Innovation and Commercialization 2

Innovation does not necessarily proceed linearly from basic scientific research to product development; it is an iterative process of both matching market needs to technological capabilities and conducting research to fill gaps in knowledge, whether during product conception, product design, manufacturing, marketing, or other phases of the innovation process. Commercial success depends as much on the ability of firms to establish and protect a proprietary advantage in the marketplace as it does on their ability to generate new scientific and technical advances.

The process of innovation varies dramatically across industries and product lines. In some industries, like pharmaceuticals, innovation depends heavily on scientific breakthroughs; in others, like electronics, it derives more from product and process design. In addition, innovation takes on different characteristics throughout product and industry life cycles. Nascent industries exhibit high levels of product innovation as firms attempt to settle on the primary characteristics and architectures of their new offerings; later phases are characterized more by process innovation, as firms attempt to improve their means of manufacturing existing product lines. Government policies to facilitate innovation and commercialization can be more effective if they recognize the varying conditions leading to success in different industries and address the many barriers firms face in all stages of innovation, from emergence to maturity.

THE PROCESS OF INNOVATION

Technological innovation is the act of developing and putting to use new products and processes. It demands novelty in either the product/process/service, the application, or both. Innovation therefore includes not only the development of entirely new products, processes, and services that create new applications, but also the development of new products, processes, and services for use in existing applications (e.g., integrated circuits replacing vacuum tubes in electronic applications), or the use of an existing product, process, or service in a new application (e.g., manufacturers of flat panel displays adapted semiconductor manufacturing equipment to their needs). Innovation is more than just invention, which is the act of devising new products, processes, and services that are not obvious to someone skilled in the field and that represent clear departures from prior art.[1] Innovation requires that inventions be reduced to practice; that new products, processes, and services be designed, manufactured, and adopted by users. Many inventions are never put into practice—some because they cannot meet users' cost and performance requirements, others because they are technologically infeasible.

No single model accurately depicts the process of innovation; innovation occurs differently in different industries and product lines as firms attempt to develop products and processes that meet market needs. In the pharmaceutical industry, for example, innovation is closely coupled to scientific discoveries and follows a fairly linear pathway through manufacturing and marketing, although firms often begin constructing manufacturing facilities while the drug is undergoing clinical trials. Few other obstacles impede the innovation process in pharmaceuticals: new products can often be protected from imitation by strong patent protection, markets are quite easily identified and quantified, and third-party payment systems (i.e., insurance companies and Health Maintenance Organizations (HMOs)) relax some of the cost constraints on new products.[2] In contrast, innovation in the semiconductor industry derives more from new product design and improvements in manufacturing technology than from advances in basic science; product life cycles tend to be short (not longer than 3 years in most cases) and consumers are highly sensitive to cost, making commercial success more uncertain. In the commercial aircraft industry, innovation is highly centralized in a few producers who act as integrators of components from a broad range of suppliers, product cycles are several decades long, and manufacturers work closely with users to define product specifications and costs.

As these limited examples suggest, innovators face different obstacles in developing and marketing new products, processes, and services, and must proceed through a different set of steps to successfully bring a new invention to market. Not only do differences in industry structure and the nature of markets impose different constraints on the innovation process, but science, technology, and innovation are linked in different ways in different industries. These observations suggest that innovators follow many different pathways through the innovation process, and that attempts to facilitate innovation and the commercialization of emerging technologies must take different forms.

The Linear Model

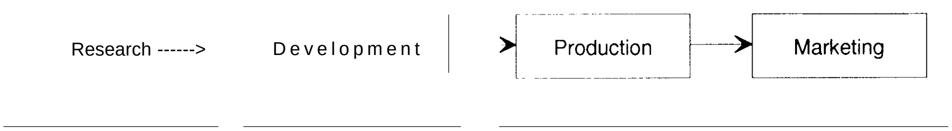
Public policymaking regarding innovation has long been based on the linear model of innovation. In its simplest form, this model postulates that innovation begins with new scientific research, proceeds sequentially through stages of product development, production, and marketing, and terminates with the successful sale of new products, processes, and services (see figure 2-1). As such, the linear model implies that the way to maintain leadership in markets for high-technology goods is to maintain leadership in basic scientific research. Though the model recognizes that development, production, and marketing activities lie between research and product sales, it views these processes more as part of the innovation pipeline than as major obstacles to commercial success.

The linear model gained considerable support after World War II, in part because it explained the

[1] In order to be considered for a patent, new products, processes, and services must be both novel and nonobvious to someone experienced in the field. Many inventions are never patented, either because of the time and effort required to acquire a patent, or because inventors do not wish to publicly disclose the operation of their new product or process.

[2] Recent changes in the health care industry, including the rapid growth of health maintenance organizations (HMOs) and the frequent mergers between hospitals and medical practices, are altering the process of innovation in medical technology by placing a greater premium on cost-effective treatments and diagnostics. See Gerald D. Laubach and Annetine C. Gelijns, "Medical Innovation at the Crossroads," *Issues in Science and Technology*, spring 1995, pp. 33-40.

FIGURE 2-1: The Linear Model of Innovation



SOURCE: Office of Technology Assessment 1995

genesis of important new military capabilities. The atomic bomb derived almost directly from fundamental research in elementary physics; radar derived from research into microwave radiation. The Department of Defense (DOD) further embedded the linear model into federal policymaking by instituting accounting categories for research and development (R&D) that corresponded to individual cells in the linear model. In its current form (revised slightly in FY 1995), the DOD model breaks the innovation process (referred to as research, development, test, and evaluation, or RDT&E) into seven stages. numbered 6.1 through 6.7 (see box 2-1). Projects move sequentially through the categories, from basic research through development and manufacturing, as the technology matures and is applied to new military systems. Because DOD funding dominated federal R&D expenditures throughout the postwar period and drove much of the U.S. research agenda, these categories permeated the thinking about innovation in the United States.

The linear model was further legitimated by Vannevar Bush, science advisor to Franklin Roosevelt, whose treatise, *Science, The Endless Frontier,* became the template for postwar technology policy in the United States. This document stated that funding of basic research would fuel development of technologies that could help advance many social goals, including national defense. health care, and industrial competitiveness. Bush saw funding of basic research as a fundamental mission of the federal government, noting that industry had several disincentives to adequately support long-term fundamental research. He believed, however, that further development and application of new technologies was the sole province of industry, which was better suited to interpreting market needs and identifying lucrative investments.

Effects on Policy

Government policy toward commercial innovation has followed the linear model to a large degree. Support provided specifically for *commercial* innovation has traditionally been limited to funding of basic scientific research. Institutions such as the National Science Foundation (NSF) and the National Institutes of Health (NIH) provide support for basic research, much of it conducted in U.S. universities. Other policies attempt to create an environment conducive to innovation through legal mechanisms such as tax codes, patent law, and antitrust regulations. Such tools tend to operate on an economy-wide level, making no distinctions between industries, though the effects often vary considerably across different industries. For example, changes in the tax code to allow faster depreciation of capital equipment would likely have a greater effect on the semiconductor industry than on pharmaceuticals because of the high cost of semiconductor manufacturing equipment and the large contribution capital expenditures make to semiconductor production costs. Changes in patent law, on the other hand, would likely affect the pharmaceutical industry more than semiconductors because patents are used more frequently in the pharmaceutical industry to protect against imitation.

[3] Vannevar Bush, *Science, The Endless Frontier: A Report to the President* (Washington, DC: U.S. Government Printing Office, 1945).

BOX 2-1: DOD's Research, Development, Test, & Evaluation (RDT&E) Budget Categories

6.1 *Research:* New concepts are developed through laboratory research.

6.2 *Exploratory development:* Promising research results are applied to preliminary laboratory devices,

6.3 *Advanced development:* Technologies are demonstrated in representative systems through Advanced Concepts Technology Demonstrations, and prototypes are developed

6.4 *Demonstration and validation:* Technologies that meet an articulated operational need are demonstrated and validated.

6.5 *Engineering and manufacturing development:* The product/system incorporating the new technology is redesigned for manufacturing.

6.6 *RDT&E management support:* Provides overhead and management funds for all RDT&E activities.

6.7 *Operational system support:* Systems in production or already fielded are improved and upgraded through the incorporation of new technology.

SOURCE: Richard M Nunno, "Defense R&D in the 1990s," IB-93096 (Washington, DC Congressional Research Service, July 18, *1994),* p. 1.

Other support for innovation has come from mission agencies of the federal government, such as DOD, the Department of Energy (DOE), and the National Aeronautics and Space Administration (NASA). Much of the $71 billion in federal R&D spending in 1994 (see table 2-1) promoted initiatives of interest to the federal government that are typically not addressed independently by the private sector. Though mission-oriented R&D does not attempt to directly influence commercial applications of technology, it can have an indirect effect by strengthening the science and technology base from which commercial firms can draw and through more explicit attempts to spin off or transfer government technologies to the commercial marketplace.[4]

Pursuit of government missions has often exerted a strong influence on commercialization of civilian technologies. Decisions by DOD to use integrated circuits (ICs) in the Minuteman missile systems and by NASA to use ICs in the Apollo program provided the first markets for the new technology, and coaxed firms to invest in manufacturing capacity. Commercial firms such as IBM had decided against using ICs in their latest products because of the uncertainty over the reliability of the new technology. Other research funded by DOD generated technologies that were quickly adopted for commercial applications. Today's Internet traces its history to the ARPANET, a computer network established by the DOD's Advanced Research Projects Agency (ARPA) around 1970. ARPA-funded research on gallium arsenide for millimeter wave communications systems and on high performance computing has found its way into wireless communications systems and parallel computers sold in the commercial marketplace.

At times, the federal government has explicitly moved beyond a strict interpretation of the linear model in order to facilitate the development of particular innovations or industries. Since 1987, the federal government, acting through the DOD, has provided funding of $90 million to $100 million annually to support the efforts of SEMATECH, a consortium of major U.S. semiconductor

[4] John Alic et al., *Beyond Spinoff: Military and Commercial Technologies in a Changing World* (Boston, MA: Harvard Business School Press, 1992).

