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**Abstract**
What is discontinuous about the moment of radical technological change? We suggest that the discontinuity typically does not lie in a radical advancement in technology itself; rather, the discontinuity stems from a shift of an existing technical lineage to a new domain of application. Seeming revolutions such as wireless communication and the internet did not stem from an isolated technical breakthrough. Rather, the spectacular commercial impact was achieved when an existing technology was re-applied in a new application domain. We use the biological notion of speciation events, which form the basis for the theory of punctuated equilibrium, to reconcile the process of incremental change within a given line of technical development with the radical change associated with the shift of an existing technology to a new application domain. We then use this lens to explore how managers can cope with, and potentially exploit, such change processes.

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**The Emergence of Emerging Technologies**

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# The Emergence of Emerging Technologies

**Ron Adner and Daniel Levinthal**

What is discontinuous about the moment of radical technological change? We suggest that the discontinuity typically does not lie in a radical advancement in technology itself; rather, the discontinuity stems from a shift of an existing technical lineage to a new domain of application. Seeming revolutions such as wireless communication and the internet did not stem from an isolated technical breakthrough. Rather, the spectacular commercial impact was achieved when an existing technology was re-applied in a new application domain. We use the biological notion of speciation events, which form the basis for the theory of punctuated equilibrium, to reconcile the process of incremental change within a given line of technical development with the radical change associated with the shift of an existing technology to a new application domain. We then use this lens to explore how managers can cope with, and potentially exploit, such change processes.

Discussions of technology evolution have offered sharply contrasting perspectives of the pace and mechanisms of technological change. On the one hand, we have arguments regarding the gradual, incremental nature of technological change (Dosi, 1983; Basalla, 1988; Rosenbloom and Cusumano, 1987). In contrast, others have offered the image of technological change as being rapid, even discontinuous (Tushman and Anderson, 1986; D'Aveni, 1994). Indeed, the locus classicus of evolutionary perspectives of technological change (Schumpeter, 1934) offers the dramatic imagery of "waves of creative destruction". How can these contrasting perspectives be reconciled?[1]

The theory of punctuated equilibrium (Gould and Eldridge, 1997), developed in the context of evolutionary biology, provides a powerful framework to integrate ideas of gradual change in underlying science with apparent discontinuities in the commercial application of technologies.[2] Gould and Eldridge confronted a fossil record that seemed inconsistent with the gradualist interpretation of Darwin's ideas. Contrary to the expectation of an incremental process of descent with modification, they identified periods in which there seemed to be bursts of evolutionary activity. Their resolution of empirical evidence and Darwin's Theory was to note the importance of speciation events --- the separation of one evolving population from its antecedent population, which in turn allows populations to follow different evolutionary paths.

There are two critical features of speciation. One is that it is genetically conservative ---that is, speciation is not triggered by a transformation of the population. Second, the speciation event

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[1] The arguments in this paper draw on our previous research into the nature of technology evolution and technology competition (Adner and Levinthal, 2000; 2001a; 2001b; Levinthal 1998; and Adner 2002).

[2] Mokyr (1990) applied the notion of punctuated equilibria to the process of technical change. However, his argument hinges on the presence of occasional, dramatic mutation events and not the notion of speciation events that are critical in the underlying theory of punctuated equilibrium as developed by Gould and Eldrigde (1977) and as applied to the process of technical change by Levinthal (1998).

allows the two populations to grow quite distinct as a result of their now different selection environments.

What can this framework tell us about the evolution of new technologies? How can it help resolve the discordant images of both gradual and radical technical change? In particular, how can it help us identify those critical transition points when emerging technologies realize commercial importance?

The analogue of speciation in technological development is the application of existing technologies to a new domain of application. Technological discontinuities are generally not the product of singular events in the development of the technology itself. As in the biological context, the critical factor is often a speciation event, transplanting the existing technological know-how to a new application domain where it evolves in new directions. The technological change associated with the shift in domain can be quite minor; indeed, in some instances, there is no change in technology.

While the speciation event is, in an immediate sense, technologically conservative, it may have significant commercial impact. In the new application domain, the resources available and selection forces present may result in rapid subsequent technical development. Consider these ideas in the context of the development of wireless communication technology. Wireless communication technology has, at many junctures, been heralded as revolutionary, including the introduction of wireless telegraphy, radio broadcasting, and wireless telephony. However, beneath these seemingly radical changes was a gradual technological evolution within a lineage in which dramatic changes were initiated by the application of existing technology to new domains of application:

- **Laboratory device:** Wireless communication technology started as a laboratory device used by German physicist Heinrich Rudolph Hertz to test Maxwell's theories on electromagnetic waves. The critical functionality in this domain was the reliable measurement of electromagnetic waves.

