# An Overview of Innovation

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*Models that depict innovation as a smooth, well-behaved linear process badly misspecify the nature and direction of the causal factors at work. Innovation is complex, uncertain, somewhat disorderly, and subject to changes of many sorts. Innovation is also difficult to measure and demands close coordination of adequate technical knowledge and excellent market judgment in order to satisfy economic, technological, and other types of constraints—all simultaneously. The process of innovation must be viewed as a series of changes in a complete system not only of hardware, but also of market environment, production facilities and knowledge, and the social contexts of the innovation organization.*

## INTRODUCTION

Commercial innovation* is controlled by two distinct sets of forces that interact with one another in subtle and unpredictable ways. On the one hand are the market forces, that is, such factors as changes in incomes, relative prices, and underlying demographics that combine to produce continual changes in commercial opportunities for specific categories of innovation. On the other hand, the forces of progress at the technological and scientific frontiers often suggest possibilities for fashioning new products, or improving the performance of old ones, or producing those products at lower cost. Successful outcomes in innovation thus require the running of two gauntlets: the commercial and the technological.

Since innovation, by definition, involves the creation and marketing of the new, these gauntlets, singly and in combination, make the outcome of innovation a highly uncertain process. Thus, an important and useful way to consider the process of innovation is as an exercise in the management

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*We use the modifier "commercial" to indicate that in this chapter we exclude military innovations, which have certain distinctly different characteristics.

and reduction of uncertainty. Generally, the greater the changes introduced, the greater the uncertainty not only about technical performance but also about the market response and the ability of the organization to absorb and utilize the requisite changes effectively. This strong correlation between the amount of change and the degree of uncertainty has important implications for the nature of appropriate innovation under various states of knowledge and at various points in the life cycle of a given product.

The systems used in innovation processes are among the most complex known (both technically and socially), and the requirements for successful innovation vary greatly from case to case. Thus, a general discussion of innovation requires the exploration of a number of dimensions and the use of caution in deciding what can be generalized. Such a discussion must also make sure that the implicit models of the innovation process are adequate, since the use of simplistic models can seriously distort thinking. All of these matters will be dealt with, to some degree, in this chapter.

Within the technological realm it is possible to confine one's thinking exclusively to certain kinds of performance criteria. If one were indifferent to cost considerations, for example, one could devise a large number of technically feasible alternatives for improving the speed of an airplane, or the durability of an automobile, or the purity of a chemical. But technical success (or any purely mechanical measure of performance) is only a necessary and not a sufficient condition in establishing economic usefulness. Indeed, it is obvious from a casual examination of the proceedings in our bankruptcy courts that an excessive or exclusive preoccupation with purely technical measures of performance can be disastrous.

It is worth recalling that the overwhelming majority of the inventions recorded at the U.S. Patent Office were never introduced on a commercial basis. It is also worth recalling that, among more than 1,800 successful innovations tabulated by Marquis (in Tushman and Moore, 1982), almost three-quarters were reported as having been initiated as the result of perceived market needs and only one-quarter from perceived technical opportunity.

At the same time, many characteristics that would have important advantages in the marketplace cannot be realized because they cannot be achieved with current technical infrastructure or are barred by the workings of nature. For example, the laws of thermodynamics place an absolute limit on achievable efficiencies of machinery and on achievable fuel consumption of airplanes and automobiles. The limits of known metallurgical practice place a current feasible upper limit on the temperatures used in numerous machines and processes, and that limit yields only slowly under continuous scientific and developmental efforts. The accuracy of parts is controlled by the available manufacturing processes, and that in turn limits what can be made to work reliably at a given point in time.

As noted, both technical and market needs must be satisfied in a successful innovation. In innovation, one nearly always deals with the optimization of many demands and desiderata simultaneously. Successful innovation requires a design that balances the requirements of the new product and its manufacturing processes, the market needs, and the need to maintain an organization that can continue to support all these activities effectively.

If a technological improvement is to have a significant economic impact, it must combine design characteristics that will match closely with the needs and tastes of eventual users, and it must accomplish these things subject to basic constraints on cost (and frequently other, legally mandated requirements). Commercial success turns on the attainment either of cost levels that are below available substitutes or creation of a superior product at a cost that is at least not prohibitively expensive in comparison with lower-performance substitutes. Higher performance is commonly attainable at a higher price. However, to choose the optimal combination of price and performance at which a firm should aim calls for considerable knowledge of market conditions, as well as a high order of business judgment in making decisions with respect to timing. Success demands not only selecting the right cost and performance combination, but also judging just when the timing is right for the product's introduction.

In the early 1950s, the British introduced a commercial jet (the Comet I) two years or so before the United States did. Yet the American entries quickly won the competition because of substantial performance improvements that became available shortly after Comet I made its commercial appearance. Moreover, of America's two initial entries into the field of commercial jets—Boeing's 707 and Douglas's DC-8—the 707 emerged as the more successful. In part this was due to the fact that Boeing entered the market earlier; but perhaps even more important was the speed with which Boeing corrected some initial misjudgments about the optimal size and range requirements of the new aircraft. Attention to and prompt action on “feedback signals” from users are an important, often critical, part of innovation. This point will be discussed in a more general context below.

More recently, the aircraft industry offers another important example of how excessive preoccupation with purely technical performance characteristics can be a recipe for financial disaster. The Concorde is a brilliant engineering achievement, but also a very costly commercial failure. Although it can indeed cross the Atlantic in about half the time required by a 747, its fuel costs per passenger mile are at least 15 times as great.

Solar energy is another example. It has many attractive characteristics, and at least its share of articulate spokesmen, but it is unlikely to be widely adopted in electric power generation until it at least approaches the cost of other sources. At present that would require an order-of-magnitude reduction in solar costs.

These observations are intended to suggest how closely intertwined the technological and economic realms are in determining the success of a technological innovation. One might therefore expect to find numerous treatments of these technological and economic interrelationships in the economics literature. Unfortunately, such treatments are very rare.

These observations are also intended to suggest the hazards and pitfalls that may be involved in invoking the wrong criteria for success in judging the significance of an innovation. Potential consumers may not attach a sufficiently great value to the superior performance of a highly sophisticated new technology—the number of people prepared to pay a premium of several hundreds of dollars for shortening a transatlantic flight by a few hours turned out to be rather small. Even that innovator par excellence, Thomas Edison, failed this test with his first invention. He created a machine that would tally votes in the Congress, essentially instantaneously, only to be told by several congressmen that it was the last thing they wanted. As a result, Edison wrote in his journal a resolution never again to spend time on an invention until he was sure a sound market was in prospect.

In a different dimension, it is a serious mistake (increasingly common in societies that have a growing preoccupation with high technology industries) to equate economically important innovations with that subset associated with sophisticated technologies. One of the most significant productivity improvements in the transport sector since World War II has derived from an innovation of almost embarrassing technological simplicity—containerization. Although it has brought in its wake very substantial reductions in labor-handling costs, that particular innovation required only easily understood modifications of ship designs and dockside equipment; the primary barrier was resistance from the unions. This particular form of resistance illustrates another point. The operating systems of concern in innovation are not purely technical in nature; they are rather strongly intertwined combinations of the social and the technical—"sociotechnical systems" is a useful descriptor and a useful way to think about such institutions.

Both points are important. Technological sophistication is not something that is intrinsically valued in the marketplace. Major sources of cost reduction are so valued, regardless of their technical source or degree of sophistication. And one ignores the social aspects of the operating systems at no less peril than the technical.

Economists have, by and large, analyzed technological innovation as a "black box"—a system containing unknown components and processes. They have attempted to identify and measure the main inputs that enter that black box, and they have, with much greater difficulty, attempted to identify and measure the output emanating from that box. However, they have devoted very little attention to what actually goes on inside the box; they have largely neglected the highly complex processes through which certain inputs are transformed into certain outputs (in this case, new technologies).

