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The Breakthrough Dilemmas

Invention is a flower. Innovation is a weed.
—Bob Metcalfe

Breakthroughs

Breakthroughs take people by surprise. They are rare events, arising from scientific or engineering insights. They are called "breakthroughs" because they do something that most people did not realize was possible. Breakthroughs create something new or satisfy a previously undiscovered need. Big breakthroughs often have uses and effects far beyond what their inventors had in mind. Breakthroughs can launch new industries or transform existing ones.

Few companies actively look for breakthroughs. Interest in breakthroughs is sporadic, tending to arise when companies see trouble ahead because the market demand or profitability of their products is declining. Eventually this decline happens for all technologies. The intensity of interest in funding the kind of research that creates breakthroughs varies. It often correlates with where a company's products are on the technology-adoption curve.

Technology-Adoption Curves

High-technology businesses go through recognizable business cycles. After fragile and delicate beginnings, they grow rapidly and robustly. When they reach maturity they stop growing. Eventually they decline.

Paul Saffo is a senior researcher at the Institute of the Future.[1] When Saffo looks at companies and technology trends, he thinks about the long view. He is familiar with S-curves. For Saffo, technology-adoption curves

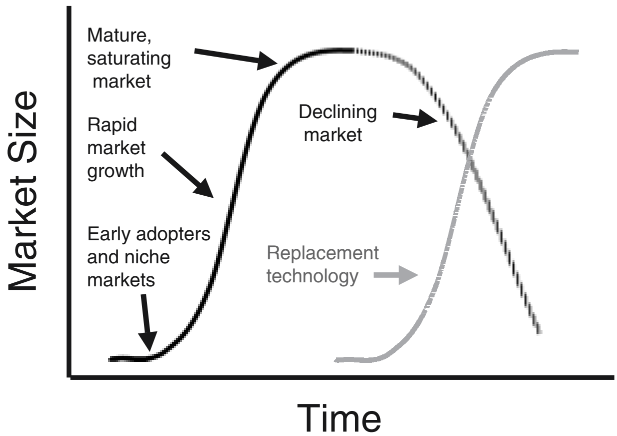

Figure 1.1
The adoption of technologies follows an S-shaped curve. The second curve represents the rise of a new technology that will replace the first technology in the market.

are part of the predictable landscape. They explain deep truths about how the innovation ecology works. Saffo:[2]

> There is a pattern here where science makes progress and creates a new technology. The technology starts to grow up and impact people's lives. Eventually it plateaus and the main part becomes routine. Then cost-cutting measures drive manufacturing overseas.
>
> You can plot this out in S-curves. The first phase is the solo inventor, like Doug Engelbart[3] working decades ahead of everyone else. When you start to get closer to the inflection point, you have teams working together, like Apple and its Macintosh team. As the S-curve matures and heads toward the top, the business becomes bigger and more bureaucratic. That's where "creative destruction"[4] comes in because the more something becomes bureaucratized, the more room it leaves at the bottom for individuals and small teams of heretics to redefine the game in new ways. The cost of innovation goes up when a technology becomes bureaucratized.

The *technology-adoption S-curve*[5] (figure 1.1) begins with an invention. In the early part of the curve when the technology is new and immature, the market is small. It is limited to a few early adopters and small niche markets. As a technology matures and reaches the mainstream, businesses enter a phase of rapid growth. They focus on competition with other businesses, improve their products to meet evolving customer needs, and increase their market share. At the market peak, there is often consolidation for market share and economies of scale. When a market saturates, businesses look for other growth opportunities.

The videocassette recorder business and the videotape rental business illustrate the growth and decline of a technology. Video tape recorders were invented in the 1950s, but the first videocassette recorders intended for home use were developed by Sony in 1964.[6] In the early stages, there were legal challenges concerning copyright issues, and there was a standardization struggle between two formats (Beta and VHS). In the 1980s, the rental market grew and many rental stores were opened. Eventually the rental market consolidated; Blockbuster's share was about 40 percent. In the 1990s the VCR business began to decline as a result of competition from other technologies, including cable and satellite television. After DVDs came along, network-enabled DVD mailing services (e.g., Netflix[7]) appeared; by 2002 they had reached about 600,000 customers. This pattern of a slow beginning, a period of rapid growth, a market peaking and consolidating, and competition from new technologies is typical of high-technology industries.

Sometimes companies increase their markets by expanding into new geographic areas. When it is possible, they move manufacturing or other parts of the business overseas, chasing cheaper labor. Eventually, the original business is displaced by new businesses that then enter their own periods of rapid growth, eroding the market of the original technology.