- **Wireless telegraphy:** The development of wireless telegraphy was driven by the ability of Marconi to generate financial backing for a corporation to pursue the commercial application of electromagnetic waves to serve remote locations such as ships and lighthouses for which wired telegraphy was not an alternative (Garrat, 1994). For this second application domain of wireless telegraphy, a new functionality of distance was required. Researchers focused on enhancing the power of transmitters and increasing the sensitivity of receivers. The effort to develop superior receivers for wireless telegraphy (and an effective repeater for wired telephony) ultimately led to the development of the vacuum tube (Aitken, 1985).

- **Wireless telephony and broadcast radio:** The vacuum tube provided the basis for a continuous wave transmitter, a technology that allowed for the transmission of voices and was readily applied in the new application domains of radiotelephony and broadcasting. Wireless telephony was initially used for public safety purposes, such as police and emergency services. Only in recent years has wireless technology penetrated more mainstream, mass consumer markets. The application of the vacuum tube to broadcast radio first emerged with ham (wireless telegraphy) operators and then was rapidly refined by the already established corporate entities of Westinghouse, RCA, and General Electric.

The initial prototype of the technology that entered each new domain, whether it was Hertz's laboratory equipment, Marconni's early wireless, or broadcast radio, was readily derived from the existing state of knowledge. The shifts in application domains, however, were significant breakpoints in the technology's development because they signaled a shift in selection criteria --- a shift in the critical functionality by which the technology would be evaluated. In addition, the shifts radically changed the resources available to support the development of the technology. Contrast Hertz's assembly of components laying about the laboratory he took over in Karlsruhe, Germany with Marconni's ability to generate financial backing for a corporation to pursue the commercial application of electromagnetic waves as an alternative to wired telegraphy (Garratt, 1994) and the commitment of resources by the already established corporate entities of Westinghouse, RCA[3], and General Electric to its refinement.

Yes, wireless communication technology has undergone extraordinary change in the hundred years since Hertz's experiments. However, the dramatic breakthroughs that set the technology on a new course were as much discoveries of new domains of application, as advances in the underlying technology. These "speciation" events were, of course, made possible by wonderfully creative development efforts that commanded tremendous amounts of time and financial resources.[4] However, these efforts were supported within the existing application domains. Broadcast radio and wireless telephony could not have been possible in the absence of continuous wave transmitters, but the impetus to develop that technology and the resources to do so came from efforts to enhance

[3] The name Radio Corporation of America (RCA) is potentially confusing in this context. RCA was founded by General Electric, AT&T, and United Fruit (joined latter by Westinghouse) in order to pool their patents in the pursuit of wireless telegraphy (Aitken, 1985). RCA was not founded in anticipation of broadcast radio and indeed the emergence of broadcast radio shortly after the founding of RCA caused considerable conflicts among the parent companies.

[4] Indeed, more generally the role of intentionality and choice in technology development clearly distinguishes it from processes of biological change. We apply the biological framework to understand the nature of the selection environment acting on possible technologies and, in particular, the niche structure of the resource space, but we are not assuming a process of blind variation generation. Indeed, we assume, and argue that actors should try to anticipate the structure of the possible selection environments in which they can develop a given technological initiative.

the distance and clarity of wireless telegraphy and AT&T's interest in developing an effective repeater for long-distance, wired phone service.

Thus, a technology undergoes a process of evolutionary development within a given domain of application. At some juncture, that technology, or possibly set of technologies, maybe applied to a new domain of application. The technological shift necessitated by this event is modest. Just as biological speciation is not a genetic revolution – the DNA of the organism doesn't suddenly mutate – technological speciation is not usually the result of a sudden technological revolution. The revolution is in the shift of application domain. The distinct selection criteria and new resources available in the new application domain can result in a technology quite distinct from its technological lineage. Framing technology evolution in terms of speciation leads us to differentiate between a technology's *technical development* and a technology's *market application.* This distinction is useful in understanding broad patterns of technological change, and leads to specific strategic implications for technology management.