Technologists, on the other hand, have been largely preoccupied with the technical processes that occur inside that box. They have too often neglected, or even ignored, both the market forces within which the product must operate and the institutional effects required to create the requisite adjustments to innovation.

The purpose of this chapter is to peer into that black box and to examine the nature of the technological transformation process, but without losing sight of the external forces of the marketplace or the importance of the internal requirements of the institution making the innovation. There is no need to belabor the point that technological innovation is absolutely central to economic growth and to improvements in efficiency. If there is any residual doubt, one need only think back 100 years to 1885 and ask, “Would any commercial firm operating as it did then survive in today's economy?” The relevant questions are not whether innovation is necessary to increases in efficiency or for survival, but rather: What kind of innovations? At what speed? And, can we understand the nature of innovation more fully in order to employ it more effectively and beneficially?

## CHARACTERIZATION OF INNOVATION

Unfortunately, the effects of innovation are hard to measure. There is no single, simple dimensionality to innovation. There are, rather, many sorts of dimensions covering a variety of activities. We might think of innovation as a new product, but it may also be

- a new process of production;
- the substitution of a cheaper material, newly developed for a given task, in an essentially unaltered product;
- the reorganization of production, internal functions, or distribution arrangements leading to increased efficiency, better support for a given product, or lower costs; or
- an improvement in instruments or methods of doing innovation.

A principal point of this chapter is that the transformation process is one that, inescapably, intertwines technological and economic considerations. Another is that the processes and systems used are complex and variable; that there is no single correct formula, but rather a complex of different ideas and solutions that are needed for effective innovation. A third is that these complexities make innovation hard to measure effectively. These themes are addressed below from several different vantage points.

It is product changes that make innovation so difficult to treat in a rigorous way. For it is often extremely difficult to measure the economic significance of product innovations or product modification. In the absence of widely accepted measures, there is no obvious way of metering the output of the technological black box.

A beginning of progress might be the explicit recognition that there are many black boxes rather than just one. This is important in three respects. First, the nature of the market problems and constraints that have to be confronted and, as a result, the manner in which innovations are generated differ significantly from one industry to another. Second, the state of knowledge in the relevant science and technology varies from industry to industry and from firm to firm. Third, the nature and the potential profitability of the output of the black box also differ very much among industries at any given time. As a result, pouring equal incremental inputs into the black boxes of randomly selected industries—A, B, C, and D—may be expected to involve very different kinds of R&D activities and to yield very different rates of return on the resources so invested.

There is evidence that the social and private rates of return on innovations are quite high. Mansfield et al. (1977), in a study of 17 innovations, conservatively estimated the median social rate of return at about 56 percent. The median private rate of return was a good deal lower—about 25 percent before taxes.

There is a further critical aspect of the innovation process that is not illuminated by the black-box approach. That is, innovations will often generate benefits far from the industries in which they originated. It turns out to be extraordinarily difficult to "map" the costs and benefits of many innovations within any single framework of industrial classification. An industry that is thought of as being highly traditional and technologically conservative—the clothing industry—is currently absorbing a number of innovations from electronics, laser technology, and chemistry. Innovations in metallurgy (or other basic materials) will find beneficiaries at many places on the industrial map. The most important advances in machine tools in recent decades have come from joining the tools to digital computers. Indeed, few sectors of the economy have been totally unaffected by the advent of the computer and the associated huge expansion in information-processing capabilities. The computer is a general-purpose, information-processing tool, and thus it provides a service that is required, in varying degrees, in nearly all sectors of the economy. Computers have radically altered both the way this chapter was written and the printing processes used to reproduce it compared with what would have been done only a decade ago. Not the least important of computer-induced changes in the context of this chapter has been in the research process itself. The R&D processes that are a central feature of research have themselves been enormously affected by the advent of the computer, and these changes are not yet nearly completed.

If we focus on a single industry, such as air transport, we can readily identify a diversity of sources of innovation coming into that sector. Many improvements in aircraft design are internally generated by aeronautical en gineers, drawing on advances in aeronautical knowledge and more specific design data of the sort made available from component and wind-tunnel testing. It is important to note that neither of these kinds of tests is science in the usual sense of the word, nor would they usually have been done by scientists. Nevertheless, they are often essential parts of the development work in innovations (and hence an integral part of engineering). The point is that innovation often demands the gathering and storing of types of information different from those obtained by scientists, and these different processes very frequently require the development of independent methodologies, theories, test procedures, codes, and the like—all of which become integral parts of engineering and production knowledge. Three excellent examples illustrating types of "engineering knowledge" that are not science, as usually defined, are given by Vincenti (1979, 1982, 1984), one in the realm of performance testing, one in shop processes, and one in analytical methodology.

Both the industrial sectors already cited—metallurgy and computers—have also served as essential sources of technological improvement to air transport. Metallurgical improvements have been a continual source of weight reduction and greater strength, leading directly to improvements in aircraft performance, both airframes and engines. More recently, the advent of new materials, particularly synthetics, offers great promise for further improvements in similar directions. The computer has drastically changed the industry in numerous ways: in cockpit control of the aircraft; in rapid determination of optimal flight paths; and in the instantaneous, worldwide reservation system. The revolutionary changes in electronics in the past generation have been so extensively incorporated into aircraft that "avionics" now constitutes a large fraction of the total manufacturing cost of an airplane.

Another aspect of innovation that makes it hard to measure is the effects of a rapidly expanding industry on its suppliers. A rapidly expanding industry nearly always generates an increased demand on other industries that produce intermediate components and materials for it. This increased demand will often stimulate more rapid rates of technical change in those supplier industries. Thus, the rapid growth of the automobile industry in the early twentieth century served as a powerful stimulant for the development of new methods of petroleum refining. (It is worth remembering that the petroleum industry antedates the automobile by several decades; but, in the late nineteenth century, before the advent of the automobile, petroleum was a source of illumination, not power. Petroleum became an important source of power only with the invention of internal-combustion engines.) In the twentieth century, the voracious demands of the automobile industry have raised the profitability and, presumably, the number of inventions, in several industries producing automobile inputs—not only petroleum but glass, rubber, steel, and plastics as well.

As noted, the impact of a technological innovation is often difficult to trace because those impacts do not always fall neatly within well-defined industry boundary lines. Sometimes, in fact, the effect of technological change may be to bring about a drastic redrawing of the previously existing boundary lines. Twenty years ago it was possible to draw clear boundary lines between the telecommunications industry and the computer industry. These lines, however, have already been blurred, and may well be dissolved, by ongoing technological changes associated with the advent of the microchip. The microchip revolution and the growing information-processing needs of business are converting computers into forms that increasingly resemble telecommunications networks, while the telephone system can already be viewed as a type of gigantic computer. As a simple piece of evidence, consider that a busy signal today may mean something very different from what it would have meant 20 years ago.

As already noted also, innovations have no obvious or uniform dimensionality. There is no generally agreed way of measuring their importance or impact. This affects our perception of the innovation process in two significant ways.

First, there is a tendency to identify technological innovation with major innovations of a highly visible sort—electric power, automobiles, airplanes, television, antibiotics, computers, and so on. There is no reason to complain about an interest in highly visible innovations—unless this leads to a neglect of other important aspects of the innovation process that happen to be less visible. The fact is that much technological change is of a less visible and even, in many cases, an almost invisible sort. A large part of the technological innovation that is carried out in industrial societies takes the form of very small changes, such as minor modifications in the design of a machine that will enable it to serve certain highly specific end-uses better, or that make it easier and therefore cheaper to manufacture; or improving the performance characteristics of a machine by introducing a harder metal, or a new alloy with a higher melting point; or by slight engineering changes that economize on some raw-material requirement, or simply substitute a cheaper material for a more expensive one where possible; or by a design change that reduces friction or vibration and therefore increases the useful life of a machine; or by a mere rearrangement of the sequence of operations, or location of operations, in a plant—such as has occurred in the steel industry—in a way that economizes on fuel inputs by eliminating the need for the frequent reheating of materials—as in the integrated steel mill or continuous casting. A large part of technological innovation is of such kinds, highly inconspicuous to everyone except a technical specialist, and often not even to him or her.