Several factors drive S-curves. During the course of an S-curve, markets grow, companies become bloated, and technical knowledge spreads. Several predictable side effects arise and shape business decisions. Competition begins, markets saturate, manufacturing costs are driven down, margins evaporate, and so on. In his book *Only the Paranoid Survive*, Intel founder Andy Grove put it this way:

> Business success contains the seeds of its own destruction. The more successful you are, the more people want a chunk of your business and then another chunk and then another until there is nothing left. . . . A strategic inflection point is a time in the life of a business when its fundamentals are about to change. That change can mean an opportunity to rise to new heights. But it may just as likely signal the beginning of the end.

Another factor—the same one that gives rise to technologies in the first place—is that new ideas arise. Old technologies get displaced by new ones. To thrive, businesses need a path to renewal. Paul Saffo continues:

What happens is that investors start to ask where a dollar invested yields the higher return. Do you invest at the top of an S-curve, trying to hold the old S-curve up at the top? Or do you begin investing in the bottom of the next S-curves to ride up with the new technologies? In that sense the bureaucratization of a maturing field sets the stage for the next wave of innovation.

In this long view of innovation cycles, technologies mature and leave more room at the bottom. *No company or country can expect to dominate a particular technology indefinitely*. Technologies either move away to other regions or are superseded by the next new thing. What creates a new opportunity at the bottom is the investment in the next round of inventions.

Technology-adoption curves reveal the business conditions that shape how a company perceives its need for innovation. Often companies don't see ahead to the erosion of their markets. Sometimes there is a substantial delay between when a downturn begins and when a company recognizes it and acts. To buffer across changing conditions, some companies diversify into multiple kinds of product. A product at its revenue peak can be a "cash cow" for products that are at other points in the cycle. Managed in this way, companies can average out the boom-bust cycle of individual technologies or products. This is the pattern for consumer electronics companies, which create new devices and media every few years.

Although S-curves help to explain what is happening when products and technologies grow and then decline, they are not themselves "the problem." They are a natural part of the cycle of renewal for technologies and innovation. They lead to surprises and crises only when companies are not paying attention.

Trouble at the Top

Today, many products in the information and communications sectors are peaking at the same time. Computers, phones, video games, video projectors, digital cameras, and printers are all based on integrated circuits and packaging technologies. These products are affected in the same way by declining profits and outsourced manufacturing, because the underlying sciences and technologies—semiconductors, computation, modular manufacturing—are essentially the same.[8] These technologies aren't going away, but their period of high profitability and rapid growth seems to be over.

Meanwhile, in other areas of manufacturing beyond semiconductors, increased outsourcing is making products from different companies more alike, since they are increasingly built from the same generic parts in shared factories. With simultaneous maturing, globalization, and displacement, a lot of change is happening at once.

The Innovation Ecology

The future is invented not so much by a heroic loner or by a single company with a great product as by the capacity to combine science, imagination, and business. An *innovation ecology* includes education, research organizations, government funding agencies, technology companies, investors, and consumers. A society's capacity for innovation depends on its innovation ecology. (The information-technology sector provides a powerful example. Roughly following Moore's Law,[9] computers doubled in power, speed, and capacity every 18 months for more than 30 years.) Today, genomics and proteomics are poised for a big run of discoveries. Exactly what discoveries, inventions, and innovations will matter most in the next decades is not yet known, but it is likely that a lot of things will happen. Ambitious scientists and engineers are drawn to the chase. They want to be the ones who make the big discoveries or invent the next big thing. Succeeding in the chase, however, requires expensive equipment, first-rate colleagues, and sustained support. Historically, this combination of resources has been found mainly at corporate research institutions.

The Breakthrough Zone

The scientific knowledge base for innovation is created by basic research, largely at universities, but new technologies are created mainly at corporate research centers. For example, after years of basic research in materials and electronics, the transistor was created at Bell Labs. Bell Labs also created many kinds of communication technologies. Laboratories at Corning Glassworks developed fiber optics after basic research on optics and glass had been done in the academic community for many decades. Laboratories at Texas Instruments and Fairchild Semiconductor invented the first integrated circuits, establishing a scalable technology for modern computers.[10] IBM research created several generations

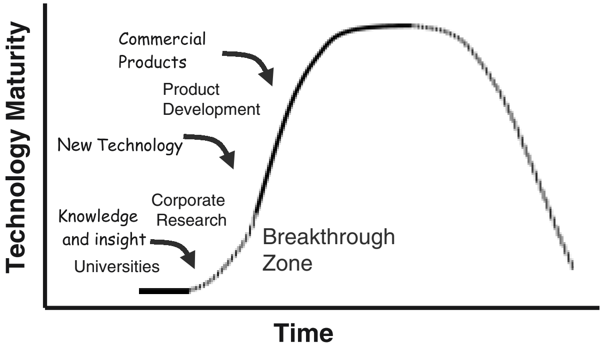

Figure 1.2
The breakthrough zone is the region between basic research and the development of a new and usable technology.

of magnetic storage technology and practical databases. Xerox PARC (Palo Alto Research Center) created the personal computer, the Ethernet, and the laser printer.