TABLE 2-1: Federal Obligations for R&D by Agency, 1994 (millions of dollars)

Department/Agency	R&D Funding[c]
Agriculture	$1,364
Commerce[a]	897
Defense	37,523
Energy	6,582
Health and Human Services[b]	10,723
Interior	589
Transportation	688
Environmental Protection Agency	656
National Aeronautics and Space Administration	8,637
National Science Foundation	2,217
Other	1,368
Total	71,244

[a]Includes $382 million in funding for the National Institute of Standards and Technology and $504 million for the National Oceanic and Atmospheric Administration.
[b]Includes $10.1 billion in funding for the National Institutes of Health
[c]Estimated obligations for 1994

SOURCE: National Science Foundation, *National Patterns of R&D Resources: 1994,* NSF 95-304 (Arlington, VA: 1995), pp. 79-80

manufacturers. Although the rationale for the program was based on national security grounds, federal participation in SEMATECH has strengthened the U.S. supplier base for semiconductor manufacturing equipment and contributed to the subsequent resurgence of the U.S. civilian semiconductor industry. While SEMATECH is frequently viewed as a success, government sponsorship of other technology programs, such as shale oil and the supersonic transport (SST), have been widely criticized.[5]

Limitations of the Linear Model

Despite its pervasive use, the linear model suffers from several drawbacks that limit its applicability. Many innovations derive not from advances in science, but from exploiting existing scientific knowledge and from recognizing potential new markets for certain types of products, processes, or services. Science nevertheless plays an important role throughout the innovation process by providing information with which to solve problems identified in design, manufacturing, or other stages of the innovation process. In addition, innovation does not always follow a linear pathway from research to marketing. Often, technological developments precede scientific research, and lessons learned from manufacturing and marketing operations can feed back into the product development process. Innovation is usually an iterative process in which designs must be continually tested, evaluated, and reworked before an invention achieves market success.

Science and the sources of innovation

Basic research, while an important part of the innovation process, is not the source of all technological innovation. Ideas for new products and processes derive from many sources: new science, new technological breakthroughs, new perceptions of market demand, or customers themselves. U.S. firms indicate that just 58 percent of their new R&D projects derive from ideas generated by their scientific and technical staff; the remaining 42 percent derive from marketing and production departments or from customers, although considerable variation exists across industries (see table 2-2). Japanese firms demonstrate an even greater

[5]See, for example, Linda R. Cohen and Roger G. Nell, *The Technology Porkbarrel* (Washington, DC: The Brookings Institution, 1991).

TABLE 2-2: Sources of R&D Projects for 100 Firms in the United States and Japan, 1985

	R&D		Marketing		Production		Customers	
Industry	Us.	Japan	U.S.	Japan	U.S.	Japan	U.S.	Japan
Chemicals	45%	49%	25%	23%	14%	15%	8%	3%
Electrical	90	47	7	21	1	5	1	27
Machinery	56	44	21	22	4	11	18	20
Autos, instruments, and metals	51	48	25	8	12	26	11	13
Average, all respondents	58%	47%	21%	18%	9%	15%	9%	15%

SOURCE: Edwin Mansfield, ' Industrial R&D in Japan and the United States: A Comparative Study, " *The American Economic Review* May 1988, p 227

reliance on ideas generated outside their R&D departments. This even applies in industries such as electronics, in which U.S. firms report that 90 percent of R&D projects are suggested by their R&D departments.

Development of new products, processes, and services is guided by a knowledge of both market needs and scientific and technological capabilities. The former helps determine the types of products likely to yield a financial return, as well as the cost and performance attributes required; the latter provides insight into viable means of serving the market need. Many attempts have been made to determine the relative contributions of these two forces-often referred to as *market pull* and *technology* push—in eliciting innovation, but such analyses suggest that innovation is strongly influenced by both (see box 2-2). Innovation is a

BOX 2-2: Technology Push v. Market Pull

New innovations are both pushed along by new scientific and technological discoveries and pulled along by market forces. Several studies have attempted to discern the relative Importance of technology push and demand pull in stimulating innovation, but the results are Inconclusive,

One set of studies traces the histories of particular innovations in particular firms in an attempt to discern whether critical events during the innovation process were motivated by new science and technology or better perceptions of market need.[1] These studies tend to conclude that market pull dominates the Innovation process. One representative study finds that market needs motivated research in 45 percent of the innovations studied; potential gains in manufacturing—which the authors consider a type of market-driven Innovation—accounted for another 30 percent. In only 21 percent of the 567 innovations examined in five Industries was technology considered the driving force [2] Such studies, however, tend to suffer from imprecise definitions of market need and view innovation from the perspective of the innovating firm, whose motivations in innovation should be market-oriented Studies such as the Department of Defense's HINDSIGHT,[3] which examined successful military development programs but considered only critical events that occurred 20 years or less before commercialization tend to ignore most of the long-term influence of basic research because of their short time horizons

(continued)

[1] R. Rothwell et al., "SAPPHO Updated Project SAPPHO Phase 11, " *Research Policy* November 1974; J. Langrish et al. , *Wealth from Knowledge: A Study of Innovation in Industry* (New York, NY: Halsted/John Wiley, 1972), S Meyers and D G Marquis, *Successful Industrial Innovation* (Washington, DC National Science Foundation, 1969), J M Utterback, "Innovation in Industry and the Diffusion of Technology, " Science, Feb. 15, 1974.

[2] S Meyers and D G Marquis, *Successful Industrial Innovation* (Washington, DC National Science Foundation, 1969)

[3] Office of the Director of Defense Research and Engineering, *Project HINDSIGHT* (Washington, DC U S Department of Defense 1969)

BOX 2-2: Technology Push v. Market Pull (Cont'd.)

Another set of studies looks more broadly across companies, industries, or economies in an attempt to link economic growth or competitive success to R&D and market demand.[4] These analyses demonstrate a much greater dependence on technology push as the dominating factor in innovation. The evidence cited in such works suggests a weak relationship between the size and sophistication of national markets and the performance in technological Innovation. Much higher correlations are found between national Innovative performance and supply side factors such as the number of large firms, levels of R&D, and capabilities in fundamental research.[5] This observation applies equally well to comparisons of the innovative performance of Industries within a national unit. Differences in rates of Innovation across Industries are more closely related to factors such as producer concentration and technological opportunity than to market factors.[6] Demand theories do not easily explain the wide variations in performance of Individual industries with respect to technological innovation and productivity growth.

Together, these studies demonstrate that both market pull and technology push play a role in initiating Innovative activities. Few Innovations can be categorized as examples of technology push or demand pull in a clear and unambiguous manner, and few can be described as a linear sequence with a clearly defined starting point.[7] Innovation is an iterative process that responds to both demand and supply side forces. Successful innovations tend to undergo extensive modification during development. This IS due to changes in perceptions of user requirements and of producers' abilities to offer the product, process, or service with the necessary features at an acceptable cost.

Technology push does appear to play a larger role than demand pull in major, revolutionary innovations. One study notes that recognition of a discovery's potential usefulness served as the impetus for Innovation in over 14 percent of the major innovations (which, themselves, represented 13 percent of their total sample), while identification of a particular market need served as the impetus in just 6 percent of the cases. [9] For minor Innovations, the study finds that technology push was important in just 5 percent of the cases, while need identification was important in more than 18 percent. The study also finds that the most Important factor delaying successful innovation—occurring in 32.5 percent of the cases—is Insufficient development of a complementary technology. In 22.5 percent of the cases, there existed at first no market or need; and management failed to recognize the need for the innovation in 76 percent of the cases. For major innovations, the lack of market and lack of complementary technology factors were of equal Importance, while for minor innovations, the lack of complementary technology was more Important than lack of market.

SOURCE Off Ice of Technology Assessment, 1995

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[4] C Freeman, *The Economics of Industrial Innovation* (Cambridge, MA MIT Press, 1982), K Pavitt, *The Conditions for Success in Technological Innovation* (Paris: Organisation for Economic Cooperation and Development, 1971)

[5] Pavitt, Ibid , p 53

[6] David Mowery and Nathan Rosenberg, "The Influence of Market Demand Upon Innovation A Critical Review of Some Recent Empirical Studies, " *Research Policy.* vol. 8, 1979, p 144

[7] J. Langrish et al., *Wealth from Knowledge: A Study of Innovation* in *Industry (New* York, NY: Halsted/John Wiley, 1972)

[8] Ibid.

process of trial and error, of finding workable solutions to known or perceived market needs. Innovators continually try to find new applications for science and technology and ways of satisfying market demands, but not until technology push and market pull are combined do innovations find market success.

Though not unique in its ability to initiate innovation, science nevertheless plays a critical role throughout the process. Scientific discoveries can pave the way for numerous innovations—and industries—as the linear model suggests. Today's semiconductor technology derives from scientific research into solid state physics; the biotechnology industry derives from recent advances in molecular biology. In these cases, long-range theoretical investigations into the nature of the physical universe provided new knowledge that, in turn, opened entirely new avenues for approaching particular problems. Such science is typically pure, long-range science, needed to test predictions of existing theory or to more fully develop that theory. Because it helps construct the theoretical framework describing natural processes, such research often takes many years—even decades—to translate into practical applications.

Science and scientific research also contribute to other stages of innovation. Product developers often conduct scientific research to solve technical problems that arise during the design of a product, process, or service. Manufacturing engineers also rely on scientific research to overcome manufacturing problems. In chemicals, better understanding of catalyst and chemical reactions can lead to improved yields or lower production costs. In semiconductors, improvements in the capability of microprocessors or the storage capacity of memory chips rely on research into manufacturing techniques that allow more devices to be packed onto an individual integrated circuit. Research performed to support development activities is often geared toward understanding the ways in which the components of a complex system interact and the properties of the overall system created by multiple interactions. Research in the production stage is often conducted to investigate ways of manufacturing particular components of a system and to find ways of reducing costs through the use of special equipment or less expensive materials. In products developed for the commercial marketplace, systems and process research are not only necessary to the proper functioning of the innovation, but are often more important than basic science in reducing costs and improving performance.

Many firms distinguish between research activities undertaken to explore and develop a new body of knowledge and those pursued to solve particular problems in the development process. In the former case, the goals of the research are often diffuse and the benefits are difficult for any one company or institution to monopolize. In the latter case, research results are more targeted and the results easier to appropriate. Researchers, therefore, tend to collaborate more widely on the former type of R&D and to share information more freely. In the latter case, researchers will usually try to solve the R&D problem with internal resources or with limited use of outside capabilities.

Science feeds into the innovation process in other ways as well. Scientific researchers often develop analytical tools that engineers later use in designing product, processes, and services. Scientists also create instrumentation, lab techniques, and analytical methods that eventually find their way into industrial process controls. Examples include electron diffraction, the scanning electron microscope, ion implantation, synchrotron radiation sources, phase-shifted lithography, and superconducting magnets. Such instrumentation is often developed in pursuit of basic research, but is later adapted for manufacturing purposes.

