnetic ferrites, video-tape recorders, oral contraceptive pills, electron microscopes, and matrix isolation). Of the 341 distinct key research and development events judged to be important to these innovations, three-fourths came from work believed to be motivated by the search for knowledge and understanding without special regard for application.

Marquis and Allen (*7*), in studying information flow in various R & D laboratories, have been struck with the important role of persons to whom colleagues often turn for technical advice and critiques. These persons, whom they call "technological gatekeepers," are typically heavy readers who also have wide contacts with scientific and technical workers in other organizations, including active researchers in universities.

Rosenbloom and Wolek (*8*) also underlined the importance of information obtained from the external scientific and technological communities. They reached their conclusion by analyzing the responses of 2000 scientists and engineers from 13 establishments of four corporations and the responses of 1200 members of the Institute of Electrical and Electronic Engineers, who were queried on where and how they received useful information from a source other than their immediate circle of colleagues.

Still another valuable source of information about the interaction of science and technology is the National Academy of Sciences Report for the U.S. House of Representatives Committee on Science and Astronautics (*9*). For example, Suits and Bueche, in analyzing many case histories in the General Electric Research Laboratory, have emphasized the diversity in the types of innovations, the source of the "nucleating event," and the nature of the flow of crucial information.

Several recent articles in *Science* connecting frontier fields of research with developments in technology also give important insights. For instance, Townes (*10*) emphasizes the element of surprise, which could not be planned, in the innovations made possible by quantum electronics. Also, Shirley's discussion (*11*) of the interaction between experimental nuclear physics and the development of instrumentation for chemical research illustrates the synergistic effect in what might appear to be two quite independent fields.

In summary, these studies show three things.

1) Although the discovery of new knowledge is not the typical starting point for the innovative process, very frequently interaction with new knowledge or with persons actively engaged in scientific research is essential.

2) Innovation typically depends on information for which the requirement cannot be anticipated in definitive terms and therefore cannot be programmed in advance; instead, key information is often provided through unrelated research. The process is facilitated by a great deal of freedom and flexibility in communication across organizational, geographical, and disciplinary lines.

3) The function of basic research in the innovative process can often be described as meaningful dialogue between the scientific and the technological communities. The entrepreneurs for the innovative process usually belong to the latter sector, while the persons intimately familiar with the necessary scientific understanding are often part of the former.

Model of the Innovative Process

The innovative process may be described (*12*, pp. 21–31) as a complex feedback-type information processing system. One can bring the role of scientific research into focus by looking for the individual science-technology interactions in this information flow. To achieve this focusing, the nature of both the scientific and technological communities should be kept in mind.

Historical and sociological studies (*13*) suggest that science and technology are two relatively independent worlds, each with its own values, goals, and methods. The members of the scientific community pursue the goal of the discovery and organization of new knowledge. New science may forge ahead with relative independence from an ambient technology, although the results of research are made available to both scientists and technologists in many ways. Members of the technological community pursue innovation and related activities. Technological events are usually initiated within technology, in the presence, however, of an ambient, but often important, science.

Thus, the gross picture is that technology usually feeds upon technology and scientific research usually feeds upon other science. It is essential, however, to emphasize the intensity, variety, and effectiveness of the dialogue between the two communities.

This interface is dynamic, varying greatly among different science-technology pairs, and also chronologically for a given area of application. Industries such as communications and computers are much more closely coupled with science than the railroad and agricultural-equipment industries are. Transistor technology was more closely coupled with solid-state physics 15 years ago than it is today.

Any study, such as the Department of Defense Project Hindsight (*4*), which concentrates on isolating the points of origin of technological events will usually reveal that they lie within technology. However, it is invalid to conclude from this finding that "undirected" research—that is, research in the scientific community, not related directly to the technology concerned—was of little help to the innovation which occurred. On the contrary, the other studies cited in this article make it abundantly clear that this research is a highly essential part of the innovative process. It is unfortunate that some people have quoted the first interim report of Project Hindsight, concerning the small identified contribution of "undirected" academic research to weapons system development, without taking into account the severe limitations of the Project Hindsight methodology (*4*) for evaluating the contribution of such research.