The path to new technology has been similar in the biotechnology sector. Restriction enzymes were discovered and methods for sequencing DNA were developed at universities in the United States and the United Kingdom.[11] Subsequently, sequencing methods were refined in industrial labs, and automated DNA-sequencing machines were built. Polymerase chain reaction for amplifying or replicating DNA was discovered at Cetus.[12] In the arena of drug discovery, basic research is followed by systematic searches for effective drugs. With improved technology, these searches are getting faster, but drugs and medical appliances still take years to develop and then several more years to test in clinical trials. Because of the many unknowns and hurdles in developing biotechnology,[13] success usuallly requires genuine breakthroughs.

Basic research, which establishes a knowledge base, takes place largely at universities. However, universities can carry research only so far. Their educational agenda takes precedence, and they cannot focus sustained resources to develop a technology much beyond basic research. They rely heavily on graduate students to carry out the research. Just as the students really master their area, they graduate. Many of them go on to work in corporate research laboratories. These laboratories have historically been the main institutions with the skills and staying power to take a new technology to the point where it can be applied to create products. These labs create teams of the brightest people from each generation to tackle hard problems. This is the center of the breakthrough zone.

A Phase Model for Innovation

Studying 100 years of development in the chemical and aluminum industries, Margaret Graham and Bettye Pruitt[14] characterize innovation in an industry according to five detailed phases. The first is the *borrowing* phase, in which companies borrow the initial knowledge and practices from universities. In the *internalization* phase, companies hire scientists and engineers from the universities and invest in research, hoping to gain advantages in know-how and intellectual property for products they will develop later. In the third phase, characterized as *institutionalization*, an industry sets up its own central research laboratory. As an industry matures, its researchers no longer depend as much on external sources of knowledge; this is the *specialization* phase. In the fifth phase, the technology is mature and companies focus on improving their current products. This phase is called *routinization* because the results become predictable and incremental.

Sometimes, when the market for a technology saturates, a technology company will recognize a need for breakthroughs. To go to the next level, companies must enter a *renewal* phase, essentially repeating earlier parts of the cycle. They can either reinvigorate internal research or go outside to universities or other sources. If a company fails to renew its business, the most likely scenario is for it to retrench in outsourcing manufacturing and routine client-oriented innovation for the ride down from the peak.

Figure 1.3 overlays Graham and Pruitt's phases of R&D development on the technology-adoption S-curve. It shows how the center of gravity for innovation on a technology shifts over time. Innovation typically begins at universities with basic research that yields discoveries and insights. It then moves to corporate research labs, where a usable technology is created. Finally it moves to product-development organizations.

Basic research—the first stage of innovation—takes place over many years. Since much of it is done at universities, it depends for support on government agencies and on corporate sponsors. The next phases of

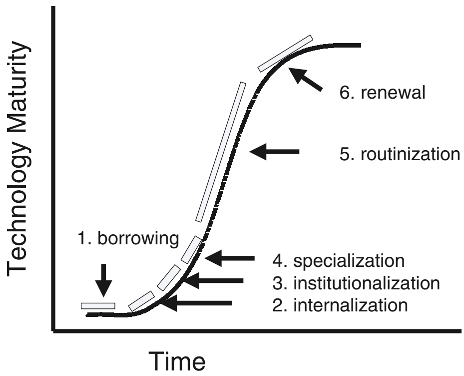

Figure 1.3
Phases in a company's R&D development overlaid on the technology-adoption S-curve.

innovation, which take place in industrial research laboratories and later in product-development organizations, depend largely on private investment by individual companies. This part of the innovation process is vulnerable to instabilities in funding as the fortunes of companies fluctuate and as investment priorities shift.

Losing Sight of Breakthrough Research

Although investment in research and development (R&D) rose in the period 1980–2000, the focus has shifted toward development and toward the short term.[15] Inattention to the long term has resulted in a decline in the kinds of investment that yielded many breakthroughs in the last century.

In the private sector, the demand for short-term profits and quarterly reporting of revenues diverted attention away from long-term perspectives and led to economic churning. In the 1980s, the churning took the form of corporate mergers and acquisitions. Rather than invest in the creation of new technologies, companies sought to acquire technologies and market share by buying other companies. The 1990s saw the rise and fall of the "new economy" and of startup companies. Again, more attention was paid to what could be had quickly than to breakthroughs and sustainable advantages. The focus shifted from long-term research to short-term research and incremental improvements. In the public sector, national laboratories such as Sandia, Lawrence Livermore, and

Oak Ridge began shrinking and redefining their missions. In the private sector, research institutions shrank and some were broken up.[16] In addition, research was redirected across the information-technology sector. To some extent, these changes reflect a healthy shifting of resources away from older technologies and toward fields with greater opportunities for growth, such as the life sciences and biotechnology. Nonetheless, the overall ecology has shifted, and important factors that contributed to success are now weaker than before.