The pathway through innovation

Innovation rarely proceeds in a linear fashion from one well-defined stage to the next. Most innovations take a much more complicated route from invention to marketplace. Often, market perceptions generate ideas for new products that, in turn, stimulate scientific research. In addition, advances in technology can precede advances in the science base (see box 2-3). The Wright brothers, for example, knew little, if anything, about formal

BOX 2-3: Linkages Between Science and Technology

Technology is often considered the practical application of science. As such, it is commonly thought to depend on and follow behind advances in the underlying science. This progression is certainly true in some cases. The discovery of radio waves—a result of Hertz's attempt to follow up on predictions made by Maxwell several years earner-clearly paved the way for technological advances in such areas as radio, television, and communications. The discovery of superconductivity has paved the way for magnetic resonance imaging and high-strength industrial magnets.

Such an understanding of technology is limited, however. Technology is not merely the application of knowledge generated by scientific activity; it is a body of knowledge about certain classes of events and activities. It is a knowledge of techniques, methods, and designs that work, and that work in certain ways and with certain consequences, even when one cannot explain exactly why. Science and technology are best thought of as two parallel streams of cumulative knowledge that have many interdependencies and cross relations, but whose internal connections are much stronger than their cross connections. As a result, technological progress is not necessarily dependent on scientific progress.

Technology itself often dictates its own path of development along what have been referred to as technological trajectories. Just as science is often considered to operate under distinct paradigms that determine relevant problems and approaches for solving them, so, too, does technology operate under particular paradigms that consist of sets of procedures, definitions of the relevant problems, and details of the specific knowledge related to their solution. Each technological paradigm defines its own concept of progress based on its specific technological and economic tradeoffs. A technological trajectory is the direction of advance within a technological paradigm.

Technological knowledge often *precedes* scientific knowledge and signals lucrative areas for scientific research. Torricelli's demonstration of the weight of air in the atmosphere was an outgrowth of his attempt to design an improved pump. Carnot's creation of thermodynamics was an attempt to understand the efficiency of steam engines some 50 years after Watt introduced the invention itself. Joule's discovery of the law of conservation of energy derived from an interest in alternative sources of power generation in his father's brewery; and Pasteur's development of bacteriology emerged from his attempt to deal with problems of fermentation and putrefaction in the French wine industry. These limited examples show that basic science can—and often does—arise out of an attempt to understand a narrow technical problem.[1]

Technology also drives science by providing a huge repository of raw data for scientists to scrutinize in developing better scientific theories. Successful development of a new device often stimulates scientific research to better understand its operation and improve its performance. The natural trajectory of certain technological improvements identifies and defines the limits of further improvement, which in turn focuses subsequent scientific research. In some cases, the advance of knowledge occurs only by actual experience with a new technology in its operating environment, as has occurred in aviation, for example. One of the central features of high-technology industries is that technological progress identifies the directions of new scientific research offering a high potential payoff. In telecommunications, transmission over longer distances, and the introduction of new modes of transmission, have generated basic research into the interactions of electromagnetic radiation with weather and atmospheric conditions.

SOURCE: Nathan Rosenberg, *Inside the Black Box: Technology and Economics* (New York, NY: Cambridge University Press, 1982) pp. 141-159; Harvey Brooks, "The Relationship Between Science and Technology, " *Research Policy,* vol. 23,1994, p 479, Giovanni Dosi, "Technological Paradigms and Technological Trajectories, " *Research Policy,* vol. 11, 1982, pp. 147-162

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[1] Giovanni Dosi, "Technological Paradigms and Technological Trajectories, " *Research Policy,* vol. 11, 1982, pp. 147-162 Examples are from R R Whyte (ed.), *Engmeermgf'regress Through Trouble* (London: The Institution of Mechanical Engineers, 1975)

aerodynamics theory; yet, through consistent refining of designs, they successfully developed the first airplane. Development of the microprocessor also derived more from advances in technology than in science, as improvements in semiconductor manufacturing techniques reduced the size of devices that could be fabricated on an integrated circuit (IC) and allowed the multiple component parts of a microprocessor to be fabricated on a single IC.

Parallel computing is a more recent example of a major innovation that derived from advances in technology that preceded the underlying scientific theory. Parallel computers use multiple processing units simultaneously to conduct data- or computation-intensive calculations. Parallel computers did not derive from basic research into the nature of algorithms for parallel computation, but from an attempt to overcome the bottleneck on processing speed imposed by reliance on a single processor. Initial activities centered around the design and construction of prototype machines with different internal architectures for linking multiple processors (which in some designs number more than 1,000) and memory. These activities fall into the category of engineering design and development, not scientific research.

Of course, the availability of parallel computers has stimulated basic research on algorithms for parallel computation, which will enable these computers to be used more efficiently. As with all electronics technology, parallel computing builds on a base of fundamental scientific knowledge about solid state physics. The components that comprise the processors and memory chips used in parallel computers could not have been made without that understanding. Several versions of parallel computers incorporate gallium arsenide processing units in an attempt to increase processing speed. But such research, in itself, did not trigger the development of parallel computers.

A further blurring of the lines between stages in the innovation process has resulted from deliberate attempts by firms to revamp their product development processes. In the past, large companies with corporate research laboratories, such as AT&T, DuPont, IBM, and Xerox, organized their product development activities as a linear progression from research lab to marketing. Corporate laboratories independently generated new science and technology and transferred their results to the product development divisions. They, in turn, designed new products, constructed prototypes, and passed the designs to the manufacturing divisions for production. This model often caused mismatches between the output of the research labs, the needs of the product designers, and the capabilities of the manufacturing process, resulting in wasted effort, high costs, and low quality.[6]

This model has been replaced, to a large degree, by concurrent forms of product development in which responsibility for new product development is given to a project team consisting of representatives from the research, development, manufacturing, and marketing divisions. Such organization reflects the desire to incorporate insights from each of these areas of expertise into the original conception of the innovation, making it simpler to target corporate research toward commercial goals and eliminate downstream problems that often hampered manufacturing and marketing.

Furthermore, innovation is a highly iterative process, characterized by constant feedback from markets. The personal computer, for example, went through several iterations by SRI, Inc. and Xerox Corp., among others, before the Apple II became a success. The automobile and airplane went through similar periods of refinement. This process allows experience gained in later stages of innovation, such as manufacturing and marketing, to feed back into earlier stages, such as basic re-

[6] Council on Competitiveness, *Picking Up the Pace* (Washington, DC: Council on Competitiveness, 1988); David A. Hounshell and John Kenly Smith, Jr., *Science and Corporate Strategy: DuPont R&D, 1902-1980* (New York, NY: Cambridge University Press, 1988); and OTA interviews.

search and product design. As new products and processes are tested in the marketplace, firms learn first-hand about the performance and cost attributes demanded by consumers, and use that information to develop improved versions of the product, process, or service. In this way, the development and adoption of innovations are closely interrelated. Adoption, rather than representing the end point of the development process, constitutes the beginning of an often longer process of redesign whereby the design can be iterated, research can be conducted to identify means of improving performance or reducing cost, and manufacturing problems can be resolved.[7]

Alternative Views of Innovation

As these observations suggest, technological innovation is more that the direct translation of new scientific knowledge into marketable products; rather, it is a more complex process of developing and putting to use new products, processes, and services. This process can take many forms: 1) development and application of new products, processes, and services to satisfy previously unmet market needs, as the linear model implies; 2) development and application of new products, processes, and services—usually based on new science and technology—to existing market needs; 3) use of existing products, processes, and services in new applications; and 4) incremental improvements to existing products, processes, and services for their existing applications. Each type of innovation presents different challenges to innovators. Impediments to progress can range from a limited science and technology base, to competition from existing technologies, to unreceptive markets.

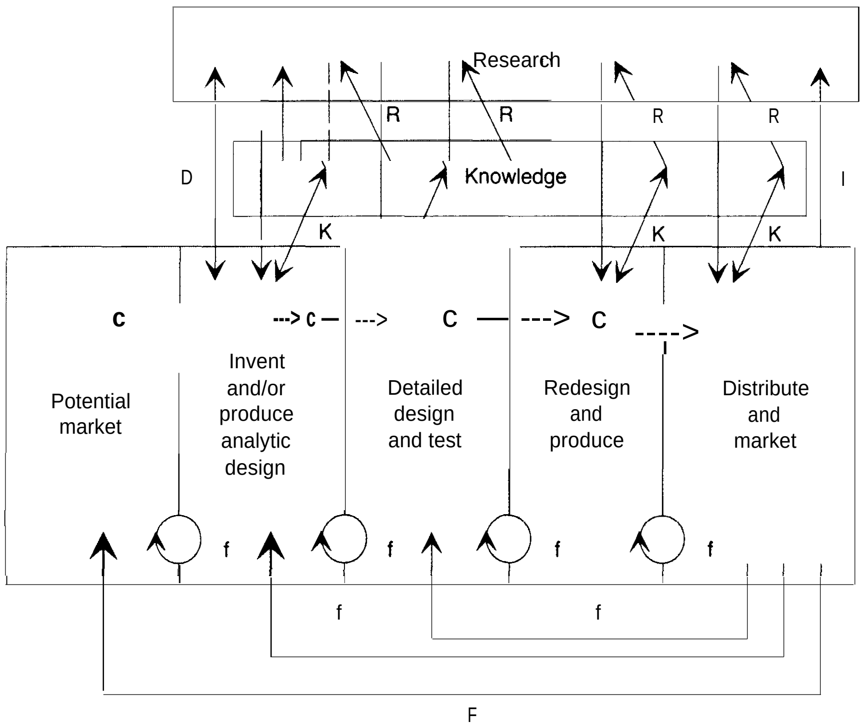
One attempt to model the complex interactions between science, technology, and innovation is the Chain-Link Model of innovation.[8] In contrast to the linear model, the chain-link model allows for feedback between stages of the development process, and separates science from the development process to highlight the multiple roles science plays in innovation. The chain-link model breaks down the process of developing new products, processes, and services into five stages: 1) recognition of a potential market; 2) invention or the production of an analytical design for a new product; 3) detailed design, test, and redesign; 4) production; and 5) distribution and marketing (see figure 2-2). The process typically proceeds linearly, but is supplemented by feedback between adjacent stages that iterates each step as necessary (arrows marked ‘f’ in figure 2-2). In this way, a problem identified in the design and test phase, for instance, forces innovators to attempt a new design. Additional feedback from users in the marketplace is also incorporated into each stage of the process (along the pathways marked ‘F’) to help ensure that the design of a new product—and the technological capabilities incorporated into it—matches the demands of the marketplace.

This model allows for several different types of innovation. First, new scientific discoveries can create new opportunities for novel products and processes, much as advances in physics laid the groundwork for development of the integrated circuit. New science and technology often provided new means of serving existing markets, displacing existing technologies in the process. Integrated circuits, for example, provided a new means of modifying electronic signals, and eventually replaced vacuum tubes in most applications. Second, newly recognized market needs can stimulate the development of new products and processes that are based on existing technologies, though some additional R&D may be needed. IBM’s PC and Sony’s first portable transistor radio, although based on existing

[7] Annetine Gelijns and Nathan Rosenberg, “The Dynamics of Technological Change in Medicine,” *Health Affairs*, summer 1994, pp. 30-31.

