Avoiding the Pitfalls of Emerging Technologies

Article *in* California Management Review · December 2000

DOI: 10.2307/41166030

CITATIONS
172

READS
3,097

2 authors:

George S. Day
University of Pennsylvania
44 PUBLICATIONS **3,873** CITATIONS

SEE PROFILE

Paul Schoemaker
University of Pennsylvania
107 PUBLICATIONS **16,913** CITATIONS

SEE PROFILE

Avoiding the Pitfalls of Emerging Technologies

George S. Day
Paul J. H. Schoemaker

Emerging technologies[1]—such as gene therapy, interactivity and electronic commerce, intelligent sensors, digital imaging, micro-machines, or super conductivity—have the potential to remake entire industries and obsolete established strategies.[2] This is exhilarating for the attackers who can write—and exploit—the new rules of competition, especially if they are not encumbered by an existing business.

For incumbents, however, emerging technologies are often traumatic. Most of these firms feel they must participate in the markets that emerge. Their first reason is defensive, driven by the belief that the newcomers are plotting to use the new functionalities to attack their core markets. Home banking via the Internet is already happening, although no one knows how widely it will be adopted. Yet many bankers are filled with trepidation that the banking industry will be profoundly reshaped.[3] Their second reason is the converse of the first: if the emerging technology realizes its potential, it will be too attractive to ignore. However, the odds of large, established incumbents prevailing in these emerging markets are generally poor (see Table 1). In this article, we address the questions of *why* these incumbents have so much difficulty with disruptive technologies, and *how* they can anticipate and overcome their handicaps.

Challenges for Incumbents

There are four common pitfalls for incumbents that erode their commitment and put them at a disadvantage with an emerging technology. The basic theme is that established firms may resist participation at the outset, or that they

Portions of this article will appear in George S. Day and Paul J. H. Schoemaker, editors, *Wharton on Managing Emerging Technologies* (New York, NY: John Wiley and Sons, 2000).

TABLE 1. Patterns of Technological Innovation

	Who Gains Eventual Market Leadership?		
Who Is the Lead Innovator?	**Incumbent**	**New Entrant**	**Neither/Both**
Incumbent	Electronic data processing	Helical scan videotape recorders	Optical data recording
	Float glass		Videodisc
	Synthetic fibers		Wankel auto engine
	Electronic cash registers		
New Entrant	Biotechnology	Desktop xerographic copiers	
		Electronic calculators	
		Hydraulic earth moving equipment	
		Minimill steel making	
		Portable transistor radios	
		Programmable motor controls	
		Radial tires in North America	
		RISC microprocessors	
		Semiconductor electronics	
		Steamships	
Alliance of the Two	Some Biotech firms		Recombinant insulin

Note: We have drawn on the writings of Arnie Cooper of Purdue University and Clayton Christensen of Harvard Business School for examples of emerging technologies that supplanted an established technology.

may pursue the wrong technological path. Even if these pitfalls are avoided, many established firms are unwilling to make a full-fledged commitment and persist in the face of adversity. These pitfalls have been documented with a large body of examples that forms the conventional wisdom that the attacker from the outside holds the advantage when an emerging technology threatens an existing market or technological regime.[4] The attacker's advantage has clearly been validated in the computer industry as it has evolved from competition among vertically integrated stacks controlled by DEC, IBM, Amdahl, NEC, or Matsushita to a horizontal model where competition occurs between component providers. Few of the leaders in the horizontal model, such as Compaq, Dell, Intel, Microsoft, or Netscape came from the ranks of the old vertical industry.[5] The same story has been found in the hard-disk drive industry where market leadership changed with each successive product generation.[6] Atari was displaced by Sega in electronic games, and Nintendo may be leading in the next generation.

However, this pattern is not a recent high-technology phenomenon. Attackers dislodged incumbents when ballpoints supplanted fountain pens, when diesel-electric locomotives prevailed over steam locomotives, when electro-mechanical calculators were displaced by electronic calculators, and when vacuum tubes gave way to transistors.[7]

The problems encountered by incumbents are rooted in the technological uncertainties, ambiguous market signals, and embryonic competitive structures that distinguish emerging from established technologies. Because of these differences, emerging technologies often destroy competencies by making obsolete the slowly acquired skills, knowledge, and assets that were needed to master the established technology that is being replaced.[8] This is what the Friden and Monroe companies discovered when their extensive manufacturing and strong service networks for mechanical calculators were made obsolete by highly reliable electronic calculators, or as Western Union discovered when its telegram transmission capabilities were by-passed by fax, e-mail, and overnight delivery services.

New technologies often produce a major disruption to the established trajectory of technical advances by drawing on new or different science bases, thus requiring the arduous development of new competencies. In the earliest stages of development, however, it is often not evident that the new technology will achieve a decisive relative advantage. Indeed, one of the most confusing aspects of emerging technologies is that consumer usage patterns and behavior are exploratory and formative, while solid market knowledge is non-existent and the structure of competition is embryonic.

It is difficult to infer from past experience how strong the attacker's advantage is or how severe the curse of incumbency has been. Any retrospective study of survivors and losers will suffer from a selection bias, in which dramatic successes or failures are over-emphasized relative to the gray background of thousands of less-known or observable cases (see sidebar). In industries where new technologies really delivered, such as hydraulics, RISC microprocessors, or compact disks, an incumbency disadvantage is readily seen. Yet, in cases where initially promising new technologies have so far fizzled, such as cold fusion, space colonization, home robotics, and battery-powered automobiles, many incumbents look rather clever by having been passive. Our article is especially focused on cases where new technologies are reshaping the landscape, in which case a passive posture would be dangerous, and where newcomers may have the edge.

A Caveat about Selection Bias

Any advice based on studying winners and losers in the technology game merits an important caveat about the selection bias. As highlighted in Table 2, firms face profound uncertainty about the eventual success of an emerging technology, and yet must take a stance (ranging from passive to highly aggressive) with respect to that technology. We most celebrate those cases where firms boldly pursued unproven technologies that succeeded wildly (cell 1). And we scold those firms who committed the error of omission by remaining idle while the new technology triumphed (cell 3). We generally pay less attention to the error of commission (cell 2), where firms aggressively pursue a losing technology, and hardly notice those numerous cases of unsung wisdom where firms stayed away from technologies that never became successful (cell 4).

TABLE 2. Decisions Under Uncertainty

	Which State of Nature Will Ultimately Prevail?	
Decision Posture	**Technology Succeeds**	**Technology Fails***
Aggressive Stance (Commitment and Options Creating)	**Cell #1** Microsoft and PCs 3M and Post-It Notes Sony and Walkman Sun Microsystems and RISC chips Amgen and Biotech	**Cell #2** RCA and Videodisc Investors in Cold Fusion Xerox and computer-to-computer faxing CitiCorp and home banking
Passive Stance (Wait and See)	**Cell #3** Encyclopedia Brittanica and CD-ROMs RCA and FM radio US Steel Co. and Mini-mills DEC and PCs Sony and VHS format Kodak and copier products	**Cell #4** Many utilities and nuclear power Monsanto and prefab plastic houses Many banks and home banking

Failure could occur because: the technology didn't work or couldn't be scaled up to commercially viable production rates; a better technology superseded it; or it was ahead of its time.