Consider what has happened in electric power generation. Electric power generation has had one of the very highest rates of growth of total factor productivity in the twentieth century. However, no sudden major changes in product or process have occurred in this century. Nevertheless, slow, cumulative improvements in the efficiency of centralized thermal power plants have generated enormous long-term increases in fuel economy. A stream of minor plant improvements have combined to raise energy output sharply per unit of input. These include the steady rise in operating temperatures and pressures made possible by metallurgical improvements, such as new alloy steels; the increasing sophistication of boiler design; the increase in turbine efficiency; and the addition of such components as feedwater heaters and stack economizers. The size of this improvement may be indicated as follows: it required 7 pounds of coal to generate a kilowatt-hour of electricity in 1910; the same amount of electricity could be generated by less than nine-tenths of a pound of coal in the 1960s. Yet, most people would be hard-pressed to identify any of the specific innovations that lay behind this great improvement in productivity.

Second, it is a serious mistake to treat an innovation as if it were a well-defined, homogeneous thing that could be identified as entering the economy at a precise date—or becoming available at a precise point in time. That view is, of course, encouraged by the Patent Office as well as by writers of high school history texts. But inventions as economic entities are very different from inventions as legal entities. The fact is that most important innovations go through rather drastic changes over their lifetimes—changes that may, and often do, totally transform their economic significance. The subsequent improvements in an invention after its first introduction may be vastly more important, economically, than the initial availability of the invention in its original form.

There is quantitative confirmation of this point in a careful study of technical progress in the petroleum-refining industry in the twentieth century. John Enos (1958) examined the introduction of four major new processes in the petroleum-refining industry: thermal cracking, polymerization, catalytic cracking, and catalytic reforming. In measuring the benefits for each new process he distinguished between the “alpha phase” (or the cost reductions that occurred when the new process was first introduced) and the “beta phase” (or cost reductions flowing from the subsequent improvement in the new process). Enos found that the average annual cost reduction generated by the beta phase of each of these innovations considerably exceeded the average annual cost reduction generated by the alpha phase (4.5 percent compared with 1.5 percent). On this basis he concluded: “The evidence from the petroleum-refining industry indicates that improving a process contributes even more to technological progress than does its initial development” (Enos, 1958:180).

A very similar kind of experience could be found in many industries. The fact is that inventions, in their early stages, are typically very crude and primitive and do not even begin to approach the performance characteristics or productivity levels that are attained later on. Consider the performance characteristics of the telephone around 1880; the automobile, vintage 1900; or the airplane when the Wright Brothers achieved their first heavier-than-air flight in 1903—in that form, at best a frail and economically worthless novelty. Or consider the computer around 1950. In innovation after innovation it is the subsequent improvement process, within the framework of an initial innovation, that transforms a mere novelty to a device of great economic significance. There are many instances in which the learning associated with cumulative production of a given item reduced costs by a factor of two or three, including airline costs per passenger-seat mile, automobiles, and industrial chemicals. In the instance of electric light bulbs and semiconductor components, the cost reductions have been more than five to one. There is little doubt that other products and services would show similar trends if data were available in appropriate form.

But whether an innovation will in fact be introduced, and whether it will even be deemed worthwhile to spend money on its improvement, depend not only on its own cost and performance characteristics, but on the range of available alternatives. Once again, the ultimate criterion is economic. For example, synthetic rubber was known to be technically feasible for a long time. The basic scientific research needed to make synthetic rubber had been largely completed before the outbreak of World War I. However, so long as natural rubber was available at low cost, as it was during the interwar years, the commercial prospects for synthetic rubber were extremely dim. Synthetic rubber became economically significant when wartime circumstances sharply reduced the supply of natural rubber, raised natural rubber prices, and created a strategic crisis. These effects drastically improved the prospects for the synthetic product. Until the special conditions generated by World War II, synthetic rubber simply constituted an economically inferior technology, and it deserved to be neglected. It is also worth noting that, once the investment in the development of synthetic rubber had been made, for wartime purposes, and the unit cost reduced along the learning curve of cumulative production, a stable market did develop within the peacetime economy in many applications. This also illustrates the different priorities between the military and commercial sectors. Military developments hinge primarily on performance, including strategic questions of supply. Commercial developments hinge primarily on economic criteria. But the subsidization of development for military reasons can, and has in several very important instances, reduced commercial costs to the point that firms will develop the product. As noted by Nelson (1982), this list includes not only synthetic rubber but also jet aircraft, semiconductor manufacturing processes, and the computer.

Thus, there is no necessary reason why new technologies should replace old ones merely by virtue of their newness. Newness is not, by itself, an economic advantage. Old technologies will often persist, even in the face of new technologies that appear to offer decisive advantages, because the old technologies retain advantages in particular locations, because the old technologies remain competitive due to access to certain low-cost resource inputs, or simply because of persistent performance advantages in certain specific uses. Old technologies are often also spurred into new phases of improved performance through innovations by the arrival of a new competitor. Water power thrived as a source of industrial power in the United States more than a century after James Watt introduced his improved steam engine, and still thrives today, in far more efficient forms, in certain situations. Roughly a third of the electric power supplied in the network at Stanford University is from water power—Pacific Gas and Electric happens to have the highest ratio in the United States currently. Even today vacuum tubes have not been completely displaced by semiconductors. They remain indispensable, for example, for some power transmission purposes. A useful and instructive study of the race between two different products in modern times that covers a number of points we have omitted here for space reasons is the discussion of the origins of the aircraft turbojet engine by Constant (1980).

## MODELS OF INNOVATION

There have been a number of attempts in recent years to impose some sort of conceptual order on the innovation process, with the purpose of understanding it better and providing a more secure basis for policy formulation. Unfortunately such attempts, often by scientists and by spokesmen for the scientific community, misrepresent the innovation process by depicting it as a smooth, well-behaved linear process. Such exercises badly misspecify the nature and the direction of the causal factors at work.

We have already seen that innovation is neither smooth nor linear, nor often well-behaved. Rather, it is complex, variegated, and hard to measure. We have also seen that there is a need for an adequate and understandable model on which to base our thinking. Before introducing an improved model that should assist us in thinking more clearly about innovation, this section first describes the model embodied in the conventional wisdom and discusses its shortcomings.

### The Linear Model

The generally accepted model of innovation since World War II has been what a few authors have called “the linear model.” In this model, one does research, research then leads to development, development to production, and production to marketing. These events are implicitly visualized as flowing smoothly down a one-way street, much as if they were the “begats” of the

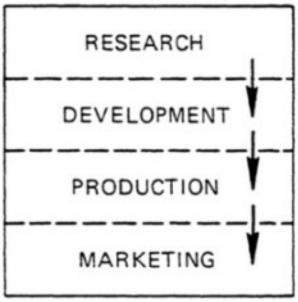

FIGURE 1 The conventional "linear model" of the linkage of research to production.

Bible. A sketch of this model is given in Figure 1. The linear model distorts the reality of innovation in several ways, and most serious students of innovation have now come to recognize those distortions. However, improved models have not yet come into widespread use. Consequently, the linear model is still often invoked in current discussions, particularly in political discussions. This continued use should not surprise us, since, as Thomas Kuhn (1967) has argued, we do not abandon a model for thinking about a complex situation until we have a better model to put in its place.