[8] This description of the product/process development model is based on a model developed by Stephen Kline at Stanford University. See Stephen J. Kline and Nathan Rosenberg, “An Overview of Innovation,” in Ralph Landau and Nathan Rosenberg (eds.), *The Positive Sum Strategy* (Washington, DC: National Academy Press, 1986), pp. 275-305.

FIGURE 2-2: Kline-Rosenberg Chain-Link Model of Innovation



KEY: C = central pathway of innovation; D = scientific discoveries that generate radical innovations, F = market feedback, f = iterative feedback between stages; I = innovations that contribute directly to scientific research, such as the microscope and telescope; K = contributions of existing knowledge to the renovation process, R = research used to solve problems encountered throughout different stages of innovation.

SOURCE: Stephen J Kline and Nathan Rosenberg, "An Overview of Innovation," *The Positive Sum Strategy: Harnessing Technology for Economic Growth,* Ralph Landau and Nathan Rosenberg (eds.) (Washington, DC National Academy Press, 1986), p 290

technology, opened vast new markets. Third, innovation can be incremental. Existing products can be enhanced to improve performance or lower costs, or they can be modified slightly to be used in new markets. New software development has enabled personal computers to expand into a wide variety of applications, such as word processing, database management, and electronic communications. These types of innovation differ in the ways they incorporate R&D, in the barriers they face, and in the types of innovations they generate.

Science- or Technology-Driven Innovation

Science usually plays a subservient role in innovation, providing answers to questions posed at different points in the innovation process. However, scientific or technological discoveries do, at times, act as the genesis of new innovations by creating entirely new ways of serving existing or new markets. This often occurs in industries such as pharmaceuticals, chemicals, and materials—that are characterized more by discovery of new products than by their design—but scientific and

TABLE 2-3: Time Required To Commercialize New Materials

Material	Invented	Commercialized
Vulcanized rubber	1839	late 1850s
Low-cost aluminum	1886	early 1900s
Teflon	1938	early 1960s
Titanium	mid-1940s	mid-1960s
Velcro	early 1950s	early 1970s
Polycarbonate (bullet-proof glass)	1953	1970
Gallium arsenide (semiconductor)	mid-1960s	mid-1980s
Diamond-like thin films	early 1970s	early 1990s
Amorphous soft magnetic materials (for transformers)	early 1970s	early 1990s

SOURCE: Thomas W. Eagar, "Bringing New Materials to Market" *Technology Review,* February/March 1995, pp. 42-49.

technological advances are responsible for creating major changes in other industries as well. Scientific and technological research has generated new products such as lasers, liquid crystal displays, and integrated circuits, each finding its way into myriad products, serving different markets.

Translating new science into new products is typically a slow, laborious process. New materials typically experience a 20-year lag between invention and widespread adoption (see table 2-3); lasers took decades to advance from a laboratory curiosity to an integral component of communications systems, medical devices, and consumer electronics. Much of the difficulty in commercializing scientific breakthroughs is in determining suitable applications and understanding the engineering limitations of new devices. In many cases, the science is still not sufficiently understood for scientists and engineers to select the application with the highest probability of successor the most favorable financial return.

New technology often finds its greatest success in products that were not even conceived of at the time of discovery. Low-temperature superconductors, for example, found their greatest application in medical magnetic resonance imaging (MRI) devices, which were not conceived of until six or more decades after the discovery of superconductivity. In this case, as in many others, additional pieces of information were needed before the innovation could be realized. MRI technology depended not only on the availability of high-field superconducting magnets, but of nuclear magnetic resonance spectroscopy, computer imaging, and fast signal processing technologies as well. None of these was available when superconductivity was first discovered in 1911, or when the first practical superconducting materials were found in the 1960s.[9] Similarly, the applications of lasers to communications systems had to await the development of fiber optics with low loss at laser wavelengths of light, over which optical pulses could be routed.

Considerable time and effort must be allocated to applied research in which the capabilities of the new technology in different applications are evaluated. This process often requires considerable trial and error because performance cannot be predicted with accurate models. For example, the recent discovery of buckeyballs—spherical ensembles of carbon atoms whose bonds mimic the stitching on a soccer ball—touched off a flurry of speculation regarding possible applications, including: Teflon-like ball bearings; cage-like structures for transporting atoms (especially radioactive ones) inside the human body; sieves for filtering nitrogen out of natural gas; or protecting transplanted organs by allowing sugars and amino acids, but not viruses and antibodies, to

[9] See U.S. Congress, Office of Technology Assessment, *High-Temperature Superconductivity in Perspective,* OTA-E-44 (Washington, DC: U.S. Government Printing Office, April 1990).

pass.[10] Development of any of these applications is years away as researchers attempt to further examine their feasibility and limits to their use.

High-temperature superconductors (HTS) provide another example of this phenomenon. Superconductors present no resistance to the flow of electrons below a certain critical temperature. High-temperature superconductors, typically ceramics, have critical temperatures above 35 degrees Kelvin (35° K). The more recently discovered HTS materials, based on compounds of yttrium, barium, copper, and oxygen (YBaCuO) or mercury, barium, calcium, copper, and oxygen (HgBaCaCuO), have critical temperatures well above 75° K (about 90° K and 140° K, respectively). This allows them to be cooled with liquid nitrogen, which is much cheaper and easier to handle than the liquid helium used to cool low-temperature superconductors (LTS).

Since the discovery of HTS in 1986 by researchers in IBM's Zurich research laboratory, scientists and engineers have attempted to exploit the technology in a number applications: large magnets for the Superconducting Supercollider or for separating metallic impurities from industrial powders; electric power transmission; electronic computers; filters for wireless communications systems; and sensors for detecting magnetic fields.[11] Each of these applications has presented developers with numerous engineering challenges that slowed progress in many areas. Because they are ceramics, most HTS materials are brittle, making them difficult to use in applications such as flexible wires. Engineers attempting to develop superconducting wires for use in magnets or power distribution have had to find ways of handling the material without breaking it or cracking it, which interferes with its superconducting capabilities. They have also had to design cooling systems for different applications, whether underground power transmission wires or base stations for cellular telephony. Use of HTS in computers is currently limited by the manufacturers' ability to create arrays of electronic switches called Josephson junctions with features as small as 100 angstroms—the length of about 30 atoms and 35 times smaller than the smallest features found in state-of-the-art production semiconductor circuits. While HTS could reach the marketplace as early as 1996 in the form of filters for wireless communications systems, large market growth is unlikely to occur until after the year 2000.[12]

Innovations based on new scientific or technological developments often have difficulty gaining initial market acceptance. Sometimes this happens because the new product is introduced before the market has had time to develop—or has expressed demand for the product. Innovations that follow the linear model are particularly prone to such problems because they are often pursued in response to newly derived technical capabilities, rather than newly recognized market needs. Considerable changes in the market environment may be necessary to induce sales of the new technology.

Market-Driven Innovation

Most new product and process development is not initiated by new science, but instead is an attempt to meet perceived market needs by drawing on existing technology and on the pool of scientific knowledge. This process has been described as *demand articulation*, a process whereby firms use market data to translate vague notions of market demand into a product concept and then decompose the product into a set of development

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[10] Hugh Aldersey-Williams, "The Third Coming of Carbon," *Technology Review*, January 1994, pp. 54-62.

[11] This last application uses another characteristic of superconductors, the so-called Meissner effect, whereby superconductors expel magnetic fields from their interior by generating electrical currents on their surface.

[12] See Donn Forbes, "Commercialization of High-Temperature Superconductivity," unpublished contractor report prepared for the Office of Technology Assessment, June 1995.

BOX 2-4: Xerography as a Market-Driven Innovation

The initial development of xerography, the means for copying documents using a dry, photoelectric effect, highlights the market-driven model of innovation. The impetus for xerography stemmed not from the discovery of photoconductive materials—materials that change their conductive properties when exposed to light and formed the heart of early xerographic processes—but awaited the recognition of a need for a new copying process. This happened in 1935 when Chester F. Carlson, a patent attorney, realized that he needed a better way to copy paper documents. The constant need for multiple copies of patent specifications to be sent to inventors, associates in foreign countries, and others demanded a process faster than carbon copying, which required documents to be retyped or errors to be corrected on multiple copies.

Carlson examined many alternative methods for reproducing documents. He determined that chemical processes would not suffice because of the variation in inks used on originals (some were typewritten, others used India ink, pencil lead, or ink), and began looking for photographic mechanisms that made use of the only feature common to all documents: the high contrast in the light-reflecting characteristics between the paper and the markings. He began reviewing literature on the ways in which light interacted with matter—photoelectric effects and photoconductivity in particular—and found a paper describing a method for facsimile transmission in which gas ions were deposited onto a drum made of electrostatic materials to create an electronic image of the original document. The document could be made visible by dusting a fine powder onto the drum,

Carlson developed a similar process for copying paper documents. He used high-voltage ions to precharge an insulating material that would become conductive when exposed to light (a photoconductor). He then projected the image of a document onto the photoconductor to create a photostatic image and covered it with a fine powder to make it visible. The image could then be transferred to a sheet of paper. Carlson patented his invention in 1937. Though photoconductive materials had been discovered as early as 1873, their application to document reproduction had not previously been considered, Carlson's invention of xerography, in turn, stimulated considerable research into photoconductive materials and the theory of their operation, as Carlson, and later other researchers, attempted to Improve on the basic invention.

SOURCE: Battelle Columbus Laboratories, *Interactions of Science and Technology in the Innovative Process: Some Case Studies,* final report prepared under contract for the National Science Foundation, Mar 19, 1973, chapter 7, Joseph Mort, "Xerography A Study in Innovation and Economic Competitiveness," *Physics Today,* April 1994, pp. 32-38.

projects.[13] Through this process, the need 'or a specific technology or set of technologies is expressed and R&D efforts can be targeted toward developing them.

In the market-driven paradigm, innovative activity takes the form of a search for the best technology or product to meet the anticipated or expressed need. Often, the technology already exists and only needs to be acquired (if not currently existing within the organization) and modified for anew application. At other times, additional R&D is necessary to develop the technology, but the type of research performed will be much more applied than in the early stages of a science-driven innovation, searching for a technology that performs a specific function within a well-defined set of parameters (see box 2-4). In attempting to develop a VCR for home use, for example, Sony

[13] Fumio Kodama, *Emerging Patterns of Innovation: Sources of Japan's Technological Edge* (Boston, MA: Harvard Business School Press, 1 995), p. 8.

realized that it would need to find a way of recording video information onto a narrower tape than the one used by the broadcast industry, and it adopted the helical scan technology developed by a researcher at Toshiba several decades earlier. Sony also recognized that the electronic circuitry used to correct fluctuations in color in industrial VCRs was too bulky for a home device, and developed a way to eliminate the problem by reducing the carrier frequency used in the device.