The bias to report unevenly on the four cells in Table 2 (relative to their true base rates) runs deep in both academia as well as the popular press. This bias is hard to avoid due to the way history is recorded (e.g., cell 4 is nearly invisible to outsiders) and quirks in what attracts our human interest. The selection bias in turn may cause serious distortions and limitations in any advice based on best practice, popular wisdom, or the singular insights from any one entrepre-

neur who succeeded against the odds. With this caveat in mind, our article focuses especially on cell 3. We believe that many established firms (although by no means all) find themselves unwittingly in this cell owing to various waves of technological innovation that are sweeping the industrial landscape. Our solutions describe strategies that help firms move from cell 3 to 1, as Microsoft did when it aggressively rolled out its browser and Internet strategy, or as Monsanto did when profoundly transforming itself from a chemical to a life-sciences company that now excels in plant genetics and crop yield improvement. The other path of correction, namely how to pull the plug on a losing technology (i.e., moving from cell 2 to 4) merits attention as well, but is not our focus. Likewise, we say little about how to remain in cell 1 when the fog surrounding the new technology has not yet lifted, nor about how to master cell 4 purposively rather than through simple inaction or a bias toward the status quo. At this time, however, cell 3 is much on the minds of senior managers in large firms, either in the form of Internet anxiety or other profound concerns about myriad new technologies that might impact anywhere along the value chain and cause havoc.

When Foster identified the attacker's advantage over thirteen years ago, he did find some established firms that had embraced technological discontinuities and maintained their leadership. There are some notable current examples as well of large companies that have successively embraced emerging technologies:

- Microsoft has been aggressively moving to overcome its late entry into the Internet by redirecting a large portion of its R&D budget to Internet-related projects and by investing heavily in the production of digital content.
- Monsanto has undergone a complex makeover by shedding its cyclical chemicals business to concentrate on pharmaceuticals and agricultural and food-ingredient operations that exploit several billion dollars of investments in agricultural biotechnology.
- Intel was able to exit the semiconductor memory business and successfully devote itself to microprocessors, despite deep-seated beliefs that memories were the backbone of the firm.[9]
- Charles Schwab, the original discount investing firm, successfully launched an investing web-site despite the high initial cost of switching to one low on-line commission for all trades. The shortfall was soon made up with productivity gains and new revenue from giving customers personalized information in real time.

In our search for viable strategies to follow when incumbents are threatened with technologies, we conducted over thirty interviews with best-practice companies. Also, under the aegis of the Emerging Technology Management Research Program at The Wharton School, we organized numerous workshops

with senior managers whose core businesses were being challenged. We found four ingredients[10] necessary to prevail in the face of an emerging technology:

- attend to signals from the periphery;
- invest in a learning capability;
- maintain flexibility by adopting an options perspective; and
- maintain organizational separation.

Each of these ingredients enables an established firm to side-step one or more of the potential pitfalls of emerging technologies.

Pitfalls for Established Firms

The emergence of a challenging technology such as interactive computing or electronic commerce is seldom a surprise. Most managers attend industry conferences, read the trade press, buy consulting studies, talk with customers, and generally monitor developments in their field. The problem is that each of these sources tends to offer conflicting opinions that are reflected in divergent views within the firm. The inherent ambiguity of an emerging technology, and the new markets it creates, coupled with the dominance of traditional thinking frameworks, make established firms vulnerable to four related sequential pitfalls: delayed participation; sticking with the known technology; reluctance to commit fully; and lack of persistence.

Pitfall One: Delayed Participation

When faced with high uncertainty, it is tempting and perhaps rational to just "watch and wait." A watching brief may be assigned to a development group or to a consulting team commissioned to study the implications. Whether there is any organizational energy behind these probes depends critically on whether there is a credible champion for the emerging technology within the firm, who offers an alternative paradigm for encoding the weak external signals.

Managers use mental models to simplify and impose order on ambiguous and volatile situations in order to reduce uncertainty to manageable levels. These are sensible adaptations to what the managers have learned from their past experience.[11] Managers see what they are prepared to see and either filter out or distort what does not fit their mental maps.

The mental models of established firms are helpful for incremental innovations within familiar settings, but they become myopic and dysfunctional when applied to unfamiliar situations such as emerging technologies. Using the lens of the familiar may lead to an inappropriate framing of the opportunity. When IBM considered adding the Haloid-Xerox 914 copier in 1958, the main concern was whether the existing electric typewriter sales force could handle the product. The focus was on spreading the selling cost of this division over two product lines, rather than viewing it as an entirely new business for IBM. Since

copiers did not look attractive within this narrow frame, the opportunity was rejected.[12]

Emerging technologies are often framed as suitable only for narrow applications that are not demanded by existing customers, who often favor the current features. It is easy to dismiss such unproven technologies on the grounds that their small markets will not solve the growth needs of large firms. Of course, all large markets were once in an embryonic state with their origins in limited applications. IBM at first did not see the great opportunity in PCs. They were deemed to be entry systems from which buyers would eventually move to mainframes.

Managers tend to compare the first imperfect and costly versions of the emerging technology against the refined versions of the established technology. Of course, pictures from electronic cameras initially lacked the resolution of chemical emulsion film; personal digital assistants were at first disappointing because of the limitations of the Apple Newton in 1993; the first electronic watches were bulky, heavy, and unattractive; and the Internet continues to frustrate because of slow response, limited content, and uncertain benefits. This makes it easy to dismiss or underestimate the long-run possibilities.

Pitfall Two: Sticking With the Familiar

The choice of technology path is inherently difficult because of doubts about whether the technical hurdles can be overcome and which standard or architecture will prevail as the dominant design. The problem is most acute with emerging technologies derived from radical innovations such as photorefractive keratectomy, high temperature super-conductivity, or recombinant DNA technology. Even revolutionary innovations derived from the convergence and recombination of previously independent streams of existing technologies are hard to predict. For example, the extrapolation of computer disk storage costs suggests that optical technologies will overtake magnetic technologies within 10 to 15 years. However, a third technology based on solid state memory storage is developing at an even faster rate and may overtake optical within 20 years.[13]

The most demanding technology choices are those where there are competing and multiple versions vying to be the dominant design, as occurred historically with the light bulb and more recently with VCRs, modems, and digital wireless telephones. A design dominates when it commands allegiance of the market, so that competitors and suppliers are forced to adopt it if they want to participate in the market. This represents a milestone in the emergence of a technology for it enforces standardization that enables product or network economies to be realized, and it removes a major inhibitor to the wide adoption of the technology.

Often there is fierce competition among firms to set the industry standard around their approach in hopes of gaining an enduring advantage. Wars for standards involve complex issues of lock-in effects, network externalities,

positive feedback loops, increasing returns, switching costs, and the size of the installed base.[14] Above all, each firm must know which kind of standards battle it is facing, which in turn hinges on the compatibility of its own new technology with prior technology as well as that of rivals. The stakes may be very large, for if another design or standard prevails, the losers are trapped. Witness the struggle to set standards for HDTV, which encompasses the display technology to be used for television receivers as well as standards for delivery, transmission, and emission of images.[15]

The odds of picking the familiar but wrong technology path go up when:

- Past success reinforces certain ways of problem solving. Previous choices about appropriate technology solutions may lead the firm to search in areas that are closely related to their current skills and technologies. Thus, their capabilities limit what they can perceive and develop effectively.
- The firm lacks in-house capability to appraise the emerging technology fully. Thus, it may be underestimated or feared. Running a branch banking network is very different from electronic commerce, for example. Consequently, banks may at first shy away from offering electronic services.
- A proprietary mind-set gets in the way. The instinct of a large company with a proprietary position in its core market is to find a comparable proprietary position with the new technology that will lock in customers. Such a move makes customers suspicious, however, especially in today's open system environment.