Can other elements of the innovation ecology pick up the slack for corporate research? One way to gain perspective on this question is from the vantage points of institutions at the two ends—the basic research end at universities and the product-application end at startups or development organizations.

John Hennessy has been involved both in business and in academia. He co-founded MIPS Computer Systems (now MIPS Technologies, Inc.). Before becoming president of Stanford, he was the university's provost, its dean of engineering, and a professor of electrical engineering. Hennessy believes that long-term research is fundamentally in the public interest, and that it is becoming difficult for corporations to sponsor such research[17]:

> Universities need to do things in the innovation process that are beyond what industry can look at. That role is likely to become larger with either the collapse or redirecting of the large-scale industrial research labs. If you look around at labs like Xerox PARC, Bell Labs, and IBM, these are all places which had 10- or 20-year visions of where they were trying to go. But in the modern corporate environment you simply can't support that kind of work. Basic research is mainly for the public good. It has become too hard to support it in modern corporate America. Nobody wants to do the basic research that will ensure that the industry continues to innovate as opposed to giving them a technology advantage in their next five-year time frame.
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> One of the things that was absolutely admirable about what happened in industry was the ability to make a large-scale long-term commitment to pursuing a concept. You see this whether you look at Xerox PARC, Bell Labs, or IBM research and you look at innovations like the Alto [figure 1.4] or the transistor or magnetic disks. It is hard to get that kind of collective excitement and focus in a university. It is very difficult to get a commitment that will last for that many years and involve enough people to make that kind of collective breakthrough.
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> Universities are good at doing discontinuous research, but I don't know whether they can do it on that kind of scale. It depends on how we set ourselves up. We depend on governmental research grants, but those have gotten more focused and short-term over time and are less open ended than they were.

Figure 1.4
An Alto personal computer, developed at PARC in the 1970s. Courtesy of Palo Alto Research Center.

Many of the people in industry realize that it is necessary to have speculative long-term research. I think that they would rather pay part of the bill at the university and then share in the benefits than to pay the whole bill themselves and have everybody share in the benefits anyway.

Still, I worry about whether we can get the critical mass and scale in universities that is necessary to attack very-large-scale problems. That will be dependent on funding models that bring together creative and interested philanthropists, government, and industry.

Hennessy's analysis frames a significant challenge for the innovation ecology. Basic research is in the public interest and will continue at universities. Corporations are increasingly focused on product development and very-short-term research. The bridge between basic research and applications—the crucial work of the breakthrough zone—is disappearing. This leaves an innovation gap and raises concern about the health of the innovation ecology.

During the dotcom craze of the 1990s, it seemed that startups could do everything. Chuck Thacker is a prolific inventor perhaps best known for his role in creating the first personal computers. Looking out at the dotcom phenomenon from his position at the Digital Equipment

Corporation's Systems Research Center, Thacker was worried. Smart people were leaving research laboratories and universities to start companies. Of course many of the companies failed quickly, but new ones were formed just as quickly and some people seemed to be doing very well.[18] "At least until very recently," Thacker recalled, "if you had a good idea you would take it up to Sand Hill Road.[19] I was actually worried until the huge technology collapse that industrial research labs were doomed because of the things that were being done by startups. That is less true now, certainly." Thacker's comments reflect the widespread confusion and uncertainty in the research community about startups during the 1990s. (Weren't the startups doing high technology and everything that the research community did? Did they have a better chance than research labs or universities of getting their ideas out?)

Corporate research labs enjoyed sustained funding that allowed them to pursue problems, whereas universities and startup companies simply couldn't afford to support research groups for long periods.

The Breakthrough Dilemmas

A technological society depends on breakthroughs. The future always brings surprises. The challenges arise from such factors as growing populations, increasingly scarce resources, and a straining ecology. More sophisticated knowledge and technologies are our best hopes for coping with new challenges.

One might expect business, education, and government institutions to be well prepared to the breakthroughs that society will need. As it turns out, however, breakthroughs are quite rare, and creating them is a subtle affair. Businesses, educational institutions, and government funding agencies are all involved in breakthroughs, but most of their attention is necessarily devoted to routine business rather than breakthroughs. By optimizing their routine activities, these institutions can create barriers that get in the way of creating breakthroughs. We call these barriers *the breakthrough dilemmas*.[20]

The Breakthrough Dilemmas for Corporations

Corporations face two breakthrough dilemmas. One arises when corporations stop funding breakthrough research. The other arises when they sustain research funding but fail to exploit the innovations. In both scenarios, the corporations lose.