In the linear model, there are no feedback paths within the ongoing work of development processes. Nor are there feedbacks from sales figures or from individual users. But all these forms of feedback are essential to evaluation of performance, to formulation of the next steps forward, and to assessment of competitive position. Feedbacks are an inherent part of development processes as we have already illustrated above.

In an ideal world of omniscient technical people, one would get the design of the innovation workable and optimized the first time. In the real world of inadequate information, high uncertainty, and fallible people, nothing like this happens. Shortcomings and failures are part of the learning process that creates innovation of every kind. Innovation accordingly demands feedback, and effective innovation demands rapid, accurate feedback with appropriate follow-on actions. Radical, or revolutionary, innovation prospers best when provided with multiple sources of informational input. Ordinary, or evolutionary, innovation requires iterative fitting and trimming of the many necessary criteria and desiderata. In either case, feedbacks and trials are essential.

Another difficulty with the linear model flows from the fact that the central process of innovation is not science but design. A design in some form is essential to initiating technical innovations, and redesigns are essential to ultimate success, for the reasons just stated concerning the need for several types of feedbacks. The problems that are thrown up by the processes of designing and testing new products and new processes often spawn research—true science—and have in some instances even given rise to new branches of mathematics. Moreover, science often is dependent, in an absolute sense, on technological products and processes for its advances. Over the course of history thus far, it is moot whether science has depended more on technological processes and products than innovation has depended on science. Much of the pressure to create new materials is the result of direct feedback on problems encountered in creating such devices as steam turbines, jet engines, combustors, semiconductors, solar energy cells, and numerous other products. In his work on the electric lighting system, Edison was forced by the needs of the system to pay a mathematician to work out the analysis of the parallel circuit—despite Edison's often-expressed contempt for scientists and mathematicians. The parallel circuit is an advance so basic that, without it, electrical engineering as we know it today is unthinkable. In the process of solving problems of the flow over wings, L. Prandtl was forced to invent a mode of analysis that later gave rise to a whole branch of mathematics—today called asymptotic perturbation theory. These examples are not isolated ones; there are many others.

Thus, in a complete picture we must recognize not only that innovation draws on science, but also that the demands of innovation often force the creation of science. As we all know, the interactions of science and technology in the modern world are very strong. But this should not lead us to accept the common wisdom that “technology is merely applied science,” for, if we do, our thinking about innovation will forever remain muddled. The illustrations just given, showing that innovation often creates science and the need for feedback, ought to be enough, in themselves, to warn that something is wrong, but they are only some of the reasons for rejecting the simplistic formulation of the linear model.

The idea that innovation is merely applied science is so firmly entrenched and has been so often repeated that it is worth a few sentences to define science, so that we can see its important but limited role more clearly. For our purposes, we can take science to be “the creation, discovery, verification, collation, reorganization, and dissemination of knowledge about physical, biological, and social nature.” The two main components of science that affect innovation are (1) the current totality of stored human knowledge about nature and (2) the processes by which we correct and add to that knowledge. The new additions and corrections to science each year that constitute current research are but a small part of the whole. And it is the whole of our knowledge about nature that we bring to bear, insofar as we can, when we confront a problem in innovation. The idea that we could do important innovation with this year's and last year's science as the only input is ludicrous when examined in any depth whatsoever. The design of nearly any new modern system without the accumulated knowledge in mechanics, kinematics and orthographic projection, electromagnetism, or thermodynamics is essentially impossible. And, in many instances, this list must be enlarged to include biology, chemistry, quantum mechanics, optics, biochemistry, and so on. Science is by no means unimportant, but what we need to recognize clearly is that most innovation is done with the available knowledge already in the heads of the people in the organization doing the work, and, to a lesser extent, with other information readily accessible to them. It is only when those sources of information fall short of solving the problem that there is a need for research in order to complete a given innovation.

Thus, the notion that innovation is initiated by research is wrong most of the time. There are a few instances in which research sparks innovation, and these are often important, revolutionary innovations, as in semiconductors, lasers, and current genetic developments; but, even then, the innovation must pass through a design stage and must be coupled to market needs if it is to reach completion. And, as noted above, the invention, or alpha, stage almost always has small economic impact; the innovation must nearly always also pass through a number of "add-on," or beta, phases before it has large economic consequences. Moreover, the beta-stage work may involve little or no science. It will be done utilizing primarily what the people in the innovating organization already know, not only about science, but also about the infrastructure of the technologies of their time, the way their own organization works, and the nature of the ultimate market to the extent it is known.

Even more important, from the viewpoint of understanding innovation, is the recognition that when the science is inadequate, or even totally lacking, we still can, do, and often have created important innovations, and innumerable smaller, but cumulatively important evolutionary changes. Recently, a member of the National Academy of Engineering, highly versed in dynamics and control, attempted to analyze the stability of an ordinary bicycle with a rider—and failed. No acceptable analysis is known. But this lack of theory did not prevent the invention of the bicycle a century ago, nor did it prevent a multitude of beta-phase improvements in bicycle design that have cumulatively created a reliable, relatively inexpensive, and useful machine. Nor does the absence of understanding of the theory of stability prevent a 5-year-old child from mounting a bicycle and with a few tries learning to stabilize the human–machine system. Had the idea been true that science is the initiating step in innovation, we would never have invented the bicycle.

In addition to these shortcomings, the linear model shortchanges the importance of the process innovations that play a crucial role via learning during continued production. Many examples have been cited in this chapter that illustrate the reality of this process of learning through cumulated experience in production of a stable product.

In sum, if we are to think clearly about innovation, we have no choice but to abandon the linear model. What then do we put in its place?

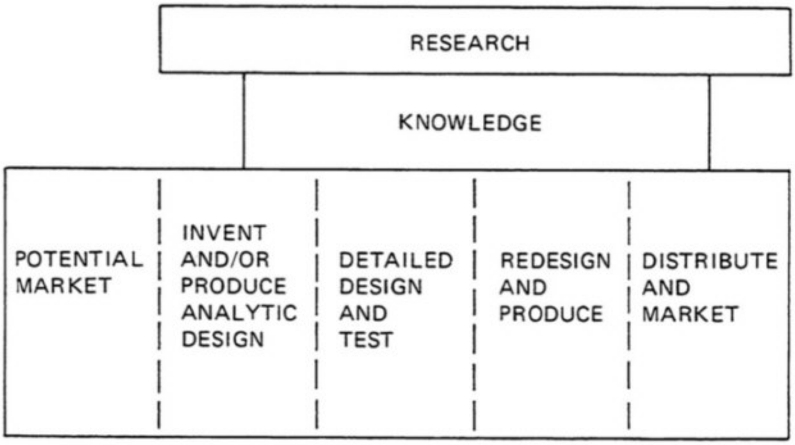

FIGURE 2 Elements of the "chain-linked model" for the relationships among research, invention, innovation, and production.

## The Chain-Linked Model

One possible alternative to the linear model, called the "chain-linked model," is shown in Figure 2 and Figure 3. A more detailed discussion of this model is given by Kline (1985). Figure 2 shows the elements in the chain-linked model. In this model of innovation there is not one major path of activity, but five. Some discussion of each of these paths follows.

The first path of innovation processes (see Figure 3) is called the central-chain-of-innovation. It is indicated by the arrows labeled "C." The path begins with a design and continues through development and production to marketing. It is important to note immediately that the second path is a series of feedback links marked "f" and "F" in Figure 3. These feedback paths iterate the steps and also connect back directly from perceived market needs and users to potentials for improvement of product and service performance in the next round of design. In this sense, feedback is part of the cooperation between the product specification, product development, production processes, marketing, and service components of a product line. H. W. Coover (in this volume) makes the same point forcefully in terms of a clear example and its effects in one company. This point will be raised again in the discussion of the implications of the chain-linked model.