Pitfalls one and two are both rooted in two familiar decision-making biases. First, most people have an aversion to ambiguity and risk[16] such that a relatively known prospect usually is preferred over an unknown prospect of equal expected value.[17] Second, a deep-seated preference for the status quo puts the burden of proof on those wanting change. This status quo bias is partly due to our greater sensitivity to losses than to comparable gains.[18]

Pitfall Three: Reluctance to Fully Commit

When firms from an established industry attempt to adopt a threatening technology, such as mechanical typewriter firms making electric typewriters or steam locomotive firms making diesel locomotives, they often enter reluctantly with token or staged commitments. One study of 27 established firms found that only four entered aggressively while three didn't participate at all in the threatening technology.[19] The remaining 20 made a modest initial commitment which gave the entrants from outside the established industry enough time to secure a strong market position. Why are leading firms repeatedly unable or unwilling to make aggressive commitments to an emerging technology once they decide to participate? Five plausible explanations or causes have been proposed.

The first is that managers are rightfully concerned about the possibility of cannibalizing existing profitable products or about resistance from channel

partners, and thus they hold back their full support. Both IBM and DEC were reluctant to push distributed networks that would undercut their highly profitable mainframe computers. When Compaq tried to follow the Dell Computer model of selling PCs directly over the Internet, their once-loyal network of resellers rebelled and they were forced to backtrack.

Second, there is a paradox in managerial risk taking in that managers tend toward *bold* forecasts on the one hand and toward *timid* choices on the other.[20] Bold forecasts can stem from overconfidence in general or, more specifically, a limited ability to see arguments contrary to the prediction. Timid choices reflect an inclination toward risk-aversion and a tendency to look at choices in isolation (rather than from a portfolio perspective).[21] So, even if strong beliefs exist about the potential of a new technology, the corresponding actions may be inadequate—as evidenced today by most newspapers' weak responses to the threats and opportunities of the Internet.

Third, when the profit prospects are unclear and appear less attractive than the current business, investments are difficult to justify under strict ROI criteria. The customary decision processes and choice criteria are biased against risky, long-term investments. There is a "certainty effect" operating such that relatively sure returns from investments in incremental product improvements for today's market are valued higher than riskier investments for tomorrow's markets.[22] This understandable bias in favor of certainty is exacerbated by the well-known shortcomings of conventional discounted cash flow analysis, where decisions are based on the time sequence of the net incremental cash returns for a project. For emerging technologies, the payouts are often staged, with further investments being contingent on reaching key milestones or resolving key uncertainties. Conventional methods can be dangerous if they severely discount long-term cash flows (by setting the discount rate too high), or do not take full account of the strategic implications, platform potential, and the gains in flexibility from participating in an emerging technology (i.e., the embedded options values).

Furthermore, the projected returns from an emerging technology are often worse than those from established or new technologies that address the predictable performance needs of current customers. This was the dilemma faced by Encyclopedia Britannica when confronted with a CD-ROM technology where disks sold for $80 each compared with $1300 for a printed set. Likewise, the gross margins in successive generations of hard disk drives narrowed and required different business models before profitable participation was possible. When gross margins for disk drives for mainframes were 60 percent, the margins for disk drives for PCs and notebooks were only between 15 and 35 percent. These slimmer margins were a real deterrent to enthusiastic participation by established players.[23] Similarly, Kodak has to contend with much lower margins for its digital imaging products than for chemical emulsion film.

A fourth explanation is that the attention of managers is primarily focused on their current customers. Thus, they dismiss or overlook new tech-

nologies that seem mostly applicable to smaller market segments they do not serve or don't understand.[24] This makes them vulnerable to unexpected attacks by outsiders who use the emerging technology as their entry platform. For example, the large copying centers that were the core of Xerox and Kodak's traditional market failed to appreciate the value of small, slow tabletop copiers. This oversight opened the way for Canon. Machine tool manufacturers dismissed the early versions of linear induction motors because they were not nearly as powerful as hydraulic systems.

Why are firms reluctant to participate actively in potentially disruptive technologies that initially attack low priority markets on their flank? The mental models that guide how managers choose strategies are strongly shaped by their intimate familiarity with existing customers' needs and may lead them to underappreciate that the "disruptive" technology may offer a different package of benefits highly valued by non-customers. This is why the manufacturers of 5.25 inch hard disks, who were highly attuned to the demands of desktop PC manufacturers for increasing memory capacity, grossly underestimated the appeal of 3.5 inch disks that were smaller, lighter, and more rugged and enabled the market for lap-tops to emerge. Often the potential for improvement of the "disruptive" technology is underestimated until the mainstream market starts to migrate from the established technology, and by then it may be too late.

Finally, successful organizations are not naturally ambidextrous. They encounter numerous, debilitating problems in balancing the familiar demands of competing in markets presently served with the unfamiliar requirements of an emerging and potentially threatening technology. Within the core business there is usually close alignment among the strategy, capabilities, structure, and culture, which in turn is supported by well-established processes and routines for keeping these elements in balance. This gives the organization a great deal of stability, which must be overcome before the new routines and capabilities needed to compete with the emerging technology can be developed.[25] Indeed, the more successful the firm, the more closely the elements of strategy, capabilities, structure, and culture will be aligned and the more difficult and time-consuming discontinuous changes become.

These five explanations are not independent; instead they commingle and reinforce each other to impair decision making, erode the necessary enthusiasm of the advocates, and cause firms to hesitate or hedge before making major commitments. These afflictions do not inhibit the new entrants who often sense the opportunity earlier, better comprehend or believe in the benefits of the new technology, and do not have any misleading history or culture to contend with.

Pitfall Four: Lack of Persistence

Suppose, however, that an established firm has managed to avoid the first three pitfalls and has made significant investments in a newly emerging technology. Will it have the fortitude to stay the course? Large companies typically have little patience for continuing adverse results. Yet, missed forecasts and dashed

hopes are commonly experienced during the gestation of new technologies that eventually do succeed. Market demand may not materialize as soon as expected, too many competitors might crowd into the market, or the technology may veer off in a new and unexpected direction. In time, the initial enthusiasm may be replaced with skepticism about when—if ever—the new technology will become a profitable business reality. This trap of weak commitment is the flip side of another well-known trap—the sunk cost fallacy. The irony is that the very firms that are overly committed to their core business (the sunk cost trap) are often too quick to pull the plug on investments in emerging technologies.

Those who truly appreciate the possibilities of the emerging technology and feel enthusiasm for any given new project are often deep in the organization and may have little influence on high-level strategic thinking. Thus, if a company's core business begins to struggle and senior managers are looking for ways to cut costs or reduce assets, the new venture is an easy target. After all, the real payoffs in the new venture may not accrue until after senior management's retirement. Thus, the political support for the venture evaporates along with the funds to nourish growth and keep abreast of fast-changing developments. For this reason, the CEO should be the champion of long-term investment in new ideas. When Gannett launched its new paper *USA Today*, it experienced over ten years of losses before it became a winner. Luckily, the concept was championed by CEO Al Neuhardt against the "better judgment" of many.