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Insert Figure 1 here

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Certainly, not all emerging technologies exhibit this pattern. Some development efforts take place in the context of research laboratories and have no commercial precursor prior to their initial, dramatic commercial applications. Examples of such innovation include genetic engineering, automated DNA sequencing, and chemical based photography. Our purpose is not to claim that all innovation follows the incremental path we are detailing here. However, we would argue that the pattern of speciation that we characterize here is far more common than is widely realized. Indeed, many emerging technologies that are viewed as having appeared dramatically and rapidly in their mainstream markets, such as xerography (Dessauer, 1971), home video recording (Rosenbloom and Freeze, 1985), and the Internet (Berners-Lee, 1999), actually have a long pre-history of technical development occurring in relative small and peripheral market segments.

*Lineage Development: Selection Criteria and Resource Abundance*

Given the speciation event, why might we observe a radically divergent technology emerge and why might this lead to a rapid pace of technological change? Within our framework, the nature and pace of technological change are driven by two elements of the selection process. One is a process of adaptation. The technology becomes adapted to the particular needs of the new niche that it is exploiting. The second element corresponds to the resource abundance of the niche. As a result, the mode of development is influenced by the particular features of the niche, while the pace of development is driven by the resources that this niche is able to provide.

A technology naturally adapts to the niche to which it is being applied (Basalla, 1988). This adaptation reflects the distinctive needs of the niche regarding functionality. The new application domain may value particular elements of functionality that were largely irrelevant to the prior domain to which the technology was applied. In the disk drive industry, we see that the attributes of size, weight, and power requirements become relevant in the new niche of portable computers (Christensen and Rosenbloom, 1995). These same attributes had had little relevance for manufacturers of desktop machines.

Needs should be viewed both in terms of the relative importance of various attributes, such as different price/performance tradeoffs among potential consumers, but also the minimal threshold of functionality for a technology to be viable in a given application domain (Adner and Levinthal, 2001). Thus, for example, a horse-less carriage that is likely to breakdown after a quarter of a mile is a novelty, not a substitute for a horse.

The other class of factors is the resources available to sustain the innovative activity.[5] While a new application domain may have a distinct set of selection criteria, if the resources in this niche are quite limited then we should not expect to observe the rapid development of new technological forms. It is the combination of distinct selection criteria and the availability of substantial resources to support innovative efforts associated with the new application domain that results in a speciation event with dramatic consequences for subsequent technological development. The pace of development becomes much more rapid if the technology is able to satisfy the needs of not only the possibly peripheral niche to which it may have first entered but, as it develops in functionality or cost is reduced, the technology is able to penetrate larger, more mainstream niches. A key to this transition is the degree to which resources (scientific, managerial, organizational, complementary capabilities) that were of value in one market niche can be leveraged in the new market niche. In this regard, consider the market journey of Global Positioning Systems (GPS) technologies, from strictly

[5] In this sense, the framework relates to the important work on the population ecology of organizations (Hannan and Freeman, 1989). Hannan and Freeman, and a now long line of significant subsequent research (Carroll and Hannan (2000) provide a recent summary of this area), highlight the role of the selection environment in determining the demography of organizational populations. In particular, the early work of Hannan and Freeman (1984) and subsequent work on resource partitioning (Carroll, 1985) demonstrate the importance of the niche structure of the resource environment, most explicitly through the concept of carrying capacity. While sharing this common footing, our work differs from ecological analysis in two fundamental ways. First, where population ecology examines organizational forms, our work explores the evolution of technological forms, which can both cross and coexist within organizational boundaries. Second, whereas population ecology assumes that organizational forms are fixed relative to their environments, we examine the ways in which technological forms change within and across distinct selection environments and resource spaces.

military applications, to geoscience and surveying applications, to trucking fleet management, to the current penetration attempts in private automobiles.[6]

*Creative Destruction --- the New Displacing the Old*

"Creative destruction" occurs when the technology that emerges from the speciation event is ultimately able to successfully invade other niches, possibly including the original domain of application. For example, the 3.5-inch computer disk drives that were initially developed for the niche of portable computers ultimately became viable for the mainstream desktop market (Christensen and Rosenbloom, 1995). Radial tires were initially developed in the distinct niche of high-performance sports cars (Sull, Tedlow and Rosenbloom, 1997; Foster, 1986) that valued the high-performance of the radial tires. The resources made available from the success of radials in this niche lead to increased efficiency in the production process. That reduction in cost, in conjunction with a different attribute of radials --- their greater longevity relative to bias-ply tires --- allowed radial tires to penetrate the mainstream niches of replacement tires and ultimately the original equipment market of automobile manufacturers.