A perceived market need will be filled only if the technical problems can be solved, and a perceived performance gain will be put into use only if there is a realizable market use. Arguments about the importance of "market

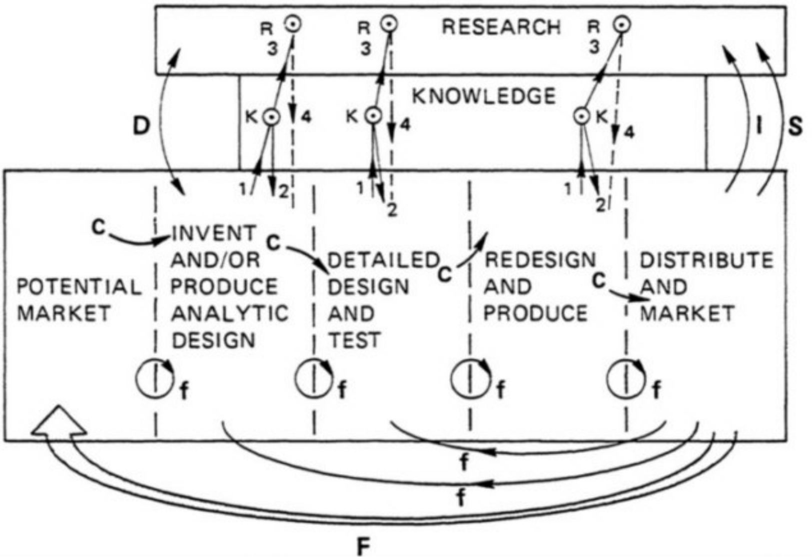

FIGURE 3 Chain-linked model showing flow paths of information and cooperation. Symbols on arrows: **C** = central-chain-of-innovation; **f** = feedback loops; **F** = particularly important feedback.

**K–R:** Links through knowledge to research and return paths. If problem solved at node K, link 3 to R not activated. Return from research (link 4) is problematic—therefore dashed line.

**D:** Direct link to and from research from problems in invention and design.

**I:** Support of scientific research by instruments, machines, tools, and procedures of technology.

**S:** Support of research in sciences underlying product area to gain information directly and by monitoring outside work. The information obtained may apply anywhere along the chain.

pull" versus "technology push" are in this sense artificial, since each market need entering the innovation cycle leads in time to a new design, and every successful new design, in time, leads to new market conditions.

We have already seen that modern innovation is often impossible without the accumulated knowledge of science and that explicit development work often points up the need for research, that is, new science. Thus the linkage from science to innovation is not solely or even preponderantly at the be ginning of typical innovations, but rather extends all through the process—science can be visualized as lying alongside development processes, to be used when needed. This linkage alongside the central-chain-of-innovation, the third path, is shown in Figure 3 by arrow "D" and links "K–R," and is the reason for the name "chain-linked model."

A much clearer view of innovation is obtained when we understand not only that the linkage to science lies alongside development processes, but also that the use of science occurs in two stages corresponding to the two major parts of science delineated in the definition of science given above. When we confront a problem in technical innovation, we call first on known science, stored knowledge, and we do so in serial stages. Only when all stages fail to supply the needed information, as often happens, is a call for the second part of science, research, needed and justified.

A current, real illustration may help make the processes clear. Suppose you want to innovate an improved carburetion-induction system for a sparkignition automobile engine—one that will run very lean in order to give improved mileage and reduce pollution. To reach this goal, you must achieve mixing of the fuel and air to the molecule-to-molecule level—something that conventional carburetion systems fail to do by a wide margin. This in turn requires an intimate knowledge of turbulent mixing processes in fluid flow. To do this job, you first ask, "Do I know a current device that will do the job?" The answer initially is, "No!" Next, you ask knowledgeable colleagues. Then you look in the literature and again find no suitable answer. Finally, you go to experts in the field and discuss what is known and what might be done. If the experts also fail to provide an answer, then and only then should you initiate research or development work to solve the problem. In the instance of the carburetion system, the R&D work has recently been done and patented by M. R. Showalter. The underlying science that will provide a firm data base for optimizing the devices does not yet exist, but is in fact suggested in current proposals by one of the authors for government-supported research. Assuming that this research is successful, the results will allow more rapid, accurate, and optimal designs, but only some years hence, since that is the time required for such research.

In sum, the use of the accumulated knowledge called modern science is essential to modern innovation; it is a necessary and often crucial part of technical innovation, but it is not usually the initiating step. It is rather employed at all points along the central-chain-of-innovation, as needed. It is only when this knowledge fails, from all known sources, that we resort to the much more costly and time-consuming process of mission-oriented research to solve the problems of a specific development task.

It is also important to note that the type of science that is typically needed is different at various stages in the central-chain-of-innovation. The science needed at the first stage (design or invention) is often pure, long-range science that is indistinguishable from pure academic science in the relevant discipline. The research generated in the development stage is more often of a systems nature and concerns analysis of how the components of the system interact and of the “holistic” or system properties that are generated when the components of the product envisaged are hooked together to obtain the complete function needed. For example, in a design of a new airplane, steam power plant, or computer, an important consideration will be the stability of the system as a whole when the various new components are put together into a single operating entity—a system. The research that is spawned in the production stage is more often process research: studies of how particular components can be manufactured and how the cost of manufacture can be reduced by improved special machinery or processes or by use of improved or less expensive materials. It is worth noting that, in industries concerned with production of materials for sale to end-producers of goods (for example, steel, rubber, semiconductor silicon), nearly the only technical innovations that bear on profit are process innovations. We do not ordinarily think of process innovations or of system analyses as science, but in many cases they are just as surely research as is the purest of pure science. Moreover, if we are concerned with commercial success, systems and process research not only are necessary ingredients but often play a more important role than science in cost reduction and improved system performance. All these matters are explicit in the chain-linked model, but missing from the linear model.

Adoption of the improved carburetion-induction system recently developed by M. R. Showalter, which offers the potential for major gains in mileage, in pollution control, in the variety of usable fuels, and in reduced cost of production compared with current equivalent systems, is meeting with very great resistance from U.S. auto companies. Such resistance is common and plays an important role in the complete picture of innovation processes. However, analysis of the sources of such resistance would take us too far afield in this chapter.

What is the nature of the designs that initiate innovations? Historically, they have been of two types, “invention” and “analytic design.” The notion of invention is generally familiar; an invention is a new means for achieving some function not obvious beforehand to someone skilled in the prior art. It therefore marks a significant departure from past practice. Analytic design, on the other hand, is currently a routine practice on the part of engineers but is little understood by the public at large. It consists of analysis of various arrangements of existing components or of modifications of designs already within the state of the art to accomplish new tasks or to accomplish old tasks more effectively or at lower cost. It is thus not invention in the usual sense. However, analytic design is currently a more common initiator of the central-chain-of-innovation than invention. Given the advent of digital computers, much more can be done via analytic design than in the past, and this form of initiation of the technical parts of innovation will likely play an increasing role in the future. Given current computer capabilities and current trends in computer-aided design/computer-aided manufacturing (CAD/CAM), plus increasing capabilities to model physical processes accurately and to locate optima, it is nearly certain that we will see in the coming decades a merging of analytic design and invention that will constitute a more powerful method for initiating technical innovations than anything we have known in the past. This merging will not happen suddenly, and it is hard at this stage to predict how far and how fast it will go. But it has already commenced, and firms that can utilize it effectively may well be able to create competitive advantages.

The discussion thus far has described three of the five paths in the chain-linked model of innovation. The remaining two need only brief discussion.

First, as already noted, new science does sometimes make possible radical innovations (indicated by arrow “D” in Figure 3). These occurrences are rare, but often mark major changes that create whole new industries, and they should therefore not be left from consideration. Recent examples include semiconductors, lasers, atom bombs, and genetic engineering.