Managerial Aspects

Thus it is abundantly clear that any organization dependent on a science-based technology is, in turn, highly dependent on the scientific community. The discussion of the organization and financing of basic research is beyond the scope of this article. Suffice it to say that the factor of surprise as a characteristic of technological development signifies that the self-interest of mission-oriented organizations requires strong support of basic research throughout the world, and appropriate design of the organizations' own activities in support of science, particularly in maintaining effective dialogue with the international scientific community (*14*). Because the utilization of new scientific knowledge in bringing about innovation increases in proportion to the intensity and effectiveness of the collaboration between the generators and users of information, the nature and mechanisms of these interactions, often called "coupling," deserve exploration (*15*).

Coupling is important to many members of the scientific community, whether they are university scientists seeking closer connection with the innovation being pursued by industry or government, or whether they are industrial or government scientists doing basic research in mission-oriented organizations. Coupling is especially important to technologists, who typically take the initiative by looking for solutions to problems. Specific goals and plans for the use of technology need to be defined, to provide a focus for interaction at the interfaces (*16*). The objectives should be dynamic, because progressive modification is usually required in the light of new knowledge and experience accumulated during the process.

By separating the several aspects or stages of introducing an innovative product, process, or service, one can appreciate the variety of the opportunities for coupling with basic science. Typical major stages of progress, correlated with the functions having the primary responsibilities for each stage, are given in Table 1. The terminology in Table 1 is that of an industrial organization, but a similar sequence of stages occurs, for example, in the introduction of a new weapons system.

As an illustration, let us consider the stage of "process definition." The Engineering Development group has primary responsibility, but needs cooperation and advice, in varying depth, from several other corporate functions. Product specifications should be under review by Applied Research and Market Research to confirm the acceptability of materials made on a pilot scale. The proposed raw materials should be scrutinized by Purchasing, and the process requirements and facilities should be evaluated by Central Engineering and Manufacturing. Preliminary cost estimates and capital requirements should be examined by Finance, while legal restrictions and patent matters should be considered by the appropriate specialists. Management may need to give the project interim approval, and Basic Research should be asked whether new knowledge bearing on the competitive feasibility of product or process has become available.

Table 1. Major development stages for the application of criteria for feasibility.

Stage	Activity with primary functional responsibility
Product concept	Applied Research
Product formulation	Applied Research
Process definition	Engineering Development
Marketing evaluation	Market Research
Process confirmation	Manufacturing
Market confirmation	Marketing
Comprehensive review	All departments
Decision to implement	Management
Corporate mobilization	All departments

In industry it is becoming widely recognized that interactions between the specialized skills represented in different organizational functions should be encouraged throughout the course of development and commercialization. To shorten the path between the discovery of new knowledge and its applications, often several types of expertise need to be focused at successive stages. This may be best accomplished through the interdisciplinary team approach. The scientific background required by the team may be provided by a member of the basic research laboratory or by a consultant.

Nature and Mechanism of Coupling

The intensity of interaction between scientists and technologists provides a basis for classifying coupling into four main types. The divisions between these types are by no means sharp.

1) "Indirect coupling" denotes lack of direct dialogue between the originators and the users of new scientific knowledge. The technologist, recognizing that recorded knowledge is likely to have an impact on the solution of his problem, conducts a survey of the literature to locate pertinent items. Here, technologists with recent postgraduate education in the relevant science have the advantage. Review articles and up-to-date monographs are of help in locating available sources of information.

Table 2. Frequency of use of coupling method.