Getting Comfortable and Then Phasing Out Research Success breeds not only a growing market but also a narrowing of focus and a complacency about sustaining research to foster breakthroughs. As a company succeeds with its products, it becomes vested in growing its product lines. Incremental improvements for satisfying current customers and increasing market share begin to matter most. Except for companies that have endured and learned from this cycle before, by the time companies have developed high-technology products they have usually entered a routinization phase. They focus on the short term and on improving existing products rather than on the long term and on creating new technologies. R&D organizations with enhanced capabilities for listening to today's customers usually have diminished capabilities for breakthrough research. Routine research and breakthrough research require different, almost opposite, cultures of innovation.[21]

Hennessy[22]:

> Disruptive technologies cause problems for existing companies because they disturb their whole product line, their margin assumptions, and what they are doing. One of the reasons that startups have been successful is that established companies are reluctant to embrace that much change.[23] The analogy that I give is that they are reluctant to shoot themselves in the foot, although that is a lot better than what will happen to them later.
>
> One of the indicators that a company is about to go into a long downward slide is when they start thinking about preserving their old customer base more than about attracting future customers. I have seen this happen in lots of computer companies. It is the beginning of the end because it means that they are basically trying to build a wall around what they have as opposed to getting more people into their camp. That is a failure in a company's ability to look far enough ahead to see that there is a new world forming out there and that they will have to play in it and figure it out.

What happens when a company hits the top of its S-curve is analogous to what happens in a military situation when there is a surprise attack. Things seemed to be going along fine, then suddenly the market becomes saturated or a competing product seems to come out of nowhere. Stanley Feder describes this situation as follows: "Customer orientation is [a] mindset, and one that can cause large companies to ride existing technological horses off the cliff's edge. Instead it is the smaller rivals, free from the customer mindset, that often are better able to invest in next-generation innovations."[24]

Mindsets are easy to overlook. When a company gets good at making a particular kind of product for a particular kind of customer, some of its reactions become automatic. It develops special "lenses" for efficiently focusing on and seeing its customers. The fault lies in the dependence on the lenses. When the world changes, the company may not be paying attention in the right way. Research is one of the means by which a company can develop new options outside its current business.

When Research Gets Away The second dilemma is faced by companies that sustain investment in research. A universal axiom is that breakthroughs contain major surprises. Even a breakthrough that occurs in the company's business area may interfere with or displace existing products. And a breakthrough may have its greatest applications in unexpected areas outside the company's main business. When that happens, the company has to manage an internal struggle over resource allocation[25]—a struggle between growing the main business and starting something new. There are many vested interests in the existing products, few vested interests in a breakthrough.

One of the most vocal critics of sustained research funding was Gordon Moore, long-time CEO of Intel. Moore strongly advocated that companies not invest in research. He believed that basic research did not directly benefit a company, and that most of the new ideas developed by research would not be usable by the company.[26]

To reap the benefits of an ill-fitting innovation, a company must either license the technology to another company or spin off a new company (perhaps with partners). Since these strategies are outside of its core business, a company has less experience and assumes greater risks. Typical hazards for the company that made the research investment include executing the new business poorly and having the individuals who made the breakthrough leave to start their own business or join another company. The companies that sponsor breakthrough research don't necessarily profit from it.

The two dilemmas detailed here make sustained funding of research for breakthroughs a high-stakes bet with big risks and big potential benefits. From the perspective of the larger society, funding breakthrough research is a good investment because *somebody* (and often many people) will benefit when products are developed.[27] However, from the perspective of an individual company with a narrow market and a specific product line, funding breakthrough research can be more akin to gambling. Even if the new technology pays off big, in the absence of effective strategies the benefits may go to other companies.

At the core of both dilemmas is the challenge of managing the costs and benefits of innovation and breakthrough research. On one path, a company may wind down research once it has launched a successful product; that then leaves the company with no capacity for generating more breakthroughs, which will be needed in the future. On another path, companies that sustain investment may not benefit from surprising breakthroughs.

Dealing with these dilemmas is the central challenge for the innovation ecology.

The Breakthrough Dilemmas for Universities

Bringing an insight to a point where it could be useful usually takes many years. Creating a technology from research done by students is problematic because students are short-timers. By the time they develop their skills, they are ready to graduate. Even when a university comes up with a usable technology, it has to find an effective way to transfer it to a product organization. (Universities do not have product organizations; their mission is education.)

Another dilemma for universities is that the knowledge needed to create breakthroughs—especially for radical innovations—often does not fit neatly within the boundaries of a single academic discipline. For example, advances in semiconductors have required intense collaboration not only in fabrication and material science but also in system design, optics, and imaging. Breakthroughs in biotechnology and medicine increasingly require not only multiple areas of biology but also engineering and computer science.