The last path, marked by arrow “I” in Figure 3, is the feedback from innovation, or more precisely from the products of innovations, to science. This pathway has been very important in the past and remains so even today. (For example, see “How Exogeneous Is Science?” in Rosenberg (1982), or Price (1984).) Without the microscope, one does not have the work of Pasteur, and without that work there is no modern medicine. Without the telescope, we would not have the work of Galileo, and without that work we would not have modern astronomy and cosmology, nor would space exploration with its various innovations have been possible. It is probable also that without Galileo's work we would not have had what we now call elementary mechanics until a much later date, and perhaps not at all. Hence the many sciences now built on elementary mechanics would also have been at best delayed. The whole course of what we know about physical nature would have developed differently. Nor has this support of science by technological products ended. Current examples include the CAT (computerized axial tomography) scanner and the BEAM (brain electrical activity mapping) electroencephalogram apparatus, which seem likely to open whole new realms of medicine and psychology. The use of the digital computer in the laboratory and in modeling difficult problems, such as turbulence, is opening new vistas in physical science. And these are only a few examples among many.

In sum, any view of the technical aspects of innovation that suggests a single, central path for innovation, or that science plays the central initiating role, is far too simple and is bound to inhibit and distort our thinking about the nature and use of processes of innovation. The chain-linked model, though a considerable improvement, is only a top-level model and therefore omits many of the details and the rich variety inherent in the totality of innovations processes in current times. The chain-linked model, however, does seem sufficient to help point up a number of conclusions.

## UNCERTAINTY IN INNOVATION

In order to see clearly the conclusions that flow from the chain-linked model, it is useful to return to several points made at the beginning of this chapter. First, the central dimension that organizes innovation, if there is one, is uncertainty. By definition, innovation implies creating the new, and the new contains elements that we do not comprehend at the beginning and about which we are uncertain. Moreover, the degree of uncertainty is strongly correlated with the amount of advance that we propose in a given innovation.

It is quite useful to think of the total range of innovations as extending continuously from those that involve almost no uncertainty to those that involve very great uncertainty. At one end we have the small, evolutionary change; we may decide to change the color of paint we use on automobiles. There is virtually no uncertainty in changing the color of paint, but it may nevertheless have important commercial consequences; it was an important ingredient of the competitive advantage in the market that General Motors created to overcome the initial lead of Ford in the 1920s. At the other end of the spectrum, we may need to make a revolutionary change. We may want to do an entirely new job, or use an entirely new product for an old job—we may want to send a man to the moon, or develop a low-cost, solid-state amplifier, to take two examples from modern times. Here the uncertainty will be very high and the initial costs of development so great that no single commercial firm may be willing to bear the costs. In such cases government subsidy, or consortium efforts, may be required to do the necessary tasks, as in the case of synthetic rubber cited above and current work in very large scale integration (VLSI) semiconductor components.

For all these reasons, it is far better to conceptualize this range as a spectrum than to think of two kinds of innovation, revolutionary and evolutionary. Where a given task lies along this spectrum of uncertainty has a major influence on many aspects of what is appropriate innovation.

The chain-linked model of innovation processes shows clearly that there are many points at which the uncertainty of the end product and processes of production and marketing can be reduced. One can do computer studies of a new device to test possibilities and optimize performance. The several uses of testing are obvious. One can pretest production methods for a new product. One can accumulate data that provide bounds on the limits that ensure stability or provide output within given quality ranges for a given process. One can do market sampling with handmade examples of a new product. In short, there is room for reduction of uncertainty at every step and in every feedback link in the chain-linked model. It is also possible to shorten the time for the total development process by using parallel paths for some of the steps of development and production set-up, but this will be risky when the uncertainty about the final design is still high.

Consideration of uncertainty helps understand why different criteria apply and different problems occur in innovation at different times in the production cycle of a product. In the early stages of a product cycle, the uncertainty is very high, and competition is primarily concerned with improvements in the technical performance characteristics of the product as they affect the consumers' needs. As these problems are solved and a dominant design type (or a few types) emerges, the industry matures, and the nature of required innovation shifts to lower-cost production of the dominant designs. At this point, therefore, innovation concerns system and process innovations more than improvement in a product's performance characteristics. Several important and valuable discussions of the impact of these shifts are given in Section I of Tushman and Moore (1982). The task of management in the early stage, while radical change is occurring and is solidifying into a dominant design, is to bring order from chaos and stabilize designs so that reasonable cost levels can be achieved by economies of scale and through the learning processes that only cumulate with reasonably long production experience with stable product designs. In the later stages, long after the product is stable, the task of management is to prevent the loss of ability to create radical innovations either from a lowering of the institutional capability in order to cut overhead costs or from bureaucratization of process and division of functions to the point that R&D, production, and marketing elements can no longer be drawn into effective, agreed goals and cooperative actions. These considerations have important implications for the ways in which institutionalization of R&D is carried out, but there is not sufficient space to explore them here. Coover (in this volume) makes the important points well.

For the technical parts of the innovation process, it is also important to recognize that the state of knowledge in the underlying science and technology strongly affects the cost and time requirements of innovation projects. Knowledge in the physical and biological sciences tends to move through recognizable major stages. In the earliest stage the work in a science is descriptive; in the next stage the work becomes taxonomic; then the work passes to formation of generalizing rules and hypotheses and finally, in some sciences, to the construction of predictive models. A science in the predictive stage, such as mechanics or classical electromagnetism today, is usable immediately by anyone skilled in the art for purposes of analytic design and invention. A science still in a descriptive or taxonomic phase is far less valuable for these purposes; however, it may still be very important in guiding the in novative work. When the state of science is not in a predictive stage with regard to the particular problems in hand, there is no choice but to carry out development of innovations by means of the much longer, and usually much more expensive and uncertain process, of cut and try. In the current era this is seldom a wholly blind process; it is much more often what one could call “guided empiricism.” One starts with all available knowledge and makes the first best estimate of a workable design, then proceeds to build it, test it, incorporate learning, redesign, retest, incorporate learning, and so on (sometimes ad nauseam). An important aspect of this set of processes is that the speed of turnaround is a critical factor in the effectiveness of innovation. It follows that the same departmentalization of function that is so desirable for high-volume production may become a major deterrent to successful innovation. When the relevant knowledge is not in a predictive state, the best source for new designs is usually the practice found to be successful in old designs—science may be largely or wholly irrelevant. There is little doubt that the failure to make this distinction about the state of knowledge underlies many fruitless arguments about the value, or lack of value, of science in innovation; in some instances science is essential, a sine qua non, but in other instances it is wholly irrelevant; and there is everything in between. A current example of the lack of sufficient science for design purposes and therefore of the need to rely on prior art is combustion spaces, fireboxes. The results of this lack of predictive science (note that there is no dearth of data and experience) are very high costs in development, long lead times (e.g., for the combustion space in new models of jet engines), and a strong and reasonable conservatism on the part of designers (e.g., of stationary boilers). The development of new proprietary drugs also remains largely in this class currently. There are numerous other examples. It is important that technical experts make clear to managers the state of knowledge in this sense.

For these reasons, there still remain crucial portions of high technology industries in which attempts to advance the state of the art are painstakingly slow and expensive because of the limited guidance available from science. The development of new alloys with specific combinations of properties proceeds very slowly because there is still no good theoretical basis for predicting the behavior of new combinations of materials; the same applies to pharmaceutical drugs. Many problems connected with improved pollution control are severely constrained by the limited scientific understanding of the combustion process, and by the fact that the design of a combustion “firebox” remains in 1985 still an art based primarily on the results of prior designs—not on science. The development of synthetic fuels is at present seriously hampered by scientific ignorance with respect to the details of the oxidation reactions in various forms of coal. The designs of aircraft and steam turbines are both hampered by the lack of a good theory of turbulence.