This successful "invasion" of the mainstream niche is the dramatic event on which commentators tend to focus. However, that dramatic invasion is the outcome of a substantial period of development in a relatively isolated niche. Prior to any lineage development, there is little possibility that the new technological form can out-compete the refined version of an established technology in its primary domain of application. As Rosenberg (1976) argues in his analysis of the

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[6] We note that resource availability is a function not only of actual penetration of larger markets, but also of actors' expectations of this penetration. For example, the US Congress's 1994 decision to open the Internet to commercial transactions released a wave of resources in the expectation that the internet would penetrate a number of large, new application domains.

development of the machine tool industry, even those technologies that ultimately became widely diffused general purpose technologies initially focused on the needs of a particular application domain.

What permits the new technology to have some basis of viability is the existence of niches, or peripheral elements of existing niches, that exhibit a somewhat different set of selection criteria. Such peripheral niches may also serve as safe havens for technologies whose primary application domains have been invaded. For instance, the teletype endured even with the full development of telephone technology, because it had the attribute of providing a written record that was valuable in business transactions, as well as allowing for asynchronous communication. Its demise awaited the development of an alternative form of written networked communication --- improved facsimile technology and the development of large scale computer networks. A final component in the persistence of a technology in a given domain of application are various forms of switching costs. These may be costs incurred by individual actors, or more tellingly, costs associated with network externalities (Arthur, 1989; David, 1985).

*New Combinations and New Application Domains*

In our discussion of speciation, we have highlighted a particular form of recombination --- the combination of an existing technology with a new context. Clearly, other sorts of recombination occur as well. The development of the CAT scanner for medical imaging, for example, illustrates the linking of two formerly disparate technologies. CAT scanning (Trajtenberg, 1990) drew upon X-ray technology, which was already applied in the medical imaging domain, and computer technology, which had been applied to data processing (see Figure 2). Of course, to make these new combination effective in the context of medical imagining, computer science work on appropriate imaging algorithms had to be developed as well as significant design changes in X-ray machinery to allow for rotation and multiple scans.

Cases in which literally "off the shelf" technology can be applied to a new context are likely to be rare. However, even in an example such as the CAT scanner, it is important to note that the tremendous performance improvements and cost reductions in computer processing power that made the CAT scanner possible occurred for reasons quite apart from any possible technological opportunity of medical imaging. Note also that the expenditures that supported these advances dwarf the relatively modest expense of developing imaging algorithms or data storage systems that were specialized to the medical imaging niche (Trajtenberg, 1990).

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Insert Figure 2 here

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The notion of new combinations has been put forward most famously in the context of the study of technical change by Schumpeter (1934). Schumpeter (1934: 66) posed the notion of innovation as "carrying out new combinations", where a new combination could take on one of five different forms: (1) a new good, (2) new method of production, (3) new geographic market, (4) new source of supply, (5) new organization of an industry.

A critical issue from our perspective is whether the new form, or combination, competes for resources against the antecedent forms from which it was derived or whether it derives resources from other niches in the environment. The former case may generate a process of creative destruction whereby the new form *substitutes* for the prior form in that same application domain. However, we suggest that new combinations are more likely to find their initial home in a new application domain or in the peripheral realm of the existing niche.[7] It is this property of not initially competing in the niche space of the antecedent form that defines the property of speciation.

Thus, we are highlighting a particular type of Schumpeterian 'combination" --- the introduction of an existing technology into a new application domain, in contrast to the usual focus on new to the world products or processes. Many of these creative recombinations produce new forms that prove unviable in the market place. Witness the many variants of pen-based computing and personal digit assistants (PDAs) that have been commercial failures (McGahan, Vadasz, and Yoffie, 1997). Yet, unlike biological processes, technological evolution is not restricted to processes of random variation and environmental selection. Agents of technical change can actively monitor for hopeful new variants. Our encouragement for such Schumpeterian entrepreneurs looking at existing emerging technologies is to pay particular attention to market niches that will accept the technologies in their present form. Deploying emerging technologies in these early markets can be a means of both realizing profits in the near term and providing valuable feedback regarding the demand for possible attributes of technical functionality to support and guide their further development.