Universities are mainly organized around departments representing specific fields. New professors seeking tenure in a particular department take a big risk if following a problem to its root takes them too far from the interests of their home departments. This tends to limit cross-disciplinary research to professors who already have tenure.

For students pursuing doctoral degrees, the multi-disciplinary quality of breakthrough research creates special barriers. Institutional structures at universities are optimized for students pursuing a degree in a single field. Different fields have different methods, different knowledge, and different evaluation criteria. When a doctoral research project crosses or combines fields, the arrangements of thesis committees and funding support fall outside the standard modes and require more negotiations.[28] If the research is carried out by several students in a multi-disciplinary team, there is the added complexity of coordination and credit assignment. Finally, graduates whose work crosses and combines fields may find that this creates obstacles. Field-centric recruiting committees find that the work is outside their expertise or that the qualifications of the cross-disciplinary candidates fall outside the consensus-determined needs for the department.

The organization of universities into departments fits the historical pattern according to which most academic research is basic research. For this reason, most of the training at universities takes place within departments.

The Breakthrough Dilemmas for Federal Granting Agencies

In the United States, federal agencies also have breakthrough dilemmas in funding and managing research programs. These programs generally receive more proposals than they can fund and need to select projects by fair evaluation criteria.

The evaluation criteria for basic research and those for applied research are quite different. Basic research programs are supposed to create new knowledge. Following academic practices, these are usually organized by discipline, and proposals for research are usually judged by people within a discipline. Because breakthrough research is often multi-disciplinary, it tends not to fit well into basic research funding programs.

Applied research programs are intended to solve known and important problems. Because of the sense of urgency, applied research projects are judged by whether they can make rapid and effective progress. This drives applied research in the direction of low-risk and incremental approaches. There is little room for experimentation or for theoretical work in applied research. Because breakthrough research typically requires the creation of new knowledge by novel approaches, it often runs counter to institutional expectations for applied research. The challenge for federal granting agencies is to find ways to fund research that is likely to lead to breakthroughs.

A Brief History of Corporate Research

It is said that one of the important inventions of the 20th century was the corporate research lab.[29] Corporate labs powered the explosive innovation that characterized the century. With globalization and other social changes, corporate research labs are now evolving with the rest of the innovation ecology.

The first era of industrial research organizations in the United States (1880–1906) coincided with the rise of big business. At the beginning of the 20th century, a few large companies, including General Electric, American Telephone and Telegraph, Dupont, and Standard Oil, opened laboratories to create technical and business advantages. The GE lab, founded by Charles Steinmetz, was the most famous. It became known as "The House of Magic." Its staff grew from eight in 1901 to 102 by 1906. About a third of the staff members had scientific training. After accounting, research was the first centralized function in business. The GE lab's main role was to keep the company informed about new discoveries in science and technology. By the early 1900s there had been much progress in basic science. Before the creation of corporate research institutions, most scientific research was done at universities. Little attention was given to commercial applications. The first corporate research labs were created to fill the gap between scientific insights and the creation of technologies for industry.

The second era of industrial research (1906–1926) was affected by World War I and by the rise of international competition. During the war, industrial research was stimulated by an infusion of government funding and a moratorium on patent controls. During this period, there was also much growth in federal funding to state universities. The universities focused on the application of science and engineering. Many of the companies, especially in the chemical and metallurgy industries, gained commercial advantages from the development of plastics, synthetics, and advanced metals during the war. During this period there was a national emphasis on quality and productivity. The National Bureau of Standards,[30] founded in 1901, coordinated research being done in companies with that being done in research institutions and that being done at universities. Companies built up excess production capacity during the war, and one role for the laboratories was to create new categories of products that could use this capacity. Many foreign-trained researchers were "imported" to staff industrial labs.

The third era of industrial research (1926–1950) was affected by the Great Depression and then by World War II. The improvements in productivity for industrial processes that had helped in World War I led to market saturation and loss of jobs during the Depression. There was a widespread perception that humanistic studies were needed to find ways to catch up with the advances in scientific discovery. The purpose of research shifted toward creating new businesses. The competitive business environment became more complicated. The new technologies created by research dominated the market, and competition was limited by the enforcement of patents. Antitrust legislation was introduced to counter the economic effects of the concentration of patents, sometimes by one company in an industry. Federal funding for research grew from $48 million in 1940 to $500 million in 1945. The scientific benefits of World War II were felt mainly in the industries that produced aircraft, electrical goods, and instruments. The role of science in ending the war was very clear in the public mind. There was broad public interest in funding science. The National Science Foundation, a major institution for government funding of research during peacetime, was founded in 1950.