Like science-based innovations, demand articulation can be a slow process as developers address the many technical problems confronting them. The VCR took 20 years to develop from an expensive, closet-sized device into a consumer product; xerography took nearly four decades. In addition, demand articulation requires that firms maintain a broad base of technological competence so they can absorb and adapt technologies from related industries. The success of Apple in commercializing the personal computer, for example, was aided in large part by its ability to identify competent producers of the key components of its device: microprocessors, displays, and storage devices. Demand articulation also thrives on brisk competition between companies that must maintain a tight focus on consumer demand and may be more willing to experiment with alternative solutions.[14]

Incremental Innovation

While science-enabled and market-driven innovation generate radically new inventions that transform markets, most innovation takes the form of incremental changes to existing products and processes. Incremental innovation improves both product features and manufacturing processes, and is an important part of a company's competitive standing. Once a new concept has been proven in the marketplace, competition quickly shifts to quality, price, and performance, with less competitive emphasis on fundamental changes in product or service characteristics.[15]

Incremental innovation differs fundamentally from both science-driven and demand-articulated innovation, in which new, fundamental knowledge is used to create new types of products. Incremental advances occur cyclically and, despite proceeding in an evolutionary fashion, can produce sizable cumulative effects. Incremental innovation has yielded continuous improvements in computer memory, the speed of microprocessors, and the thrust-to-weight ratio of jet engines. Greater increases in performance often are derived from continual improvements in existing product technologies, rather than from the introduction of radical new technologies.[16]

Incremental innovation places different requirements on science and technology than does the science-driven model of innovation. With incremental innovation, new ideas can be incorporated into the product only during a limited window of opportunity at the beginning of the product development cycle, before the design has been firmly established. New ideas introduced at a later date will often require redesign of the product and delay market introduction. In addition, new ideas need to be reasonably well developed, understood, and tested to avoid unforeseen problems that could delay the delivery schedule. To be successful, incremental innovation requires small, evolutionary advances instead of larger, more revolutionary ones, so that product performance and manufacturing techniques can be well understood. New technology-based products and the processes used to manufacture them are rapidly becoming so complex that producers do not completely understand them. Manufacturers of integrated circuits, for example, cannot completely characterize the processes used to inject or diffuse

[14] Ibid., p. 151.

[15] Ralph E. Gomory and Roland W. Schmitt, "Step-by-Step Innovation," *Across the Board*, November 1988, pp. 52-56.

[16] Ibid., p. 53.

TABLE 2-4: Ratio of Innovation Times for U.S. and Japanese Firms, 1985[a]

Industry	Japanese Estimates	U.S. Estimates
Chemicals	096	104
Rubber	1,10	1,16
Machinery	1,23	1 17
Metals	118	0.99
Electrical	1.42	103
Instruments	138	1.00
All industries	1.18	106

[a]Based on data provided by 50 Japanese and 75 American firms U.S. firms' cycle time divided by Japanese firms' cycle time

SOURCE Edwin Mansfield. "The Speed and Cost of Industrial Innovation in Japan and the United States External vs. Internal Technology, " *Management Science,* October 1988, p 1158

ions or chemical dopant into a semiconductor wafer.

Time to market is critical in incremental innovation, so firms must attempt to reduce development times. Companies with shorter product development cycles can bring new technology quickly to market and benefit from more frequent feedback from consumers. During the mid 1980s, U.S. firms lagged their Japanese competitors in cycle times in a number of industries (see table 2-4), hurting their competitiveness. Fast cycle time requires close ties between development and manufacturing so products can be designed for easy manufacturing and technical problems can be identified early in the process. As a result, successful incremental innovation requires that firms become efficient at all the functions of innovation: research, design, development, manufacturing, and marketing. Having access to complementary assets, such as distribution or service networks, is often a critical element in competitive success. 17

The relative decline in U.S. industrial competitiveness during the 1980s has often been attributed to the nation's inability to master incremental innovation. As foreign nations have improved their technological capabilities, relative to the United States, they have improved their ability to rapidly adapt U.S. technologies and improve on them.[18] U.S. companies responded by devoting more of their resources to the development of new products, processes, and services, rather than improving on existing ones (see table 2-5). U.S. firms have increased their efforts in the area of product/process improvement in the last decade, and improved their competitive performance as a result.

TABLE 2-5: Composition of R&D Expenditures in the United States and Japan (by percent of total industrial R&D expenditures)

R&D expenditures devoted to	United States	Japan
Basic research	8%	10%
Applied research	23	27
Products (versus processes)	68	36
Entirely new products and processes	47	32
Projects with less than O 5 estimated chance of success	28	26
Projects expected to last more than 5 years	38	38

NOTE: Columns do not add to 100 percent because the categories are not mutually exclusive

SOURCE Edwin Mansfield, "Industrial R&D in Japan and the United States: A Comparative Study, "*American Economic Review*, vol. 78, No 2, May 1988.

[17] Alic et al., op. cit., footnote 4, p. 20.

[18] Raymond Vernon, "International Investment and International Trade in the Product Cycle," *Quarterly Journal of Economics,* May *1966, pp. 190-207.*

TABLE 2-6: Characteristics of Innovation in Different Phases of Industrial Development

	Stage of Development		
Characteristics	**Introductory**	**Growth**	**Mature**
Predominant type of Innovation	Frequent major changes in products.	Major process changes required by rising volume	Incremental for product and process, with cumulative improvement in productivity and quality
Competitive emphasis	Functional product performance.	Product variation	Cost reduction
Stimulus for innovation	Information on users' needs and users' technical inputs.	Opportunities created by expanding internal technical capability	Pressure to reduce cost and improve quality
Product line	Diverse, often including custom designs	Includes at least one product design stable enough to have significant production volume,	Mostly undifferentiated, standard parts.
Production processes	Flexible and inefficient; major changes easily accommodated	Becoming more rigid, with changes occurring in major steps.	Efficient, capital-Intenswe, and rigid, cost of change is high.
Equipment	General-purpose, requiring highly skilled labor	Some subprocesses automated, creating "islands of automation. "	Special-purpose, mostly automatic with labor tasks mainly monitoring and controlling
Materials	Inputs limited to generally available materials	Specialized materials may be demanded from some suppliers	Specialized materials will be demanded; if not available, vertical Integration will be extensive
Plant	Small-scale, located near user or source of technology.	General-purpose with specialized sections	Large-scale, highly specific to particular products

SOURCE: William J. Abernathy and James M Utterback, "Patterns of Industrial Innovation, " *Technology Review,* June/July 1978

Innovation Cycles

Radical science-enabled and market-driven innovation and incremental innovation represent different stages in the life cycle of a particular industry or product line. Most innovation tends to proceed in characteristic cycles with long periods of incremental innovation punctuated with moments of radical change. New products, processes, and industries emerge from radical innovation, then improve, diversify, and specialize until they are displaced by another radical innovation. These distinctions correspond to three distinct phases in the product life cycle: an introductory or emergent phase, a growth phase, and a period of maturity (see table 2-6).[19]

The introductory phase is characterized by considerable experimentation with fundamentally different designs for a particular product or process. In the early days of the automobile, for example, manufacturers experimented with cars powered by gasoline, electric, and steam engines. Today, manufacturers of electronic displays are

[19] See, for example, G. Dosi, "Technological Paradigms and Technological Trajectories, "*Research Policy,* vol. 11, *1982,* **pp.** 147- 162; M. Utterback and W. Abernathy, "A Dynamic Model of Process and Product Innovation," *Omega, vol.* 3, No. 6, 1975, pp. 639-656; W. Abernathy and K. Clark, "Innovation: Mapping the Winds of Creative Destruction," *Research Policy, vol. 14, No.* 1, February 1985. pp. *3-22:* T. Durand, "Dual Technological Trees: Assessing the Intensity and Strategic Significance of Technological Change," *Research Policy, vol. 21, No. 4,* August 1992, pp. 361-380.

working with liquid crystals, plasma cells, electroluminescent, and field emission devices. During this stage of development, competition is based largely on product characteristics rather than price, as firms attempt to provide superior functionality. New firms enter the market with new designs and functions; startup firms often play a dominant role. Production methods remain flexible to compensate for changes in design, and investment in production equipment and facilities is modest.

During the growth phase, markets expand rapidly as industry settles on a set of offerings that is more or less standard, and product variation decreases. Competition begins to shift from product differentiation to cost reduction, and profit margins often decline. Innovation shifts toward cyclical improvement of existing products through the incorporation of new features and components, and toward process improvements to drive manufacturing costs down. Production processes become more stable, stimulating development of improved manufacturing equipment and capital investments. Product stability can encourage the innovating firm or others to develop complementary assets needed to further expand markets.

As the product matures, product and process innovations slow, and further improvements in performance or costs become evasive. Additional expenditures on R&D are unlikely to yield significant improvements in performance or cost. Firms must decide whether to proceed with existing product lines or develop new ones. Because of the large investments in production capability and complementary assets, mature products and processes can often resist challenges from alternative technologies—even those that offer significant technical, financial, or societal advantages. The nation's existing investment in volume production plants, refueling infrastructure, and repair facilities, for example, make it difficult for alternative-fuel vehicles to challenge gasoline-powered automobiles. Yet, continued improvement of alternative technologies often results in development of new products and processes that replace mature ones.

A critical element in the transition from an emergent industry to a growth industry is the determination of a dominant design. This design—or set of designs—is the one that emerges as most promising in the marketplace. It does not necessarily outperform all others on any particular functional attribute, but overall it meets the desires of the market. Examples of such dominant designs include: the IBM PC, which set the standard for most personal computers over the past decade, but incorporated no leading-edge technologies; and the DC-3, which became the standard for commercial aircraft, but lagged behind several competing designs in terms of range and payload.

Designs that prove successful early in the development cycle can gain momentum quickly and become established dominant designs. Once a successful design is demonstrated, others will likely copy it rather than risk a new approach. Economies of scale in production and learning-curve effects also tend to instantiate a dominant design by making it more cost competitive. Development of complementary assets can further tip the scales by making the design more compatible with existing infrastructure. An example is sequential software for single-processor computers, which makes the transition to multiple-processor machines less attractive to users. Similarly, in the home VCR market, the greater availability of VHS-format prerecorded tapes in the early 1980s accelerated the triumph of VHS players over the alternative Beta format machines.