## Patterns of Technology Evolution

[7] When speciation takes the form of occupying a wholly distinct niche it is referred to as allopatric speciation (Mayr, 1963). More typically speciation involves the exploitation of the periphery of an existing niche (Bush, 1975).

At least initially, commercial discontinuities in wireless communication took the form of providing communication services where none existed before rather than new technology for existing services. A new technology will be viable if it out-competes existing technologies on some performance criteria, whether an element of functionality or cost and thereby achieve a relative advantage. It is unlikely that a new technology will initially dominate an established technology in its primary domain of application.

For example, early wireless communications technology, despite high cost and poorer sound quality, outperformed the more refined wired systems for mobility and flexibility. This allowed it to build an initial niche in military and police communications where mobility was valued enough to outweigh the other weaknesses.

In most cases, the early domains of application are ones that not only value the distinctive functionality, but also ones that can tolerate relatively crude forms of the new technology. For example, while minimally invasive surgery techniques were applied in ninety-five percent of gallbladder procedures (a relatively simple surgical procedure) within two years of their introduction, it took years of further development before the technologies were applied in heart surgeries. Similarly, early pen-based computing could be used for structured forms and signature capture but not for tasks that required handwriting recognition.

This general pattern of industry development from a small niche to an ever broader set of niches through a series of speciation events has been observed in numerous settings. The history of the video recorder, which characterizes the transition from a peripheral niche to the mass consumer market, is illustrated in Figure 4. The technology was initially introduced for the distinct niche of broadcasters. As the manufacturing process was refined and the product design simplified, it was possible to penetrate a new niche of industrial and commercial users (Rosenbloom and Cusumano, 1987). Finally, this development continued to the point that the product was able to penetrate the mass consumer electronic market. It is important to note that, at each point in its development, video recording technology was commercially viable and profitable within the niche in which it was operating.

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Insert Figure 3 here

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In ecological terms, we might think of this as the artifact shifting from a specialist to a generalist. Video recorder development, which previously drew resources from the narrow niche of television broadcasters, could now draw on the mass consumer market to fund further advance. In some cases, the technology never goes beyond the initial peripheral market, but remains an isolated "island of application". Gallium arsenide, for example, was heralded as a replacement for silicon in semiconductors in the early 1980s based on the superior speed that it provided. However, the technology has proved commercially viable only in the context of supercomputer applications and communications devices (Wiegner, 1988). Recently, the demand for gallium arsenide has increased. In line with our arguments, this new demand is coming from the application domain of communication devices, not mainstream computing applications (Ristelhueber, 1993).

**Implications for Firm Strategy**

How can managers use this process of technological speciation to their advantage? Biological speciation often occurs through external events that separate one population from another.

However, once managers understand the process of technological speciation, they can actively look for ways to move the speciation process forward. Our recommendations do not eliminate the uncertainty inherent in emerging technologies, but provide important insights for managers to cope with and even exploit this uncertainty:

- **Focus on the intersection of markets and applications:** Technology speciation distinguishes between a technology's *technical development* and a technology's *market application.* Because of the belief that technological revolutions usually occur in the lab, managers sometimes undervalue the importance of applications. Some writers have focused on the impact of technological milestones on the rate of progress of development (Sahal, 1985). We are suggesting that, while these "supply side" considerations are important, it is critical to consider constraints and thresholds on the demand side as well. The leap to new application domains affects the attributes of the technology that are developed as well as the resources available for its development. The implication is that there are probably many technological developments that could take off, *in the proper application domain.*

  Managers need to focus attention on the issue of potential application domains. There may be a variety of technologies that are sitting in the laboratory that would begin to emerge if transplanted into the right application domains. Discussions of the management of emerging technologies emphasize long-term vision and patient investment as the key to developing nascent technologies to the point that they can have a real impact on the existing technological order. These discussions pay little attention to the market contexts in which innovations are exploited and the impact these market interactions may have on exploration activity. The wireless communications revolution came as a result of recognizing the potential applications of technology. Which technologies in your labs might have a similar potential if they were moved to the right domain?