In the fourth era of industrial research (1950–1975), the role technology had played in World War II increased the prestige and value of science in the public eye. Defense-related agencies such as the Office of Naval Research, the Atomic Energy Commission, the Defense Advanced Research Projects Agency, and the National Aeronautics and Space Administration allocated growing amounts of money to research. Companies set up new research facilities to broaden the scope of their activities, and secretive national laboratories were founded to focus on defense technologies. There was a national emphasis on research self-sufficiency and manufacturing optimization. Basic research, perceived as a driver of economic growth, attained a high status. The "brain drain" of scientists from Europe continued.

In the 1960s, there was a fresh infusion of government funding into research after the Soviet Union launched the first man-made satellite. During this period, several major scientific discoveries were made in corporate research laboratories. For example, Arno Penzias and others at Bell Labs discovered dark matter, and superconductivity was discovered at IBM. Corporate R&D attracted the brightest people and provided advanced equipment to those working on cutting-edge problems. New business competitors faced substantial barriers to entry, and companies with dominant market shares worked to stage the introduction of new technology in ways that would create obstacles for their competitors.

The fifth era of industrial research (1975–1990) was an era of rising international competition. Increasingly, companies began moving manufacturing overseas. Corporate research became decentralized and refocused on applied research and getting products to market faster. In this context, basic research organizations were increasingly seen as remote and irrelevant to corporations. Research managers had more difficulty getting innovations based on decades of basic research to market. Companies focused on growing their financial returns in existing markets, and industrial research activity declined in the early 1990s.[31]

The sixth era was shaped by the continued growth of international business competition and by the Internet bubble. Large companies adopted a more global perspective, and in the 1990s this led to increasing consolidation through mergers and acquisitions. This coincided with the establishment by international companies of multiple internationally located research institutions. With the increase in international competition, the know-how for commercial applications became more diffuse as more companies around the world began to open research laboratories. In addition, small companies increasingly entered the innovation ecology. Although they lacked the capacity to fund long-term basic research, they had the advantage of being able to evolve their business models rapidly. Cisco out-innovated Lucent not by doing its own research but by partnering with startup companies and acquiring technology from them.

In the heated economy of the 1990s, many companies emphasized quick results over innovation. Corporate management grew and became increasingly cumbersome. In an effort to counter this, there was a growing espousal of "intrepreneuring," the idea that organizations within a company should take the lead in developing new products and markets for them. Success in these endeavors was hampered by the absence of an understanding of the resources or the business skills required. The growth of the Internet bubble in the mid 1990s coincided with a growing understanding of how big companies can become structurally incapable of leading or embracing innovation and technological change. This fueled interest in entrepreneurship outside of big companies. As the economy collapsed, many people came to understand that small companies lacked the staying power and resources to develop markets.

In summary, the institutions for industrial research co-evolved with the fortunes of corporations through the 20th century. New technologies from corporate research laboratories created growth opportunities for the first big technology companies. This organized approach to industrialized science worked very effectively. By the middle of the century, the patent and know-how advantages of companies that had research laboratories led to concerns that science and patented technology were creating monopolies. Balances were sought to ensure the public good.

In the 1990s, globalization, short-term expectations, and maturing technologies began to change the game. Investors became less patient as companies expected quicker returns. Companies began relying more on outside sources for new technologies. Increasingly international competition coupled with maturing technologies led to lower profit margins and a focus on short-term profits. Companies with less cash found themselves in need of breakthrough innovations. As the 21st century gets underway, new strategies for creating technologies and breakthroughs are needed.

Strategies for a New Century

As the 20th century closed, the innovation ecology was in transition. Many of the big companies in the information sector were scrambling. There was a lively debate about the end of the personal computer era. However, the underlying issues were broader than the question of whether "personal computers improve productivity." Broad structural changes were taking place in all businesses based on semiconductors, modular manufacturing, and computation, including the computer business, the consumer electronics business, the video game business, and the business of telephone systems. Companies in all these business were going through the same kinds of transitions.

How will innovation fare in the new century? How will it fare across industry sectors, not just in the information sector? How will it be affected by increased globalization and the restructuring of industries? Will the effects of the breakthrough dilemmas leave us unprepared for the challenges and surprises that lie ahead?

Some properties of innovation and the innovation ecology will continue as they are now. Universities will continue to carry out basic research, funded by government and private grants. Government agencies will try to balance competing social needs, and will be challenged to provide stable funding for long-term projects. Venture capitalists will still fund startups and provide seed funding.[32] There will still be a gap between what basic research creates and what venture capitalists or product organizations need. We will still need breakthroughs.

Radical Research

To understand how innovation is changing, let us focus on the breakthrough zone and on what it can tell us about invention and innovation. The dominant pattern of innovation suggested by the S-curve in figure 1.2 begins with basic research to create new knowledge, which is followed by applied research to create new technologies and then by product development. A deeper look at examples of breakthrough research, however, shows that the middle part of this curve—the part represented by the breakthrough zone—is often characterized by an approach to research that is different from either applied or basic research.