COMMERCIALIZATION

Commercialization is an attempt to profit from innovation by incorporating new technologies into products, processes, and services and selling them in the marketplace. For many new technologies, commercialization implies scaling up from prototype to volume manufacturing and committing greater resources to marketing and sales activities. In industries such as pharmaceuticals and aircraft, commercialization is also contingent on receiving product approval from relevant organizations. Typically, the cost of commercialization activities

TABLE 2-7: Distribution of Costs for Developing and Introducing New Products[a]
(Percentage of Total Project Cost)

Phase of Development	United States	Japan
Applied research	18%	4%
Preparation of product specifications	8	7
Prototype or pilot plant	17	16
Tooling and equipment	23	44
Manufacturing startup	17	10
Marketing startup	17	8

[a]Survey figures for new products introduced in 1985 by 100 U S and Japanese firms in the chemicals, machinery, electrical and electronics, and rubber and metals industries.
NOTE: Totals may not add up to 100 percent because of rounding
SOURCE: Edwin Mansfield, "Industrial Innovation in Japan and the United States, " Science, Sept. 30, 1988, p 1770

far exceeds that of R&D (see table 2-7). R&D and product design comprise approximately one-quarter of the cost to introduce a new product to market.[20] Invention—defined as the conception of a new product, including some basic and applied research—represents only 5 to 10 percent of the total effort.[21] Thus, scale-up activities act as a filter for selecting inventions to commercialize. Many innovations are developed to the prototype stage or are produced in small volumes, but are not fully commercialized because the financial and managerial resources required are too great. Such innovations are often licensed to another firm, sold off in the form of a divestiture, or simply passed over.

Decisions to commercialize new technology are made by individual firms, but are closely linked to characteristics of the innovation system in which the firm operates. Manufacturers must assess the likelihood of securing funding from internal and external sources, their ability to develop or gain access to manufacturing equipment and supplies, and the size of potential markets. Without the proper infrastructure to support their efforts, firms cannot be assured of winning returns from their investment, and competitors with abetter support infrastructure may be able to capture the market. Pioneers in a new market often lose out to imitators with better financing, infrastructure, and strategy. Examples include EMI, Ltd. 's loss of the market for computer axial tomography (CAT) scanners to General Electric Co.; MITS's loss of the personal computer market to Apple and IBM; and U.S. firms' loss of much of the flat panel display industry to Japanese firms such as Sharp and Toshiba.

Many factors enter into a firm's decision to commercialize an innovation. Companies must try to assess the profitability of a new venture, taking into account its ability to protect intellectual property, the degree of existing or anticipated competition, the size and profitability of possible markets, and the cost of manufacturing and marketing activities. They must also assess their ability to harness necessary complementary assets—such as other technologies needed to make their innovation more useful, or capabilities in manufacturing, marketing, and distribution need-

[20]This figure has remained remarkably constant over the past few decades, despite the apparent changes in industry structure, globalization, and product mix. One report released in 1967 and relying on 10-year-old data found that product conception and design accounted for 15 to 30 percent of the cost of new product introduction; manufacturing preparation, manufacturing startup, and marketing startup comprised the balance. See U.S. Department of Commerce, *Teckdogica/innovation: Its Environment and Management,* report of the Panel on Invention and Innovation (Washington, DC: U.S. Government Printing Office, January 1967), p. 8.

[21]R&D is actually a greater percentage of total innovative activity than these figures indicate because many projects never make it out of R&D and because there is a certain amount of background research that is carried out without any specific project in mind. Furthermore, all of the activities listed in table 2-7 involve some technical work that is not classified as formal R&D.

ed for business success—and the degree to which the technology fits in with the company's general business plans.

Potential Markets

The overall profitability of an innovation is largely determined by the size and nature of potential markets. Market segments differ considerably along both these dimensions. At the one extreme lie large markets for undifferentiated commodity goods that maintain small profit margins. Many product lines in high-technology industries match this description: computer memory chips, consumer electronics, and low-end telecommunications equipment such as telephones and answering machines—even low-end personal computers. In order to generate suitable profits in industries with low profit margins, firms must attempt to sell large volumes of goods. Competition in these markets is therefore driven by steep learning curves (in which the cost of production drops precipitously as workers gain experience with the manufacturing process) and economies of scale that tend to concentrate market power in the hands of a limited number of firms.

At the other extreme are markets in which product differentiation and customization are the most important aspect of the product. These markets are typically small, and competition is often based on performance rather than price. Hence, they can be lucrative areas for innovative firms that have well-developed design skills. Customers in such markets are often discriminating purchasers. Examples include government programs in military or space applications, and industrial, medical, or other customers that demand high performance and are less cost sensitive than customers in consumer product markets. While these market segments are often smaller than high volume markets in consumer or commodity products, the profit margins can be higher. In semiconductor devices, market segments such as application-specific integrated circuits and static random access memories allow for product diversification at lower volumes. These areas can have lower entry barriers to manufacturing than high volume, standardized devices.

Between these two extremes lies a wide variety of markets that offer different combinations of size and profitability. The market for microprocessors for personal computers, for example, is large and boasts high profit margins—but only for leading-edge processors. Older generation processors have smaller markets and lower profit margins. In pharmaceuticals, too, new drugs can both offer high profit margins and serve large markets. The primary driver of the high profit margins in both leading-edge microprocessors and pharmaceuticals is the ability of firms to control and protect their intellectual property.

Firms must assess potential markets in relation to their proprietary advantages and capabilities. Firms tend to succeed in markets that best match their strengths, whether in developing leading-edge technology, providing high quality at low cost, or meeting rapid product development cycles. Small startup firms typically lack the marketing and manufacturing capabilities to compete in large, commodity markets, but perform admirably in many smaller niche markets. They also play an important role in commercializing emerging technologies that compete against entrenched technologies produced by existing competitors. Larger firms often lack the flexibility and desire to pursue smaller niche markets, but can dominate large markets. They also have more resources to expend on R&D to develop immature technologies.

Competition from Other Technologies

Competition from existing or alternative new technologies can shrink markets for a given innovation. Emerging technologies in their nascent stages rarely offer sufficient advantages over existing technologies in all aspects of performance, including compatibility with existing ways of doing things. As a result, their emergence often stimulates improvements in the existing technology, touching off a period of intense competition before a winner emerges. Such competition is seen

BOX 2-5: Competition Between New and Existing Technology in Lith

Advances in the capabilities of integrated circuits (ICs), such as those used in personal computers, are determined in large part by reductions in the size of the electronic components that can be patterned onto a silicon wafer. By reducing the size or minimum linewidth of these devices, circuit designers can fit more components onto a given IC, thereby increasing the capacity of a memory chip or adding additional power to a microprocessor.

The size of the smallest feature that can be created on an IC is determined by the resolution of the lithography system used to project patterns onto the substrate. Traditionally, IC manufacturers have produced devices by using lithography systems based on optical and ultraviolet wavelengths of light. Such systems shine light through glass masks containing an image of the desired circuit and pass the light through a series of optical lenses that reduce the size of the pattern on the mask by a factor of five and focus it onto a silicon wafer. The resolution of such systems is limited by the wavelength of light used, with shorter wavelengths yielding smaller resolution. Since 1970, advances in light sources, optics, and machine design have reduced the minimum resolution of optical lithography systems from about 70 microns to around 0,35 microns (a micron is one thousandth of a millimeter, or approximately one fiftieth the width of a human hair).

Semiconductor manufacturers and their equipment suppliers have long been predicting that optical lithography will soon reach its theoretical limit of resolution. As the wavelength of light is reduced, building suitable light sources becomes more difficult, and the optics become less effective at creating a tight focus. Hence, developers have investigated numerous alternates to optical lithography systems, incorporating x-rays, electron beams, and ion beams into their designs. Each of these techniques offers Improved theoretical resolution over optical systems; yet each possesses significant drawbacks as well in order to generate x-rays of the intensity needed for lithography, the system needs a large synchrotrons costing approximately $35 million, masks for such systems cannot be made of glass; and the pattern on the mask must be made as small as the desired feature size because optical lenses cannot be used to reduce the size of the pattern. Laser-generated x-rays have also been explored as an

(continued)

in many areas of emerging technology examined by OTA: 1) in high-performance computing, massively parallel computers compete against traditional supercomputers; 2) in computer displays, flat panel technologies—whether liquid crystal, plasma, electroluminescent, or field emission—compete against an existing base of cathode ray tubes (CRTs); and 3) in lithography—a critical step in the manufacture of integrated circuits—x-ray, ion beam, and electron beam technologies compete against entrenched optical steppers (see box 2-5). Continued improvement of the existing technology often slows adoption of the new technology until one or other exhibits a distinct advantage.

New technologies often have difficulty dislodging an entrenched technology because of resistance from potential users of the new product. Customers must be convinced that the new technology offers superior performance in their particular application and is reliable-characteristics a new technology cannot always achieve at first. IBM, for example, opted against using integrated circuits in its System 360 series computer. The company chose hybrid transistors instead because it was not sure the new technology would

BOX 2-5: Competition Between New and Existing Technology in Lithography (Cont'd.)

alternative to expensive synchrotrons, but such systems require a series of mirrors to focus the radiation onto the wafer. The mirrors must be polished smooth to a tolerance well beyond current Industrial practices.

Ion beam and electron beam systems overcome most of these problems; in their simplest configurations, they use narrow beams of particles to produce images rather than a broad beam of light. In this form, they cannot be used with masks and, instead, must physically draw each circuit element onto the IC—a procedure far too slow for industrial processes. Considerable work is under way to develop ion and electron beam techniques that employ either multiple beams or a broad beam of particles, but such projects are still in their infancy.

None of these alternatives has yet found use in Industrial practice, despite the fact that some systems—those based on x-rays—have been under development for 20 years. While part of the reason IS the immature state of alternate technologies, the principal reason IS that designers have continued to Improve the installed base of optical steppers. Advances in light sources and adoption of techniques, such as phase shift masks and off-axis illumination, have enabled continued improvements in the resolution of optical systems. New techniques for scanning the optical beam across the wafer (such as "step and scan") have simultaneously boosted resolution and maintained high operating speeds, or throughput, Whereas practical Iimitations were once expected to preclude the use of optical lithography below Iinewidths of 0.5 microns, current estimates indicate that optical lithography wilI probably remain the technology of choice for another decade, until resolutions drop below 0,1 microns,

Eventually, optical Iithography will reach its theoretical, if not practical, Iimit and alternative technologies will need to be Introduced into semiconductor manufacturing, At that point, semiconductor manufacturers may have to sacrifice cost or throughput in order to achieve better resolution, unless Improvements in alternative technologies can compensate for their current deficiencies, In the meantime, competition between the old and new technology will continue.