Category of coupling	Number of coupling events		
	Suits and Bueche*	Frey and Goldman*	Tanenbaum *et al.*†
1) Indirect	8	5	25
2) Passive availability	28	17	43
3) Direct participation	38	18	40
4) Gatekeeper	14	2	6

* See (*9*). † See (*1*).

It is the consensus in many organizations, particularly in those with a strong basic research component, that indirect coupling is not adequate to support an aggressive program of development in areas where many scientific discoveries are being made. The chances that technologists will comprehend the applicability of rapidly proliferating knowledge and that academic scientists will make the best possible selection of pertinent subjects of research are, it is felt, too limited to provide a sustaining base for the desired rate of innovation.

2) "Passive availability" describes the situation in which scientists are open to approach by technologists desiring their advice, but take no special initiative to stimulate the dialogues. The technologists select the areas in which they believe they can obtain help and then establish contacts with specific scientists in their quest for assistance. This process may be stimulated by establishing joint advisory committees of scientists and technologists, both for selecting research areas and for working on problems of development. If university and institutional researchers are given information about industry's and government's need for scientific knowledge, they are likely to adopt a more positive attitude toward cooperation in problem solving.

3) Direct participation in project work by scientists as consultants or advisors establishes a two-way partnership. Establishment of joint workshop groups promotes knowledge of interface problems on the one hand and of information resources on the other. Organizational and financial arrangements that allow scientists to take part in demonstration phases of projects induce appreciation of the difficulties of practical application. Exchanges of university and government-industry scientists can be productive. Limited support of applied research in universities can catalyze coupling.

One of the most successful techniques for establishing direct participation is the organization of interdisciplinary project teams, discussed by Bass (*17*) and by Hughes (*18*). In this type of operation each problem is assigned to a group of individuals, with different skills and backgrounds, who often apply their expertise on a part-time or interim basis. A team leader coordinates the attack: he determines the degree of effort needed from each member, and the timing of that effort; establishes the pattern of communication and liaison; and has overall responsibility for completion of the task.

The interdisciplinary approach, whether formal or informal, is also a pragmatic technique for information retrieval. Each participant may be expected to have thorough knowledge of his specialty. When his efforts are focused on a specific objective, he can effectively review and select those items that are important to the solution.

4) The "gatekeeper" function is a means used by many organizations to encourage coupling by direct action. A few gifted individuals are assigned responsibility for seeking instances in which an exchange of information between scientists and engineers is thought to be desirable and then for bringing about such exchanges either directly or through stimulation of the appropriate dialogues.

"Gatekeepers" must be competent scientists with broad research interests yet with a bent toward practical applications. This combination of talents is rare, and success in this operation also requires the attribute of being able to communicate effectively and persuasively with both scientists and technologists. "Gatekeepers" may, and often do, act on a part-time basis, continuing direct participation in research projects to maintain their intimate contact with new knowledge in their spheres of interest.

5) The technique of communication used depends on many factors, such as the nature of the problem, the size and type of organization, the physical location, and the personalities of the individuals. When we analyzed 244 coupling events identifiable in 27 of the case histories discussed by Suits and Bueche (see *9*), Frey and Goldman (see *9*), and Tanenbaum *et al.* (*1*), we found passive availability and direct participation predominating (see Table 2). Even though the identification and classification involved considerable subjectivity, the parallel structure of the data suggests that this is a valid conclusion.

Summary

It is certainly true that basic scientific research is an essential part of the innovative process. It is important that we continue to attempt to understand further, and to communicate, the real nature of this role. It is also essential that we use this understanding to ensure that society obtains maximum benefit from scientific research and that the scientific community benefits from these growing relationships.

We believe that in many organizations the scientific and technological communities are quite effectively coupled now, but the growing importance of the process of change requires greater attention to such coupling. The Federal Council of Science and Technology program for improving the relationship between federal laboratories and universities (*19*), the American Chemical Society studies of university-industry relations (*20*), and the strong plea made by Herring (*21*) for additional review articles are important strides in this direction.

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