Patience for continuing losses will be further strained if the firm has already suffered losses with related ventures and the corporate memory starts to draw unflattering parallels to the latest failed undertaking. CitiCorp and McGraw-Hill were understandably cautious about the promise of electronic commerce after having been burned ten years ago in large-scale electronic global petroleum trading. Their joint company, called Gemco, utilized a private network to connect 70 information providers, with hundreds of traders and a bank. The network was used for gathering information, negotiating and striking deals, making payment, and clearing trades. Although the technology worked as intended, Gemco eventually failed because the widely dispersed traders did not want to change their interaction patterns to conform to the central network's dictates.

The tendency to lose patience and make half-hearted commitments has been a recurring phenomenon. As noted earlier, a key study found that 8 of 24 established firms that entered markets for an emerging technology that was succeeding subsequently withdrew, and most did not resume their efforts until the viability of the new product was demonstrated by outsiders.[26] At that point, it was usually too late to achieve leadership. In summary, what matters more than the financial commitment a company makes is senior management's emotional and strategic commitment. There must be a deep, shared conviction at the top that the new technology defines the future of the company.

Crafting Solutions

With all the uncertainties surrounding an emerging technology and its embryonic market, it is understandable that incumbent firms choose to participate defensively by deferring decisions, making token commitments, or looking for hybrid approaches that finesse hard strategic choices. Kodak's first instinct was to enter digital imaging with its Photo CD, which allowed consumers to transfer conventional film images onto compact disks, and thus avoid cannibalizing its core business. However, hesitation sharply reduces the odds of eventual success. The established firms that do prevail follow a more aggressive path that balances flexibility of posture with sustained commitment and follow through. This path entails four approaches: widening peripheral vision, creating a learning culture, staying flexible in strategic ways, and providing organizational autonomy. These four solutions do not correspond one-to-one with each trap, but rather address several of them at a time. Indeed, think of these four strategies as ingredients from which appropriate solutions can be crafted to fit the unique circumstances of each firm.

Attending to Signals from the Periphery

Emerging technologies signal their arrival long before they bloom into full-fledged commercial successes. However, the signal-to-noise ratio is initially low so one has to work hard to appreciate the early indicators. This means looking past the disappointing results, limited functionality, and modest initial applications to anticipate the possibilities. Many signals are available to those who look; other signals can only be seen by the prepared mind. As the philosopher Kant noted, we can only see what we are prepared to see. The winners are those who hear the weak signals and can anticipate and imagine future possibilities faster than the competition. Scenario planning has proved a powerful tool for imagining different futures and thereby preparing the corporate mind to be favored by "chance."[27]

The weak signals to be captured usually come from the periphery, where new competitors are making inroads, unfamiliar customers are participating in early applications, and unfamiliar technology or business paradigms are used. However, the periphery is very noisy, with many possible emerging technologies that might be relevant. Nowhere is the confusion greater than in the rapidly converging entertainment, telecommunications, information, cable, and computer sectors, where myriad technologies such as interactive TV, Web TV, CD-ROM, desktop Video, and satellite transmission among others combine to create new products and services. What is background noise to one player may be a strong signal to another.

The first step in deciding which signals and trends to scan is to define which emerging technologies are strategically significant. This requires breaking out of a mind-set focused on the characteristics of existing products or services and re-framing them as features that deliver direct benefits to customers or help

solve their problems. For example, customers did not want X-rays or CAT scans per se, but accurate images of tissues and bone structures that would identify anomalies. To consumers, a compact disc is just one way to store and reproduce music that suits a particular mood and occasion, so they are open to new technologies such as MP3 that store music downloaded from the Internet. Studying lead-users who are ahead of the curve can be another way to see the promise of a new technology.

Once the underlying functionalities have been defined, the next question is how well the emerging technology can deliver new features that meet customer needs and budgets relative to other competing technologies. A strategic projection of the performance potential of an emerging technology entails more than a linear extrapolation into the future. First, we should take into account the typical S-shaped relationship between performance and cumulative development.[28] It usually requires a period of significant effort before any results are seen, followed by rapid progress for relatively little effort before eventually reaching a limit. To arrive at a useful forecast, it is necessary to estimate the rate of competitors' spending on development. Also, the projection should take into account possible improvements in the established technology, since what matters most is *relative* performance. The projection has to be judged against the moving target of the established technology.

Once a technology trajectory has been projected, the challenge then is to estimate the rate of market adoption and the eventual market potential. When it is not yet apparent who the customers will be, and the most likely prospects have neither experienced the level of performance nor the features that are possible, such estimates are hard to make. Conventional market research techniques such as sample surveys, concept tests, and conjoint analysis are seldom applicable to embryonic markets and were never intended for these purposes. A different approach is needed when the market concept is ill formed, the technology is barely ready, and questions of relative cost, availability, and performance are unresolved. Rather than ask customers directly about their response to or interest in new products or services, early market research should concentrate on lead users and functionalities. Prospective customers may not be able to envision holographic PC television as a technology, but they can assess its functions and benefits relative to the present TV offerings.

Xerox's strategy for estimating the potential market for fax machines in the 1970s illustrates how customer benefits and functionalities can be used to develop estimates of markets for embryonic technologies.[29] Managers based their estimates on the extent and frequency of urgent written messages, their time sensitivity, and the form and size of the message (e.g., number of pages, use of graphics), and they contrasted the fax capability with the existing solutions (e.g., mail, voice, express delivery). Using this approach to estimating the latent demand for fax-type features—as opposed to studying responses to concept statements—Xerox foresaw a business market of approximately 1 million units. Unfortunately, Xerox chose the wrong technology path (pitfall 2), by

developing a system of sending facsimile messages from one computer to another, with the receiving computer printing out a copy using standard imaging technology. This turned out to be a much less attractive approach than having dedicated machines linked by telephone lines (with inferior thermal wax paper). Eventually, however, Xerox's view of PC-based faxing may prevail over stand-alone fax machines.

The choice of methods to be used to assess a market for an emerging technology should be guided by four considerations:

- *Paint the big picture.* The management questions the research is to address need not be elaborate or ask for precisely calibrated results. At the very earliest stages in the exploration, the issue is simply whether the potential market could be "big enough" to support the development activities. Questions of market potential, timing, and growth rate may be premature.
- *Use multiple methods.* All methods of market estimation are flawed or limited in some important respect. For instance, analogies with markets for technologies with similar characteristics are suspect because the situations may not be comparable in critical but unknown respects. Similarly, surveys of experts using Delphi methods to assemble composite forecasts of demand may be no more than a pooling of collective ignorance. While any one method is limited, a combination of methods—each asking the same question in a different way to cancel out various biases—may yield conclusions that deserve greater confidence. The process of triangulation of results looks for common themes and patterns after accounting for probable biases by averaging them out across methods.
- *Focus on needs not products.* It is a truism that prospective customers can't envision radically new products based on discontinuous innovations. However, they can be eloquent about their needs, problems, usage or application situations, and changing requirements that will dictate their eventual acceptance—but only if the right questions are asked.
- *Probe and learn.* Most successful discontinuous innovations follow a halting development path, marked by stop-and-go metamorphoses, before "emerging" from a series of market experiments with a feasible application. The trial-and-error learning that led to General Electrics's digital X-ray and also the replacement of film with computerized imaging is typical. Basic research began in 1975 in the aerospace business. Sometimes the technology was aimed at industrial applications and, at other times, at medical diagnostic imaging. After languishing in 1989, it was revived in 1993 when the Internet opened up the possibility of on-line medical consulting using digital images. This time the technology was ready and there was a strong champion to drive the project forward. The first machine was successfully shipped in 1996. This iterative sequence has been termed "probe and learn" to denote a process of successive approximations and

accumulating learning.[30] The path to market of fiber optics, cellular phones and CT scanners was guided by probes with immature versions of the product, learning from those probes, and trying again in different market segments.