In the case of aircraft, wind-tunnel tests are still subject to substantial margins of error in terms of predicting actual flight performance. Indeed, in considerable part the high development costs for aircraft are due precisely to the inability to draw more heavily on a predictive science in determining the performance of specific new designs or materials. If science provided a better predictive basis for directly specifying optimal design configurations, development costs (which constitute about two-thirds of total R&D expenditures in the United States) would not be nearly so high. These arguments constitute solid reasons for companies concerned with innovation to maintain scientific work covering the areas underlying their products, not only because the output of the work will itself produce useful long-range results, but even more importantly to be sure that in-house knowledge of scientific advances world-wide are observed, understood, and available to the development projects in the organization.

The degree of uncertainty also affects the appropriate type and amount of planning for an innovation project. Managers of most operations—production, sales, accounting, maintenance—all see planning as a nearly unmitigated benefit. For obvious reasons, they tend to believe that more planning is better planning, and better planning is better business. This is also typically true of the innovation projects that entail virtually no risk. If all we are changing is the color in the paint can at the end of the assembly line, then the change should be, and probably will be, planned in all details.

If, on the other hand, the innovation involves major uncertainties, for example, the creation of some never-before-seen item of hardware, then it is very easy to "overplan" the project and thereby decrease or even destroy the effectiveness of the work. Clear examples of how overplanning markedly decreased effectiveness are given by Marschak et al. (1967), and the idea is understood by nearly all good innovators and researchers. There is no doubt of the effect; it remains only to explain why the effect exists.

In a radical, major innovation, there is by definition the need to learn about various aspects of the work. Like fundamental research, radical innovation is inherently a learning process. The best initial design concepts often turn out to be wrong—dead, hopelessly wrong—simply because not enough is yet known about how the job can (and cannot) be done. There is also what can be called a "false summit" effect. When one climbs a mountain, one sees ahead what appears to be the top of the mountain, but over and over again it is not the summit, but rather a shoulder on the trail that blocks the view of the real summit. When one does innovation, much the same effect often occurs. One starts with problem A. It looks initially as if solving problem A will get the job done. But when one finds a solution for A, it is only to discover that problem B lies hidden behind A. Moreover, behind B lies C, and so on. In many innovation projects, one must solve an unknown number of problems each only a step toward the final workable design—each only a shoulder that blocks the view of further ascent. The true summit, the end of the task, when the device meets all the specified criteria, is seldom visible long in advance. Since good innovators are optimists, virtually by definition, there is a tendency to underestimate the number of tasks that must be solved and hence also the time and costs.

If the project is planned in detail at the beginning, the initial wrong concepts will suggest commitments (of materials, scarce talents, facilities) that are a waste of effort. Even worse, through inertia of ideas, dollars, or people, the force of prior commitments may keep the project from changing paths when it should. Thus, the overall effort may be more costly and slower than if less planning had been done initially, and the end result may be less desirable. In addition, the “false summit” effect makes tight planning of timetables very difficult, and in truly radical innovation probably counterproductive. Experienced personnel usually recognize that the “false summit” effect is a major contributor to conflicts between innovators and management and investors in innovative projects.

Does this mean no planning and no accountability are desirable in radical innovation? The answer is no. Preplanning must be focused on goals, rough overall time schedules, and budgets, and care must be taken not to make decisions that incur large costs or commitments too early in the project. Moreover, information about what is learned and the changes implied by that learning must be communicated regularly and thoroughly between innovators and managers. Finally, managers of innovation must be very clear about the differences in nature between innovation processes and those of production and other business activities.

## ECONOMICS OF INNOVATION

The preceding parts of this chapter have mainly characterized the process of technological innovation. Central features of the discussion have been the sheer diversity of activities that make up the innovation process, the variation across industry lines, and innovation's somewhat disorderly character. Any drastically simplified model of the process necessarily misrepresents—or omits—essential aspects of the innovation process. The chain-linked model introduced in this chapter provides a more accurate representation of innovation processes than earlier, simpler models. However, the forces that seem to be shaping the economics of innovation, particularly in high technology industries, must also be addressed.

### Rising Development Costs

Perhaps the most important trend is an apparent rise in the development costs of new products, especially new products that genuinely push out the technological frontier by incorporating substantial improvements in product (or process) performance. These rising development costs involve an escalation of the financial risks that are associated with innovation, and they therefore pose a serious threat to an organization's capacity to undertake innovation in the future.

In the case of the commercial aircraft industry, there is currently only one firm —Boeing—that is an active innovator of aircraft of substantially new design. Development costs of a genuinely new generation of aircraft, as opposed to mere modification of an existing aircraft, are accepted as being well over a billion dollars. Boeing has recently resorted to forms of subcontracting that involve at least some degree of risk sharing on the part of the subcontractors. These development costs, and the accompanying large-scale financial risk, also figure prominently in the increasing recourse to international consortiums—as in the case of the European Airbus and the earlier, ill-fated Concorde.

The size of development costs and the associated financial risk in the commercial aircraft industry are, admittedly, at the extreme end of the spectrum. Nevertheless, similar trends are apparent in many high technology sectors. Development costs of nuclear power reactors have skyrocketed because of mounting safety and environmental concerns, as a result of which construction of nuclear power plants has been brought virtually to a halt in the United States. But even more conventional power-generating equipment, which is not plagued by the special problems of nuclear power, also confronts technological and other performance uncertainties of a kind that have resulted in very high development costs. The exploitation of new fossil-fuel energy sources, which involves complex liquefaction and gasification processes, has encountered spectacularly high development costs at the pilot-plant stage. These costs, together with changing expectations about the future pattern of petroleum prices, have led to the termination of numerous projects.

Telecommunications has encountered similar trends in recent years—the cost of the #4 Electronic Switching System is estimated to have been around $400 million. Although the electronics industry has some very different features from the other industries just mentioned, the design and development of reliable, high-capacity memory chips have drastically raised the table stakes for commercial survival. Hundreds of millions of dollars of development costs are being incurred in the international competition for higher circuit densities. In the last several years the relative importance of software development costs has drastically increased. In the computer industry, where IBM is admittedly sui generis, that gigantic, multiproduct firm has recently been supporting an R&D budget of over $2.5 billion. In the fledgling biotechnology industry, a combination of high development costs, the scale requirements to take advantage of bulk manufacture, and uncertainties about future products is already operating as a powerful deterrent to the willingness of venture capital to enter the industry. Finally, development costs and the production facilities needed to introduce a new line of automobiles now make it exceedingly difficult for any but very large, established firms to enter the market. The recent entry of Japanese firms occurred only after some years of protection in the Japanese domestic market. In Fiscal Year 1983–1984, General Motors' R&D spending amounted to $2.6 billion. In the same period, Ford Motor Company spent $1.75 billion on R&D. Although it is not entirely clear in either case what functions are in fact covered within these budgets, it is certainly clear that the table stakes of innovation are very high even in some long-established industries.

## Resistance to Radical Innovation

This raising of the table stakes for innovations appears to create significant resistance to radical innovations, as in the case of problems in smog control in automotive engines. For the reasons stated above, organizations that are good at low-cost, very high volume production segregate functions to the point that no single person or small group can make major alterations. They also tend to separate R&D from production, thus decreasing essential feedbacks and forward coupling to real changes in production. For proprietary reasons they also strongly favor in-house expertise, and this often leads to a failure to utilize outside ideas in the conceptual stage. But as the studies of radical innovation have shown, it is nearly always important to maximize the sources of ideas in the early stages of work. These studies also show it is important to isolate new innovative ideas from the fixed ideas and prejudices that nearly always characterize individuals who work for many years on a given dominant design or, worse, a few components of it. For such individuals it is always easy to find many reasons why an innovative idea won't work (as indeed it usually won't in its initial undeveloped stages). At best, they represent important dampers on the enthusiasm that is necessary to carry on the difficult work of innovation. At worst, they may deter or altogether stop promising innovative work that lies beyond their range of experience.