SOURCE Off Ice of Technology Assessment, 1995

perform reliably over the computer's lifetime.[22] IBM could not afford to field a general purpose business computer that might have a high rate of failure and require constant servicing. Instead, the first large-scale use of integrated circuitry was in DOD's Minuteman missile system and NASA's Apollo program, both of which placed a high premium on small size and low power consumption.

Many new technologies are not compatible with existing ways of doing things and require some changes in the ways customers perform certain tasks. Users of integrated circuits had to learn new design rules for creating electronic devices: users of electric vehicles have to learn to plan their trips to compensate for the shorter range of their cars. Such considerations can slow diffusion of new technologies to a crawl, and typically require that developers target their marketing efforts toward users who highly value a critical dimension of the new technology (such as small size in the case of integrated circuits) or can easily tolerate its disadvantages. Local delivery services (such as the postal service), for example, might be able to tolerate the short driving range of an electric ve-

[22] Charles H. Ferguson and Charles R. Morris, *Computer Wars: How the West Can Win in a Post-IBM World* (New York, NY: Times Books, 1993), pp. 8-9; and Arthur J. Alexander, *The Problem of Declining Defense R&D Expenditures,* JEI-14A (Washington, DC: Japan Economic Institute. Apr. 16, 1993), p. 11.

hicle and be able to recharge the batteries overnight at a central facility. As users and developers gain experience with the new technology and performance increases, markets can begin to expand.

Similarly, manufacturers of the existing technology often have a strong disincentive to invest in new technologies. By their very nature, new technologies tend to destroy the competencies that firms have developed in certain technical areas; they often require capabilities and skills different from those used in manufacturing the entrenched technology. For example, manufacturing computer displays using traditional cathode ray tube (CRT) technology is highly dependent on skills in forming picture tubes out of glass, aligning shadow masks, depositing phosphors on glass, and controlling the scanning of an electron gun using magnetic fields. In contrast, the manufacture of flat panel displays requires expertise in depositing thin film transistors on a glass substrate and minimizing contamination across an area the size of the display. Because flat panel displays require knowledge of new technologies and new manufacturing skills, manufacturers of CRTs have not, by and large, shifted into production of flat panels. They have responded to the challenge instead by improving their existing technology. Zenith has developed its flat tension mask technology, which eliminates the curvature of the CRT screen, making it more readable, and several companies have introduced CRTs that are not as deep as conventional models. For the most part, flat panel technology has been developed by entrants new to the field of displays.

Cost

The profitability of innovation depends on the costs of commercialization. In some industries or technologies, the sheer size of the investment required is the largest single hurdle to commercialization. This is particularly true in segments of the electronics industry, such as semiconductors, in which efficient-sized plants frequently cost over $1 billion to build and equip. Smaller plants cannot compete in the volume segments of such markets because they cannot spread their fixed costs over a large enough production run. Only in niche markets, with less competition and consideration of costs, can small plants compete successfully in these industries. In other industries, however, capital costs do not present as great a barrier to commercialization. Efficient consumer electronics or chemical plants can often be set up for $100 million, or can be expanded slowly over time to meet growing demand.

Uncertainties regarding cost also enter the decisionmaking process. Especially in new industries that are expected to demonstrate strong learning-curve effects, decisionmakers often cannot determine how quickly production costs will drop to a desired level. For first movers, rapid cost reduction is important to building barriers to entry and to expanding markets. For imitators trying to catch up with a market leader, uncertainties over cost make it difficult to determine the period of time required to become a competitive player in a market. U.S. manufacturers of flat panel displays, for example, are currently stymied by this second type of uncertainty. They cannot predict how long it will take them to match the manufacturing costs Japanese firms are currently achieving. As a result, they are experiencing difficulty securing financing for scaling up their manufacturing efforts.

Ability To Capture Market Share

Innovating firms must assess the degree to which competitors may capture, or *appropriate*, some of the returns from their innovation. Often, the company that is first to introduce a new product loses the market to followers who either improve on the original innovation in a timely manner or market the innovation better. Only rarely is a company the lone pioneer in a new technical area or does it possess truly unique capabilities that would preclude competition. In emerging areas of technology, such as high-temperature superconductivity (HTS) and scalable parallel computing, competition abounds and the industry is fluid. Over 20 American companies, large and small, have active research programs in HTS;[23] a similar number compete in the market for scalable parallel computers. Research suggests that firms that run in packs, rather than going it alone, are more successful in the long run because competitors can collectively contribute the research base and develop markets.[24]

In addition to direct competitors, suppliers of critical components or capabilities may also be able to extract profits from an innovation. In the market for personal computers, for example, Intel Corp., the supplier of microprocessors to most IBM-compatible machines, has benefited more than the innovator, IBM, or most other manufacturers of compatible machines. Microsoft Corp., too, by providing the operating system for IBM-compatible computers, has reaped benefits far in excess of many computer manufacturers.

Innovators have several mechanisms for protecting their innovations from competitors. They can use patents and software copyrights to legally bar other firms from copying their invention without an explicit license; they can keep their innovation secret from potential imitators; or they can take advantage of other barriers to market entry. The choice of method is, in many ways, determined by the nature of the technology itself.

Patents arguably offer the strongest form of protection, but are highly effective for only a limited number of product types, in a limited number of industries. Patents allow innovators the rights to their inventions for 20 years after the patent application is filed, allowing them a period of exclusivity during which they can attempt to earn monopolistic returns on their innovation. Patenting requires innovators to publicly disclose the details of their innovation; in some fields, competitors can then invent around the patent by devising a somewhat different way to provide the same functionality. Surveys have found that patents generally raise imitation costs 30 to 40 percent for drugs and 20 to 25 percent for chemicals, but only 7 to 15 percent in electronics (including semiconductors, computers, and communications equipment).[25] In chemicals, for instance, competitors cannot easily find an alternative compound with characteristics similar or identical to the patented substance, making imitation difficult. But in electronics and other areas, it is easier to invent around patents. The elements of a product's design and manufacture can be gleaned through careful analysis, and similar products can be manufactured that perform almost identically. This capability makes it more difficult for innovators to capture or *appropriate* the returns from a new innovation because they cannot maintain their monopoly positions for long.

In cases in which patent protection is not effective, innovators may instead opt to keep the workings of their inventions secret, to the extent possible. The law provides only partial protection for trade secrets. Firms can attempt to restrain former employees from competing with them by using knowledge gained during their employment. Similarly, they can sue firms that illegally gain access to trade secrets. But the law normally permits competitors to analyze products, figure out how they work, and find ways to produce similar products. AMD Corp., for example, has been highly successful in reverse-engineering microprocessors manufactured by Intel Corp. and selling a nearly identical product. As a result, trade secret protection is most useful for innovations whose workings can be hidden from the eyes of skilled analysts. Process innovations can often be kept secret because they can be hidden behind factory

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[23] Forbes, op. cit., footnote 12, pp. 70-104.

[24] Andrew Van de Ven, "A Community Perspective on the Emergence of Innovation," *Journal of Engineering and Technology Management*, vol. 10, 1993, pp. 41-42.

[25] Richard Levin et al., "Appropriating the Returns from Industrial Research and Development," *Brookings Papers on Economic Activity,* No. 3, 1987, pp. 783-831; Edwin Mansfield et al., "Imitation Costs and Patents: An Empirical Study," *Economic Journal*, vol. 91, December 1981, pp. 907-918.

TABLE 2-8: Effectiveness of Different Means of Protecting New Product and Process Innovations

Means of Protection	Overall Mean Process	Overall Mean Product	Range of Industry Means[a] Process	Range of Industry Means[a] Product
Patents to prevent duplication	3.52	4,33	2,6- 4,0	3 0 - 5 0
Patents to secure royalty income	3.31	3.75	2.3 -4.0	2 7 - 4 8
Secrecy	4,31	3.57	3.3- 5.0	2 7 - 4 1
Lead time	5.11	5.41	4,3 -5.9	4 . 8 - 6 0
Learning curves	5.02	5.09	4,5 -5,7	4 4 - 5 8
Sales or service	4,55	5.59	3.7 -5.5	5 0 - 6 1

[a]Measured from the 20th to 80th percentiles of 130 separate Industry means

NOTE: Rankings based on a survey of 650 Industry executives in 130 lines of business using a 7-point scale with 1 as least effective and 7 as most effective.

SOURCE: Richard Levin et al., "Appropriating the Returns from Industrial Research and Development, "*Brookings Papers on Econornic Activity,* vol. 3, 1987, p 794.

walls, but even they can eventually leak out. Secrets involving products are harder to maintain.

Many firms must, therefore, rely on other barriers to entry to protect their innovations. In industries characterized by significant economies of scale or steep learning curves, innovators can often gain protection by being first to market and rapidly expanding production. Although this strategy may often require large up-front investments in plant and equipment, it can enable companies to rapidly reduce their production costs by spreading the capital investment over a larger number of products and by allowing them to rapidly gain experience with the manufacturing process. Such experience frequently translates into lower manufacturing costs over time, as workers and managers begin to understand the subtle interactions between components of a system or the effects of changes in manufacturing conditions on product performance. Experiential knowledge of this sort, often referred to as tacit knowledge, is not easily codified and conveyed; therefore, it cannot easily be acquired by a competitor who does not make a similar investment in production.

Firms can also erect barriers to entry through superior strategies for product development, sales, or service. Rapid product development, for example, can allow an innovator to put new, improved products on the market more quickly than its competitors, thereby incorporating newer technology and responding to more recent changes in market demand. Such a strategy was particularly helpful in enabling Japanese auto and consumer electronics manufacturers to enter the U.S. market. Alternatively, innovators can attempt to dominate marketing channels or bundle new products with goods in high demand to increase their rate of penetration into the marketplace. Software companies, such as Microsoft Corp., have been particularly successful in bundling together new products and linking them closely to specific changes in hardware to increase their hold on particular market segments.[26]

In general, neither patents nor trade secrets are as effective as lead time, learning curves, or attention to sales and service in protecting innovations (see table 2-8). Hence, appropriability by the innovator is difficult to ensure through formal means in most industries. Industries that rate patenting most highly include portions of the chemicals industry (inorganic, organics, drugs, and plastics) and petroleum refining; but only the pharmaceuticals industry considers patents more effective than other means of protecting new products and processes. Industries such as food products and metal-working rate no mechanisms

[26] Some bundling strategies run afoul of antitrust considerations. Some of Microsoft's strategies have been investigated by the Justice Department for possible antitrust violations.

highly effective (greater than five on a seven-point scale) for protecting product innovations, and about one-third of the 130 industries represented in the sample—including food products, metalworking, fabricated metals, and machinery—rated no mechanisms highly effective for protecting process innovations. The remaining industries, including electronics, motor vehicles, aircraft, and instruments, rated nonpatent mechanisms as most effective.[27]

Complementary Assets

The ability to capture market share and profit from innovation is also dependent on the ability of firms to develop or acquire complementary assets—other technologies needed to make the innovation useful, and the capabilities necessary to manufacture and market the innovation. An innovation cannot be successfully commercialized without adequate manufacturing capacity and skill, suitable marketing and distribution channels, and after-sales support. Nor can innovations succeed without other technologies that interact with the new innovation. Users of new computer hardware often need specialized operating systems and applications software. Drivers of electric vehicles need a network of convenient recharging stations.