Building a Learning Capacity

The diverse sources of information flowing from the periphery create a lot of noise. There will be confusion and immobility rather than insight and action unless this information is absorbed, communicated widely, and discussed intensively so that the full implications are understood. This requires a learning capacity that is characterized by:

- an openness to a diversity of viewpoints within and across organizational units,
- a willingness to challenge deep-seated assumptions of entrenched mental models while facilitating the forgetting of outmoded approaches, and
- continuous experimentation in an organizational climate that encourages and rewards "well-intentioned" failure.

Encouraging Openness to Diverse Viewpoints

The uncertainties surrounding disruptive emerging technologies require thorough debate. The early emphasis should be on encouraging *divergent* opinions about technological solutions, market opportunities, and strategies for participating. As learning evolves, one or multiple views may emerge as a basis for *convergence* toward a few commercializable solutions that can be tested. The tone of this extended debate should be set by senior management through their willingness to bring in outsiders with non-traditional backgrounds, to immerse themselves in the stream of data, and to ask challenging questions. They must be outside their office, having conversations with informed insiders, outside experts, and customers. They must study competitive moves and analogous situations, float ideas, and seek collaborations. This can be done in diverse forums, including team meetings, outside conferences, and electronic bulletin boards. Top-down involvement will only be productive if there is active bottom-up participation. Employees from different levels bring different points-of-view and expertise, and they are typically closer to market and technology realities. As these debates proceed and arguments become more refined, the facts and positions will be in much sharper focus.

This was the process orchestrated by Hugh McColl who built Nationsbank into America's 20th-largest bank through an aggressive series of acquisitions.[31] The traditional model of consolidation leading to large banks that reap huge economies of scale is being challenged by new technologies for delivering financial services. Banking could be done by phone or home computer, stored value "smart cards," or interactive television with an in-home ATM screen. In that new world, banking might become a low value-added service activity that

simply handles transactions for a high profit electronic "store" controlled by an outsider like Microsoft. As a result, valuable client relationships would erode as the customers search the Internet for loans, mortgages, and low-cost financial services. To deal with these profound unknowns, McColl had to change his previous mode of reliance on an inner circle of advisers, bring in outsiders, listen to ideas from diverse sources within the company, and invest in a strategic technology group of 95 people (operating as internal consultants) who track trends and possibilities. The aim is to have a growth strategy to which the whole organization can respond.

As uncertainty increases, so does the potential for confusion and paralysis, which may result in a "wait-and-see" posture, delays, and lack of commitment. Organizations need a mechanism for coalescing and focusing the on-going dialogue while reducing the various uncertainties to manageable chunks. Scenario analysis achieves this through a process of collectively envisioning a limited set of plausible futures that are internally consistent and detailed. Each scenario can be used to generate strategic options, evaluate prospective investments, and assess their robustness.[32]

Challenge the Prevailing Mind-Set

Diverse viewpoints will not have an impact on the prevailing mind-set if the organization prevents it from absorbing these insights. Expansive thinking about the future is readily subverted by the rigidities and restrictions of the prevailing mental models, industry success formulas, conventional wisdom, and false analogies from the past. The limiting and simplifying operation of deeply embedded mental models raises serious questions about whether even scenario approaches can deal with profoundly disruptive and discontinuous change. The concern is that the scenario-building process anchors on the present—as shaped by the prevailing mind-set—and then projects forward to what *might* happen. By contrast, firms that successfully exploit discontinuities may have to separate their thinking from current beliefs and realities to envision what *could be* and then work back to what must be done to ensure this aspired future will be realized. Ackoff as well as Hamel and Prahalad[33] emphasize that this kind of foresight requires deep and boundless curiosity, a willingness to speculate without conclusive evidence, the liberal use of analogies from comparable situations, and deep insights into customer needs, requirements, and behavior.

Mental models can impede the unbounded thinking needed to envision disruptions, surprises, or improbable developments because they are so grounded in past experience, reinforced by on-going commitments, and impelled by the inertia of the status quo. Before the constraints of the prevailing mental models can be challenged, the texture of these mind-sets should be described through a cognitive mapping exercise that makes explicit the views and core assumptions of the management team about important forces for change and their consequences.[34] Once these views have been displayed, key uncertainties can be surfaced and the underlying assumptions challenged. The

danger of truly unbounded thinking, however, is that it becomes unbridled fantasy that is disconnected from reality. What senior managers should strive for is disciplined imagination.

Experiment Continually

Successful adaptation to the vagaries of emerging technologies requires a willingness to experiment and an openness to learn from the inevitable failures and set-backs. There are several facets to the call for continual experimentation. Sometimes it means a willingness to create a diverse portfolio of technological solutions by endorsing parallel development activities. For example, Intel undertook research on RISC chips even as microprocessors were still dominant. Continual experimentation can also mean quick prototyping by introducing early and immature versions of the product into a plausible market segment, learning from the experience, modifying the product and marketing approach, and trying again in a process of successive approximation. This is how Motorola entered the cellular phone market and how GE participated in the CT scanning market.[35] In other markets, more ambitious, formal market tests may be conducted, such as the extended tests of interactive television by the Baby Bells.

Continually experimenting and improvising with a new technology produces insights about the possibilities and limits of the technology, the responses of diverse market segments, and the competitive options that customers consider. Once important uncertainties are resolved, such learning organizations are ready to act. For example, if influencing standards is a key to success, they can better judge which elements to endorse.

Experimentation requires a tolerance for failure. The trial-and-error learning that relies on experimentation is quickly subverted if there is a fear-of-failure syndrome. Organizations that reward those who play it safe and blame risk takers for "well-intentioned" failures will quickly discourage learning. The path of learning is marked by serendipity and the knowledge gleaned from careful diagnoses of the possible reasons for failure. Unfortunately, there is often little patience for failure, and few incentives to study failures. In counter-productive environments, without well-developed learning capabilities, a diagnosis that might distinguish causes from effects is seen as a way of assigning blame. It takes concerted leadership to create a more open climate that rewards improvisation and makes learning from failures possible. British Petroleum accomplishes this through post-project performance reviews and other special learning initiatives that are prepared for the chairman of the board.

Maintaining Flexibility: Balancing Commitment and Options

Investments in emerging technologies present a dilemma. On one hand there is compelling evidence that long-run winners are often early movers who committed quickly and unequivocally to a technology path. Andy Grove of Intel argues that it takes all the energy of an organization to pursue one clear and simple strategic aim—especially in the face of aggressive and focused

competitors—and that hedging by exploring a number of alternative directions is expensive and dilutes commitment.[36] For these reasons, Intel decided not to work on enhancing the TV set and put all its energy behind developing the personal computer chip so it had the visual and interactive capabilities to offer a universal information appliance.

On the other hand, there are persuasive arguments that investments in emerging technologies should be viewed as creating a portfolio of options where the commitment of additional resources is subject to attaining defined milestones and resolving key uncertainties. These options are investments that give the investor the right but not the obligation to make further investments.[37] Additional funds are provided only if the project continues to appear promising. If prospects are no longer promising, or the level of uncertainty stays high, then management can either let the option expire, by not making further investments, or delay until the prospects are more attractive. In an options framework, managerial and financial commitment is conditional and guarded. Presumably, this limits the loss exposure to the amount of past investments, while the upside potential is not constrained.