If basic research had a slogan, it might be "Follow your curiosity wherever it leads you." Basic research is about creating new knowledge. It is guided largely by a sense of where nature's secrets will yield to scientific investigation.

If applied research had a slogan, it might be "Focus on the important problem. Don't get distracted by your curiosity." Applied research is about using what is known to solve problems. It is guided by a sponsor or client's sense of what problems are important. In its pure form, applied research does not take time out to investigate interesting "diversions."

Some of the most productive research done in the last century was neither basic research nor applied research. This alternative form of research—*radical research* or "following a problem to its root[33]"—can be a fast track to breakthroughs. It starts out like applied research when a researcher or a small team begins working on an important problem. An essential part of the approach is that the problem be important. The importance does more than ensure that the effort of finding a solution won't be wasted; it also motivates and guides the researchers.

If radical research had a slogan, it would be "Focus on an important problem, and follow that problem to its root." Radical research is guided by the problem and by the obstacles that arise.

In applied research, if there is an obstacle, the group tries to get around it. If stuck at an obstacle, the researchers look for a quick fix or give up. Applied research does not "waste time" trying to understand why something works or doesn't. In radical research, however, obstacles focus the research. Typically, a multi-disciplinary team is deployed to find perspectives on the obstacle. As the exploration deepens, more disciplines may be brought in as needed. This part of the research is like basic research, in that the energy is focused to create new knowledge.

Radical research can be strikingly efficient. Single-discipline projects judge which problems that they can tackle through the perspectives of one field. For example, someone specializing in optics would not plan a project to cure cancer. In contrast, radical research can tackle problems that don't fit neatly into a single discipline. Discoveries and insights along this journey often happen at the edges of disciplines or in what John Seely Brown calls the white space between disciplines. Following a difficult problem to its root often yields solutions that had eluded people before—that is, breakthroughs.

Open Invention and Open Innovation

Two questions are at the core of radical research: "What is needed?" and "What is possible?" Much of this book is about the interplay or dance between these questions.

To put it succinctly, radical research creates breakthroughs because of its efficiency in the collision and interplay between the two questions.

Broadly construed, product development is mainly concerned with "What is needed?" Its attention is driven to this question by its focus on addressing particular needs and solving particular problems. It pays little attention to "What is possible?" In contrast, basic research is mainly concerned with "What is possible?" Its attention is driven to this question by virtue of following curiosity and the quest for new knowledge.

There is a gap between the two questions. The results created by basic research ("What is possible?") are not ready for use in product development ("What is needed?"). Similarly, the insights gained by people trafficking in customer needs and emerging markets are not often considered by people in research. Much of the challenge in managing innovation and creating breakthroughs is about that gap. Radical research bridges the gap. It has all the sparking and zapping efficiency of a short circuit that puts both of the questions on the table at the same time.

Federal granting agencies and universities focus on the "What is possible?" side of things as they try to discover new knowledge. Growing companies and venture capitalists focus on the "What is needed?" side of things as they try to develop or discover markets. Corporate research is in the middle. That's why it is most often the home for radical research. However, when the economy is in structural turmoil it is more difficult to sustain a level of funding for bridging the breakthrough zone. Without stable funding, the breakthrough zone turns into "the innovation gap." Science and society's needs can not connect very well.

The challenge for the innovation ecology is to find stable ways to keep the breakthrough zone vibrant and productive. This productivity depends on invention (creating prototypes of new things) and on innovation (taking prototypes all the way to product, and developing new markets).

Looking at several case studies, Henry Chesbrough[34] suggests that efficient strategies for innovation essentially create more efficient markets for technology.[35] Increasingly, companies cannot create all the technologies that they will need. They need strategies for acquiring some technologies from other companies. They also need strategies for marketing their own technologies to other companies. Chesbrough characterizes these kinds of strategies under the rubric of "open innovation." He advocates open business practices for promoting and acquiring innovations.

Chesbrough's insights seem exactly right, but they address only half of the equation. They address strategies for efficient *innovation*, but not strategies for efficient *invention*. In a business climate where technology companies are building products on the same technologies and where they are outsourcing manufacturing to the same outside vendors, open innovation is not likely to save the day. Companies are already practicing open innovation. Their products are turning into commodities and their profit margins are shrinking. What open innovation misses is creating a path to renewal. Breakthroughs are needed. *No one ever created a breakthrough from open innovation.*

The dialogue between "What is possible?" and "What is needed?" requires efficient conversations between scientists and inventors on one side and marketers on the other. In short, creating breakthroughs requires not only "open innovation" but also "open invention."