## Financial Risks

Many high technology industries appear to be confronting technological trajectories that offer opportunities for rapid improvement, but also high and rapidly rising development costs. Financial risks have thus become exceedingly great. To be financially successful, the products require markets that are, in some cases, substantially larger than can even be provided by a single, moderately sized Western European country of 50 million or so. For technological and other reasons (for example, regulatory constraints in the phar maceutical industry), very long lead times are often involved that defer the prospect of full recovery of financial commitments, at best, into the far distant future (some new pharmaceutical products, such as contraceptives, must be subject to 15-year tests). In such industries not only are uncertainties over technological factors particularly great, but the large financial commitments are frequently required during precisely that earliest stage when the uncertainties are greatest.

Moreover, the very fact of rapid technological change itself raises the risk of investing in long-lived plant and equipment, since further technological change is likely to render such capital soon obsolete. If product life cycles are themselves becoming shorter, and there is evidence that they are, the agony of the risk-taking process in innovation is even further intensified. For not only has the scale of the financial commitment that is put to risk been drastically increased, the question of the precise timing in the commitment of large amounts of resources to the development process has become even more crucial. Moreover, there is abundant evidence in recent years that new, technologically complex products experience numerous difficulties in their early stages that may take years to iron out. Where this is the case, the earliest Schumpeterian innovators frequently wind up in the bankruptcy courts, whereas the rapid imitator, or “fast second,” who stands back and learns from the mistakes of the pioneer, may experience great commercial success.

## Coupling the Technical and the Economic

The whole process of technical innovation has to be conceived of as an ongoing search activity—a search for products possessing new or superior combinations of performance characteristics, or for new methods of manufacturing existing products. But this search activity is shaped and structured in fundamental ways not only by economic forces that reflect cost considerations and current supplies of resources, but also by the present state of technological knowledge, and by consumer demand for different categories of products and services. Successful technological innovation is a process of simultaneous coupling at the technological and economic levels—of drawing on the present state of technological knowledge and projecting it in a direction that brings about a coupling with some substantial category of consumer needs and desires. But what constitutes consumers' needs and desires today is sometimes different from what it will be in the future. The truly important innovations have frequently been ahead of their times, and have created a market that did not exist and was not expected by the short-sighted nor the fainthearted.

The process of R&D has often been equated with innovation. If this were true, understanding innovation would be far simpler than it truly is, and the real problems would be far simpler and less interesting than they truly are.

Successful innovation requires the coupling of the technical and the economic in ways that can be accommodated by the organization while also meeting market needs, and this implies close coupling and cooperation among many activities in the marketing, R&D, and production functions.

## CONCLUSIONS

A century ago organized innovation was rare, and innovation therefore much slower. The successful innovator could count on gaining significant competitive advantage. Today, innovation is a cost of staying even in the marketplace. Despite this, innovation as a study is quite new and still suffers from an overabundance of specialized comment and a lack of integrated, mature viewpoints in the literature. This chapter attempted to unify the economic and technological views. Since it is an overview, and brief in length, it necessarily omitted many topics and much rich detail. Despite this it seems possible, based on the joint discussion, to reach a number of conclusions.

Illustrations presented throughout this chapter show that innovation is inherently uncertain, somewhat disorderly, made up of some of the most complex systems known, and subject to changes of many sorts at many different places within the innovating organization. Innovation is also difficult to measure and demands close coordination of adequate technical knowledge and excellent market judgment in order to satisfy economic, technological, and often other types of constraints—all simultaneously. Any model that describes innovation as a single process, or attributes its sources to a single cause, or gives a truly simple picture will therefore distort the reality and thereby impair our thinking and decision making.

Contrary to much common wisdom, the initiating step in most innovations is not research, but rather a design. Such initiating designs are usually either inventions or analytic design. The term “analytic design” is used to denote a study of new combinations of existing products and components, rearrangements of processes, and designs of new equipment within the existing state of the art. Emergent computer applications, for example, appear to be merging these functions into more powerful and faster tools than have been available in the past.

Science has two major parts that directly affect innovation but have different roles. One part, stored knowledge about physical, biological, and social nature, is an essential ingredient in the bulk of current innovations. It is unthinkable for successful technical innovations to be created today without utilizing significant inputs from the stored technical knowledge in science and other forms of thought. Even inventors who decry science will have absorbed some of the modern views toward mechanics and other subjects that permeate modern thinking. But this knowledge enters primarily through knowledge already in the heads of the people in the innovative organization, and to a lesser degree through information quickly accessible to them. Research is needed only when all these sources of stored knowledge are inadequate for the task at hand.

While current research sometimes does potentiate major innovations, more frequently research is used in innovation to solve problems all along the chain-of-innovation from the initial design to the finished production processes. In the early stages of this chain, the research is often indistinguishable from the pure research in the relevant field. Later in the development, research shifts toward system and then to process questions; these forms of research are not usually considered as science, but they are nevertheless usually essential to completion of a successful product innovation. The importance of these types of research has been underestimated in the recent past, probably in part because of the use of an oversimplified “linear” model of innovation that entirely omits them as categories of research. An improved model of innovation, summarized in this chapter, indicates not one, but rather five major pathways that are all important in innovation processes. These paths include not only the central-chain-of-innovation, but also the following:

- numerous feedbacks that link and coordinate R&D with production and marketing;
- side-links to research all along the central-chain-of-innovation;
- long-range generic research for backup of innovations;
- potentiation of wholly new devices or processes from research; and
- much essential support of science itself from the products of innovative activities, i.e., through the tools and instruments made available by technology.

Two variables that provide major assistance in thinking about the nature of appropriate innovations are the degree of uncertainty in achieving success and the life-cycle stage of the product concerned. Larger uncertainty is strongly correlated with the degree of change. In the early stages of a product's life cycle, major changes in product design are occurring rapidly, and the key problem of management is to find dominant successful designs and to organize stable production and marketing around them. In the later stages of the product's life cycle, innovations typically are more concerned with process changes that reduce production costs. It is likely that a variety of changes, many of them seemingly small, will cumulate along a learning curve from very high volume production of a relatively stable product to reduce costs by a factor of at least two (and in some instances much more). After this learning stage is well advanced, the central problem in the management of innovation will usually be to avoid so much personnel reduction, specialization of tasks, and routinization of procedures that truly revolutionary advances become essentially impossible.

The degree of uncertainty in innovation also depends strongly on the state of underlying science and relevant engineering knowledge. When the underlying knowledge allows accurate predictions, far more rapid and reliable innovations are possible. When predictive knowledge is lacking, a resort to the far slower, less predictable, and more costly cut and try of "guided empiricism" is required. We tend to think of technical problems as predictive in the current high-tech area, but in reality many important areas still remain in a stage where adequate predictions are not possible, and "design-build-test: redesign . . ." remains the essential methodology for innovations.

Some organizations are very effective in high-risk, radical innovation, others in the small, cumulative, evolutionary changes that reduce costs and bring better fit of the product to various market niches. Both types of innovation are important. The control of costs is important to remain competitive in the short run, and the movement to radically improved product designs is often necessary to survival over the long haul.

In this connection, the very high costs for development of new products, the shortening product life-cycle times, and the forces tending to squeeze out independent entrepreneurs in some heavy industrial sectors all suggest that the United States may need to rethink the way it has financed and managed innovations in some types of cases.

If there is a single lesson this review of innovation emphasizes, it is the need to view the process of innovation as changes in a complete system of not only hardware, but also market environment, production facilities and knowledge, and the social contexts of the innovating organization.

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