At first glance, commitment seems to be the opposite of flexibility and you may not be able to have it both ways.[38] However, only if the commitment is *irreversible* does it directly contravene flexibility. For instance, if you make a commitment to make a cruise voyage and pay the full amount up-front, it may seem that your flexibility has been diminished. However, if you also purchase cancellation insurance (in case of illness or a death in the family) you preserve considerable flexibility to change course when needed. This is the art of options management: it involves creativity, hedging, and an ability to imagine diverse scenarios. The only downside of creating flexibility is that it may reduce the strategic signaling value of making a commitment, which truly requires irreversibility to be credible. For example, when making a pre-emptive technology move or when building a new plant to scare off others, preserving flexibility reduces the credibility of that signal. All these factors need to be balanced within the options perspective.

Microsoft is a prime example of an established firm maintaining flexibility in the face of uncertain technologies. Its much celebrated "turn on a dime" strategy, when confronted with Netscape's Internet browser, is just one instance of its pattern of purposive agility. Microsoft was already pursuing many bets as early as 1988.[39] At that time, Apple was at its peak with the superior graphical user interface of the Macintosh, making Microsoft's DOS look like a distant second. However, Microsoft was pursuing multiple options in 1988. On one front it was developing Windows; on another, it was pushing OS/2, which it co-developed with IBM. At the same time, Microsoft was introducing various application software packages, including Excel and Word, for both Windows and Apple's Macintosh. Lastly, Microsoft was in partnership with SCO, the largest provider of PC-based Unix systems.

In essence, Microsoft had developed a strong hand of cards to play in a variety of futures that could emerge. Its portfolio of options was commensurate with the uncertainties surrounding hardware and software development at the time. Questions of standards, features, channels, and delivery modes (PCs versus servers) were still to be settled. In addition to developing a robust hand of cards, Microsoft developed a culture that could quickly change strategy. Bill Gates proved a bold leader when he changed course mid-way once the threat and promise of the Internet became apparent to him.

Sun Microsystems and its allies had long been pushing for a more universal programming language (Java), which held the promise of quickly developing software code and down-loading application programs from servers. When the Internet was added to this thrust as a possible new medium for software delivery (in addition to servers and workstations), Gates recognized that Netscape might run away with the Internet market. Netscape was built in record Internet time. Two months after the release of Navigator in December 1994, Netscape had captured 60% of the browser market, creating an installed base of more than 38 million users. Netscape reached annual sales of more than $500 million in slightly over 3 years, a level that took Microsoft 14 years to reach. When AOL purchased Netscape in March 1999, it was valued over $10 billion.[40]

Netscape was a threat to Microsoft on two fronts. Its browser was poised to create a universal interface for the networked world by offering cross-platform capabilities (from personal computers to cell phones to Intranets). Second, Netscape pursued an open-standard strategy that could sway the momentum away from the Wintel standard. To its credit, Microsoft moved quickly to compete head on with this formidable new force, shifting its strategy in a few months. Hundreds of software development projects were stopped mid-way, in order to re-deploy people, money and time towards Microsoft's own browser and new Internet strategy. The Microsoft lessons: keep your options open, study your rivals intently, and change directions boldly and quickly when needed.

Managing Real Options

The basic issue is when to make an aggressive commitment that does not have a high risk of failure. Best practice suggests it is desirable in the early stages of exploration of an emerging technology to keep a number of options open by only committing investments in stages, following multiple technology paths, and delaying some projects. Once uncertainty has been reduced to a tolerable level and there is a widespread consensus within the organization on an appropriate technology path that can utilize the firm's internal development capabilities—as in the case with Intel's choice of personal computer over television as the preferred information appliance—then full-scale internal development can begin.

However, what if there are many plausible technology paths, the risks of pursuing one to the exclusion of others are unacceptable, and the firm lacks the necessary internal capabilities? This situation was faced by Rhone-Poulenc-Rohrer as they contemplated the opportunities offered by gene therapy. To

realize therapeutic rewards, many technologies would have to be integrated—ranging from the discovery of the genes and the vectors for delivering the gene, to understanding the biological mechanisms involved in cancer, cardiovascular diseases, and nervous system disorders. Not only was it impossible to master all these technologies, but the approaches were changing rapidly and many that were being pursued were probably going to be superseded. Their solution was to form a separate subsidiary, RPR-Gencell, to be the hub of a network of 19 technology partners. Each partner provided distinct research capabilities in therapeutic paradigms according to an integrating design. The network remained fluid and open as partners joined and departed, depending on whether they could achieve performance milestones based on comparisons with what had been achieved by the best available competitors. Once a therapy became commercially successful, the partners would share royalty payments. It is unclear at this time whether the RPR-Gencell approach will work.

Most other large pharmaceutical firms facing the same uncertainties as Rhone-Poulenc-Rohrer have adopted a "wait and see" posture or engaged in cautious "learning by doing." Some firms such as Merck, Schering-Plough, Eli Lilly, or Novartis have made significant investments, but as a percentage of their total development spending they are still small. The assumption is that the pioneers will either fail or, if they succeed, will become available as acquisition candidates. Pfizer especially pursues a late-entry strategy. Such a strategy is most likely to be feasible if the growth in the market is very slow, there are many competing technologies with little likelihood that a dominant design will ever emerge, and whatever technologies do prevail will be difficult to protect or easy to imitate. Ultimately, the optimal approach (ranging from betting the farm to watch-and-wait) depends on the choice set a company and its competitors face. Only careful analysis can sort out the best path for any one company guided by its long-term vision.

Organizational Separation

The culture, mind-set, risk-avoidance tendencies, and controls of an existing organization are usually stifling to an embryonic initiative based on an emerging technology. This is why large companies are counseled to set up separate organizations dedicated to pursuing a new endeavor (such as GM's Saturn division, IBM's PC unit, or Roche's Genentech investment). The objective of "cocooning" the new business is to create a boundary that enables the new group to do things differently while still permitting the sharing of resources and ideas with the parent. This also permits separate objectives, tolerance for long development cycles, and continuing cash drains, as well as differentiated measurement criteria so that the performance of managers in the rest of the organization is not jeopardized. Above all, it creates flexibility.[41] Some companies use the separation approach to create spin-offs: newly-formed companies with their own stock, board, and management teams, in which the parent retains some ownership position. Such equity carve-outs have been successfully pursued by

Thermo Electron (over 14 spin-offs), Safeguard Scientifics (over 10 spin-offs), as well as Enron, Genzyme, and The Limited (2 spin-offs each). A McKinsey study[42] reports an annual compound return of 20% for such carve-outs after three years, which is 9.6% better than the Russell 2000 index for that period. An equity carve-out offers access to capital (via a public stock offering), strategic value from the corporate center, operating independence, development of talent, and higher motivation for key personnel (through stock options and greater freedom). As John Wood, CEO of Thermedics, put it, "subsidiary carve-outs allow us to develop new business we would not otherwise have developed." By 1999, the Thermo Electron structure had to be simplified because it became too unwieldy. The stock had come under pressure, due to weakness in the Asian market, and perhaps because of too much organizational separation.

Kodak's experience with electronic imaging highlights the strategic importance of organizational separation (in whatever form). Originally, electronic imaging activities were dispersed among Kodak's chemical imaging facilities in Rochester. This had a number of negative consequences. Managers of the film business continually interfered with electronic imaging projects that were perceived as threatening the existing customer base. The company policy that all engineers be paid the same meant Kodak could not compete for higher-priced electrical engineers, even if they could be attracted to upstate New York. Because the digital imaging projects were scattered throughout the company, there was no cohesive vision and limited accountability for market performance. When George Fisher moved from Motorola to become CEO of Kodak, he assembled all the digital imaging projects within one autonomous division and demanded the division launch new products. In a departure from a traditional "go it alone" strategy, he also initiated a number of alliances to jointly develop digital imaging projects.