The lack of such complementary assets can retard the diffusion of new technologies—especially the more radical ones. Radical technologies almost always require new infrastructure, new suppliers, and often new distribution channels. During the early stages of an innovation, firms will often integrate these capabilities into their own corporate structure because they often do not exist elsewhere in the economy. As the industry grows, specialized firms tend to develop to fill these roles and companies will purchase goods from specialized suppliers.

Firms that are better able to harness these capabilities and orchestrate the contributions of the various actors responsible for creating the industry infrastructure have the best chance of succeeding in commercialization (see box 2-6).[28] Japan's success in the global marketplace has often been attributed to its ability to harness or develop complementary assets, such as manufacturing capability, that allowed it to develop new products faster than U.S. firms. Japanese firms boasted faster product development cycle times than U.S. firms and often achieved higher quality in the process. As a result, they were able to bring new and improved products to market faster than U.S. firms and win large portions of the market. Large investments in process technology rather than product technology served only to perpetuate this advantage, as U.S. firms continued to pour greater resources into product innovation.[29]

The need for complementary assets often puts small U.S. firms at a disadvantage in competing with large, vertically integrated firms, whether in Japan or the United States, that have access to complementary assets in-house. Without their own manufacturing facilities or marketing and distribution channels, small firms are often forced to align with larger firms or to license their technology to the owners of such assets. This process not only can result in the transfer of technology to rival companies and nations, but also can take longer to complete than if conducted in-house, thereby slowing the commercialization process in the United States.

[27] Levin et al., op. cit., footnote 25, pp. 795-798.

[28] For a more complete discussion of this topic, see David J. Teece, "Profiting from Technological Innovation: Implications for Integration, Collaboration, Licensing and Public Policy," in David J. Teece (ed.), *The Competitive Challenge: Strategies for Industrial Innovation and Renewal* (New York, NY: Ballinger Publishing Co., 1987).

[29] Edwin Mansfield, "Industrial R&D in Japan and the United States: A Comparative Study," *American Economic Review*, vol. 78, No. 2, May 1988.

BOX 2-6: Commercialization of Videocassette Recorders

Early competition in the videocassette recorder(VCR) industry demonstrates the importance of design, manufacturing, marketing, and experience in the successful development and commercialization of new technologies, Ampex Corp., located in Redwood City, California, gave the first public demonstration of a video tape recorder (VTR) in 1956. Ampex sold its machines to television broadcasters for $50,000. Ampex had a patent for its "transverse scanner," in which four recording heads on a rapidly rotating drum scanned across a two-inch-wide tape. Ampex licensed RCA in exchange for licenses under RCA's color television patents, in order to be able to produce color VTRs. Ampex also entered a joint venture with Toshiba to produce VTRs. Ampex remained dominant, but all three firms made money selling VTRs for commercial use. However, none of these firms pursued a long-term strategy to create a smaller, much cheaper product for home use, with easy-to-use cassettes—a videocassette recorder, or VCR.

Sony, Matsushita, and the Victor Co. of Japan (JVC, 50 percent owned by Matsushita) all pursued such a strategy, and gained a substantial share of the household market in the late 1970s and early 1980s. Many factors contributed to this success, In 1958, Japan's National Broadcasting Corp. (NHK) imported an Ampex VTR and invited Japanese firms to examine it. The three firms built on prior technical achievements, such as magnetic audio recording television receivers and semiconductors, Perhaps most Importantly, the firms consistently followed the vision of a VCR, guided by stable management with sound technical knowledge, They built several generations of machines that did not succeed as consumer products, and learned by this what was needed, All three firms developed a two-headed helical scanner, which they believed necessary to build a household product; that scanner also got around Ampex's patent,

Two leading machines emerged the Beta format, designed by Sony, first sold in 1975, and JVC's VHS format, first sold in 1976. Though second to market, the VHS format overtook Beta in 1978 and pulled farther ahead each year until the end of the 1980s, when the Beta format machines were no longer produced. JVC achieved this reversal by superior strategy in winning other firms over to its format. Sony committed to its format and then asked other companies to adopt it; JVC courted other firms before finalizing its format, and showed a willingness to listen to their ideas. Matsushita, in particular, provided valuable technical feedback. Sony was not willing to manufacture VCRs for other firms; JVC was. JVC provided considerable assistance in manufacturing and marketing. JVC pursued the European market much more aggressively,

(continued)

Fit with Corporate Goals

Firms must also decide whether a new technology fits in with their broader corporate goals. While it may seem that any innovation developed by a corporation would, by definition, be connected to the markets and technologies that the company wants to pursue, this is not always the case. Often researchers will—by following their own interests or instincts, or through pure serendipity-develop a new product or process at the level of a prototype. Once the researcher has an understanding of the innovation, he or she can then try to convince corporate management of its potential, and present a case for manufacturing. At this point, the company must decide if the innovation fits in with its corporate goals.

Companies often define their business and technology goals along three dimensions (though most strategies are a combination of all three): technology focus, product focus, and market focus.[30] New products must fit in with this strategy or vision. A technology-focused company uses

[30] Lewis M. Branscomb and Fumio Kodama, *Japanese Innovation Strategy: Technical Support for Business Visions,* Harvard University, Center for Science and International Affairs, Occasional Paper No. 10 (Lanham, MD: University Press of America, Inc., 1993), chapter 3.

BOX 2-6: Commercialization of Videocassette Recorders (Cont'd.)

and worked with its Japanese partners to define technical standards for a VCR suited to Europe's color television standard. JVC was also helped a great deal by Matsushita, which supplied the market with VHS machines faster than Sony could supply it with Beta machines. Matsushita also approached RCA to be a VCR supplier and worked quickly to satisfy (in October 1977) RCA's request for a machine that "could record a football game" (at least 3 hours). U.S. distributors believed that the format that RCA supported would probably become dominant in the U.S. market; that belief, plus the longer playing time that Matsushita offered, led U.S. distributors to favor VHS.

The VCR Installed base increased dramatically in the first half of the 1980s, triggering a dramatic increase in production, sale, and rental of prerecorded tapes. The VCR and prerecorded tape markets took off in Europe before the United States, apparently because Europe's relative scarcity of broadcast channels made watching prerecorded tapes on VCRs more attractive. European producers and distributors of prerecorded tape tended to favor VHS over Beta because VHS already had a much larger installed base of machines there, In the U.S. market, VHS did not overtake Beta decisively until the mid-1980s. However, RCA set out early on to make VHS dominate the prerecorded tape market. Starting in 1978, RCA encouraged Magnetic Video Corp. of America (MV) to produce prerecorded VHS tapes by developing equipment for high-speed fast duplication and providing cheap blank tapes, Sony similarly tried to induce Video Corp. of America to produce prerecorded Beta tapes, but was less successful. By 1980, according to one estimate, VHS made up 70 to 90 percent of U.S. cassette dealers' revenues. In both Europe and the United States, the greater availability of VHS over Beta prerecorded tapes accelerated the decline in the Beta format's percentage of VCRs produced.

SOURCE: R. Rosenbloom and M. Cusumano, "Technological Pioneering and Competitive Advantage: The Birth of the VCR Industry, " *California Management Review,* vol. 29, No 4, summer 1987, pp. 51-76; M. Cusumano, Y. Mylonadis, and R. Rosenbloom, "Strategic Maneuvering and Mass-Market Dynamics The Triumph of VHS over Beta, " *Business History Review,* spring 1992, pp. 51-94.

technology to achieve a competitive edge in the marketplace, and will enter markets that draw from a limited set of core technologies. Many small firms in the high-temperature superconductivity field fit this description, since they plan to serve a variety of markets with an array of products that incorporate HTS technology. They would likely opt against developing products or processes that do not contain HTS. Other firms, such as Chrysler, Ford, and GM, have a product focus. Their goal is to design and sell automobiles, developing or adopting whatever technologies are necessary to the success of this venture. They would likely opt against commercializing innovations that do not contribute to automotive technology. Finally, firms with a market focus attempt to serve a broadly defined set of customers, such as the military. Large firms, such as Northrop/Grumman and Lockheed/Martin, sell a number of products—tanks, aircraft, and missiles—incorporating a wide variety of underlying technologies, to a specific set of customers. At times, they have attempted to diversify into new (i.e., commercial) markets, but such attempts have often met with failure.[31]

Firms sometimes decide against commercializing innovations that could cannibalize existing product lines that have not yet reached maturity. For example, although IBM pioneered the field of reduced instruction set computing (RISC) in the

[31] See U.S. Congress, Office of Technology Assessment, *After the Cold War: Living with Lower Defense Spending,* OTA-ITE-524 (Washington, DC: U.S. Government Printing Office, February 1992), chapter 7.

late 1970s and early 1980s, the company failed to commercialize the technology because it feared it would steal market share from its own line of Series 370 computers.[32] Instead, RISC was commercialized by a startup firm, Sun Microsystems, with no existing sales to cannibalize.

Concluding Remarks

The concepts developed in this chapter help explain the complex dynamics of innovation and commercialization. As shown, successful R&D alone cannot assure commercial success in areas of advanced technology. Firms must also develop or acquire the capabilities to design, manufacture, and market new products, processes, and services. They must develop complementary technologies needed to make their innovation more useful, and find financing to support their efforts. Numerous barriers can impede the progress of even the most capable firms as they try to introduce new inventions to the marketplace, and numerous firms fail in their attempts.

From a national perspective, these lessons are equally valid. While construction of a strong science and technology base is essential to innovation and commercialization, it is not sufficient. Firms must be able to find—within their national innovation systems or abroad—the resources needed to convert new science and technology into a proprietary advantage they can defend in the marketplace. While firms can develop many of the requisite tools themselves, others often lie beyond their control. These needs can often be met through cooperative actions between firms, or between industry and government.

[32] Ferguson and Morris, op. cit., footnote 22, pp. 37-45.