How Much Independence Is Optimal?

This depends on the magnitude of the technological discontinuity and whether it threatens to erode or obsolete the competencies of the core business, the extent to which the activities and customers of the two businesses are different, and the difference in profitability. The greater the differences, the more important it is that the new business not be evaluated using the lens of the old. For completely new and disruptive technologies both *physical* and *structural* separation may be necessary and involve setting up a separate division that reports to senior management. Even when such a full degree of separation is not warranted, it is still desirable to have separate *funding* and *accounting*, so losses from the new projects are not carried by an established business unit.

The new venture also needs distinct *policies* that match the realities of building a new business. The new venture must be able to attract the best personnel and it must have the latitude to do fast prototyping and probe ill-defined markets while keeping restrictive controls and burdensome overhead to a minimum. They must be exempted from much of the routine planning and

budgeting required of their more mature siblings. Above all, the new unit should be allowed and indeed encouraged to cannibalize the established business.

Cannibalize Yourself

This was the path chosen by Bank One when they launched Wingspan.com as a totally separate and unrestricted virtual bank. The commitment of the CEO, John B. McCoy, to the venture was whole-hearted. Over $150 million was spent on marketing in the first year to launch the new bank (compared to $1.2 million spent by Internet pioneer Net.Bank). Starting fresh meant no time was wasted hooking up with Bank One's massive systems and meshing the detailed controls and personnel, pricing, and branching policies. The need to innovate at the pace of the Internet world simply dominated considerations of efficiency and compatibility with legacy systems.

What About "Synergy"?

When should the two structures cooperate? One view is that internal competition and some redundancy should always be encouraged, with different business units championing different models.[43] A more nuanced view is that the separated venture should be able to leverage the parent's strengths while avoiding absorption or subservience. It is ironic and instructive that IBM, in its quest to develop a truly new personal computer, set up a separate and geographically removed unit in 1980 that failed to tap into any of IBM's formidable technological capabilities. The IBM PC was an assembled product without any proprietary systems or semiconductors, and it quickly attracted clones.

Consider the potential for resource sharing between traditional retailers and their on-line offshoots. Established firms such as L.L. Bean, Wal-Mart, and Barnes & Noble bring visible and established brand names (that translate into much lower marketing costs), established distribution and fulfillment systems, and substantial cash flows. Furthermore, shoppers like the convenience of returning goods bought on-line to a physical store. Yet bringing together the disparate cultures of on-line and physical retailing will be difficult. The on-line business needs to be at arm's-length, to avoid being mired in the slow-moving policies of the physical stores as well as to attract and reward skilled employees who are being wooed by start-ups with stock options.

At the extreme, the new venture may absorb the parent if the emerging technology spawns a business design that obsoletes its old model. This happened when Charles E. Schwab entered on-line brokerage with e.Schwab. Their new website enabled investors to trade on-line any securities available in a regular account for a flat fee of $29.95 for any stock trade up to 1000 shares. By the end of 1997, they were the dominant on-line broker with assets that were ten times those of the challenger E*Trade.

Meanwhile, customers of Schwab's discount brokerage were still paying an average of $65.00 per trade, but getting personal service. As on-line trading

boomed, the tensions created by a two-tier pricing system that forced customers to choose between service and price were mounting. The decision was made that all trades would be priced at $29.95 despite the damage to short-run profits and revenue, even after allowing for the additional assets and heavier trading volume. Not only did this help Schwab compete against on-line rivals but it made Schwab much more of a threat to the full-service brokers, because they could now deliver personalized investment information to their customers at a very low cost.[44]

Conclusions

How can established firms compete, survive, and succeed in industries that are being created or transformed by emerging technologies? Success requires continuing support from senior management, separation of the new venture from continuing activities, and a willingness to take risks and learn from experiments. Investments should be treated as options to position the company to make informed investments at some later time—if and when the uncertainties are reduced. There should be a diversity of viewpoints that can challenge prevailing mind-sets, misleading precedents, and potentially myopic views of new ventures. The best innovators seem to be able to think broadly and to entertain a wide range of possibilities before they converge on any one solution.

These prescriptions appear directionally correct, but need tailoring to the distinctive character of each emerging technology and the particular organization involved. The design challenge is to create a high commitment organization that can cope with the tensions of high uncertainty of results while achieving alignment of all levels and functions in support of the strategic choices made. The main point is that managing emerging technologies constitutes a different game for established firms, with its own pitfalls and solutions.

Notes

1. We define emerging technologies as science-based innovations that have the potential to create a new industry or transform an existing one. They include discontinuous innovations derived from radical innovations (e.g., microrobots) as well as more evolutionary technologies formed by the convergence of previously separate research streams (e.g., the fax machine or the Internet).
2. We thank Don Doering for his detailed comments on an earlier draft. The Emerging Technology Management Research Program at The Wharton School is acknowledged for its financial support. We are especially grateful for the encouragement and deep insights provided by the executives of the past and present industry sponsors of this research program: Biogen, Cigna, Dupont, Delphi Automotive/General Motors, IBM, Knight-Ridder, McKinsey & Co., Monsanto, NSA, Procter & Gamble, Smith-Kline Beecham, Sprint, 3M, and Xerox. For details on the interviews and workshops we conducted, contact Michael Tomczyk, Managing Director, at tomczyk@wharton.upenn.edu or tel. 215-573-7722.

3. See Tab Bowers and Marc Singer, "Who Will Capture Value in On-Line Financial Services," *The McKinsey Quarterly*, 2 (1996): 78-83.
4. An early statement of this viewpoint was Richard Foster, *Innovation: The Attacker's Advantage* (New York, NY: Summit Books, 1986). Similar conclusions were reached by: James M. Utterback, *Mastering the Dynamics of Innovation* (Boston, MA: Harvard Business School Press, 1995); Alfred D. Chandler, "Organization Capabilities and Economic History of the Industrial Enterprise," *Journal of Economic Perspectives*, 6 (Summer 1992): 79-100; Rebecca M. Henderson and Kim B. Clark, "Architectural Innovation: The Reconfiguration of Existing Systems and the Failure of Established Firm," *Administrative Science Quarterly*, 35 (March 1990): 9-30.
5. David B. Yoffie, "Competing in the Age of Digital Convergence," *California Management Review*, 38/4 (Summer 1996): 31-53; Andrew Grove, *Only the Paranoid Survive* (New York, NY: Doubleday, 1996).
6. Joseph L. Bower and Clayton M. Christensen, "Disruptive Technologies: Catching the Wave," *Harvard Business Review*, 73/1 (January/February 1995): 43-53; Clayton M. Christensen, *The Innovator's Dilemma* (Boston, MA: Harvard Business School Press, 1997).
7. Clayton G. Smith and Arnold C. Cooper, "Entry into Threatening New Industries: Challenges and Pitfalls," in Howard Thomas, Don O'Neal, Rod White, and David Hurst, eds., *Building the Strategically Responsive Organization* (New York, NY: John Wiley and Sons, 1994).
8. For further details see Michael Tushman and Philip Anderson, "Technological Discontinuities and Organizational Environment," *Administrative Science Quarterly*, 31 (1986): 439-456.
9. Andrew Grove, *op cit.*
10. Note the similarities here with the study of 80 long-lived companies by Arie de Geus, *The Living Company* (Boston, MA: Harvard Business School Press, 1997). Among the companies that were at least 200 years old, four traits stood out: 1) an external orientation, 2) focus on core values, 3) experimentation in the periphery, and 4) financial conservatism. De Geus's study goes beyond technological changes, considering instead all kinds of forces. Moreover, he focuses on overall corporate survival rather than that of a single business unit. As such, the parallels are limited.
11. Supporting evidence can be found in George S. Day and Prakash Nedungadi, "Managerial Representations of Competitive Advantage," *Journal of Marketing*, 58 (April 1994): 31-44.
12. See Vincent Barabba, *Meeting of the Minds: Creating the Market-Based Enterprise* (Boston, MA: Harvard Business School Press, 1995). IBM's study of the potential for copiers also overlooked the huge demand for the copying of copies, beyond simply copying originals.
13. Chris Floyd. "Managing Technology Discontinuities for Competitive Advantage," *Prism* (Second Quarter, 1996), pp. 5-21.
14. For an extensive discussion of the issues in the context of the information economy, see Carl Shapiro and Hal R. Varian, *Information Rules: A Strategic Guide to the Network Economy* (Boston, MA: Harvard Business School Press, 1999).
15. Sam Hariharan and C.K. Prahalad, "Strategic Windows in the Structuring of Industries: Compatibility Standards and Industry Evolution," in Howard Thomas, Don O'Neal, Rod White, and David Hurst, *Building the Strategically-Responsive Organization* (New York, NY: John Wiley & Sons, 1994), pp. 289-308.
16. Robin M. Hogarth and Howard Kunreuther, "Risk, Ambiguity and Insurance," *Journal of Risk and Uncertainty*, 2 (1989): 5-35. Also see Paul J. H. Schoemaker, "Choices Involving Uncertain Probabilities: Test of Generalized Utility Models," *Journal of Economic Behavior and Organization*, 16 (1991): 295-317.

17. Daniel Kahneman and Amos Tversky, "Prospect Theory," *Econometica*, 47 (1979): 283-291.
18. Daniel Kahneman, Jack L. Knetsch, and Richard Thaler, "Experimental tests of the Endowment Effect and the Coase Theorem," *Journal of Political Economy*, 98/61 (December 1990): 1325-1348.
19. Smith and Cooper, *op. cit.*
20. Daniel Kahneman and Dan Lovallo, "Timid Choices and Bold Forecasts: A Cognitive Perspective on Risk Taking," *Management Science*, 39 (1993): 17-31.
21. Daniel Kahneman and Amos Tversky, *op. cit.* On framing in general, see Jay Russo and Paul Schoemaker, *Decision Traps: Ten Barriers to Brilliant Decision Making and How to Overcome Them* (New York, NY: Simon and Schuster, 1989).
22. Janet E. Bercovitz, John de Figueiredo, and David J. Teece, "Firm Capabilities and Managerial Decision-Making: A Theory of Innovation Biases," in Raghu Garud, Praveen Rattan Nayyar, and Zur Baruch Shapiro, eds., *Technological Innovation: Oversights and Foresights* (Cambridge: Cambridge University Press, 1997).
23. Reported by Clayton Christensen, "The Opportunity and Threat of Disruptive Technologies," Presentation to the Marketing Science Board of trustees meeting, April 19, 1996, Boston, MA.
24. Clayton M. Christensen and Richard S. Rosenbloom, "Explaining the Attacker's Advantage: Technological Paradigms, Organizational Dynamics, and the Value Network," *Research Policy*, 24/2 (March 1995): 233-257.
25. Michael Tushman and Charles A. O'Reilly III, *Winning Through Innovation: A Practical Guide to Leading Organizational Change and Renewal* (Boston, MA: Harvard Business School Press, 1997).
26. Smith and Cooper, op. cit.
27. Useful sources are Paul J.H. Shoemaker, "Scenario Planning: A Tool for Strategic Thinking," *Sloan Management Review*, 36/2 (Winter 1995): 25-40; Liam Fahey and Robert M. Randall, *Learning from the Future: Competitive Foresight Scenarios* (New York, NY: John Wiley & Sons, 1998).
28. Richard Foster, *op. cit.*; Clayton M. Christensen, "Exploring the Limits of the Technology S-Curve, Part I: Component Technologies," *Production and Operations Management I* (Fall 1992).
29. This example is adapted from Vincent P. Barabba, *op. cit.*
30. Gary S. Lynn, Joseph G. Morone, and Albert Paulson, "Marketing and Discontinuous Innovation: The Probe and Learn Process," *California Management Review*, 38/3 (Spring 1996): 8-37.
31. Nikil Deogun, "High-Tech Plunge: A Tough Bank Boss Takes on Computers with Real Trepidation," *Wall Street Journal*, July 25, 1996, pp. A1-A2.
32. Paul J. H. Schoemaker, "When and How to Use Scenario Planning: A Heuristic Approach with Illustration," *Journal of Forecasting*, 10 (1991): 549-564; Liam Fahey and Robert Randall, *op. cit.*
33. Gary Hamel and C. K. Prahalad, *Competing for the Future* (Boston, MA: Harvard Business School Press, 1994).
34. Kim Warren, "Exploring Competitive Futures Using Cognitive Mapping," *Long Range Planning*, 28 (1995): 10-21.
35. Lynn et al., op. cit.
36. Grove, *op. cit.*, p. 151.
37. William F. Hamilton and Graham R. Mitchell, "Managing R&D as a Strategic Option," *Research Technology Management*, 31/3 (May/June 1988): 15-22; Edward H. Bowman and Dileep Hurry, "Strategy Through the Options Lens: An Integrated View of Resource Investments and the Incremental-Choice Process," *Academy of Management Review*, 18 (1993): 760-782; Rita G. McGrath, "A Real Options Logic

for Initiating Technology Positioning Investments," *Academy of Management Review*, 22 (1997): 974-996.
38. Pankaj Ghemawat, *Commitment: The Dynamic of Strategy* (New York, NY: Free Press, 1991).
39. Eric D. Beinhocker, "Robust Adaptive Strategies," *Sloan Management Review*, 40/3 (Spring 1999): 95-106.
40. David B. Yoffie and Michael A. Cusumano, "Building a Company on Internet Time: Lessons from Netscape," *California Management Review*, 41/3 (Spring 1999): 8-28.
41. For insights about how Silicon Valley companies succeed in fast-changing environments, see Homa Bahrami, "The Emerging Flexible Organization: Perspectives from Silicon Valley," *California Management Review*, 34/4 (Summer 1992): 33-52; Kathleen Eisenhardt and Shona Brown, *Competing on the Edge: Strategy as Structured Chaos* (Boston, MA: Harvard Business School Press, 1998).
42. Patricia Anslinger, Dennis Carey, Kristin Fink, Chris Gagnon, "Equity Carve-Outs: A New Spin on the Corporate Structure," *The McKinsey Quarterly*, 1 (1997): 165-172.
43. Based on a report of the findings of Rajesh Chandy and Gerard Tellis, in Jerry Useem, "Internet Defense Strategy: Cannibalize Yourself," *Fortune*, September 6, 1999, pp. 121-134.
44. Erick Schonfeld, "Schwab Puts It All Online," *Fortune*, December 7, 1998, pp. 94-100.