- **Focus on selecting market contexts for a technology, rather than selecting technologies for a fixed market context**: The question should be: Where can I find an application domain in which this fledgling technology will thrive? There are many examples of novel products based on relatively crude technologies which serve intermediate markets while biding their time to enter the 'mainstream' market: solar powered calculators were proving grounds for solar cells; digital watches and calculators were platforms for early liquid crystal displays; inventory management systems and simple signature capture devices were predecessors of pen based computing. Even in these technologies, which have to date only partially fulfilled initial expectations, firms such as Sanyo, Sharp, and Casio were able to introduce profitable products into the market that allowed them to learn about and refine the technology. Contrast the experience of those firms with companies that kept development in-house until such time as they felt they could address their mainstream customers rather than focusing on a small target segment to refine the technology. For example, ARCO's investments in solar energy power stations and Apple's investments in the Newton pen based computer were prematurely transplanted to the mainstream market in which they were unprepared to thrive. Similarly, early success in speech recognition technologies has been found not by those firms targeting the mass market of Language User Interface (LUI), the holy grail that would free computer users from their keyboards, but rather in the focused niches such as telephonic applications (e.g. directory assistance) and medical and legal dictation, which were characterized by very well defined vocabulary sets and by users' high willingness to pay.

- **Understand market heterogeneity:** While increasing attention has been paid to the influence of market feedback on technology management (Abernathy, 1978; Von Hippel, 1988; Leonard Barton, 1995; Christensen, 1997; Moore, 1995), the implications of the possible *diversity* of feedback on development strategies remain relatively unexplored. Exploiting market opportunities at early stages of technology development requires closer consideration of market heterogeneity. Different consumers have different requirements for purchasing products and use different criteria when evaluating their options. Different facets of the commercial market have different thresholds of viability. These differences may be differences in magnitude, such as the level of script recognition required of pen-based computers for inventory management versus word processing applications; or they may be differences in kind, such as the relative importance of price and performance of computers for space science application versus home use.

An initiative that fails in one market subset may still be highly successful in another. For example, the first users of the xerographic process were specialty printers who used it to make offset masters. Early machines required a 14-step process to make a single copy, which prevented them from penetrating many markets. The requirements of specialty printers were sufficiently low however, and their complementary skills sufficiently high, that they were able to derive benefits from the product despite the cumbersome technology. Further, because of their understanding of the printing process, these specialty printers aided Haloid (later renamed Xerox) in expanding the market for xerography to other printing sub-fields, such as microfilm printing, that ultimately led to the corporate mainstream (Dessauer, 1971; Pell, 1998).

- **Expand your selection criteria:** While introducing greater experimentation, the company also needs to diversify the selection criteria it uses to evaluate initiatives. Because firms do not have the same internal diversity as the broad market, they cannot match the richness of the market selection environment in their own internal selection processes. The internal selection environment of an organization, which is governed by a hierarchical structure, cannot reflect the diversity of selection criteria of the independent consumers that compose the market. This is why companies often tend to overlook potential opportunities for applications of technology. Viewing the market as an amalgamation of independent selection environments, the challenge is not to accurately determine the needs of the market, but rather to recognize the variety of evaluation criteria being applied in the market's component segments.

Often times, new initiatives, even with positive feedback from the market, do not take hold and develop within established firms. A common factor in such episodes is the fact that the initiatives do not have great saliency within the operating unit in which they are based. Management may tend to find the initiative to be a distraction from their primary efforts. Initiatives in emerging markets are handicapped in two ways. First, they do not fall within the existing strategic context and, as a result, do not present obvious pursuits for the firm (Burgelman, 1991). Second, they often target markets of insufficient magnitude to attract the attention of the larger organization. Therefore, in contrast to the usual problem in experimentation of signal to noise ratios, we suggest that many business initiatives suffer from a problem of *signal-to-baseline*. Existing business activities form the baseline. If the current and near-term expectations of performance of the new initiative are modest relative to this baseline, then the scarce resource of managerial attention, as well as more conventional resources such as capital, will tend not to be allocated to them.

The most basic managerial tool to modulate the signal to baseline ratio is organizational structure. Not surprising, firms that have sustained high levels of innovation throughout their history, such as Hewlett-Packard and Johnson & Johnson, have long-standing commitments to narrow charters for their operating units. Even though many new initiatives for these companies emerge from existing operating units, these initiatives typically are ultimately pursued in the context of a new, dedicated operating unit.

- **Be careful where you look for market insights:** Because of the diversity of markets, the lessons managers take away about the potential applications of new technology may, in large part, depend upon where they look. As companies "probe and learn" about markets, what they learn may be directly related to where they probe (Morone, 1993). Generalizing market signals from a given niche to the broader market can lead to dangerous distortions in expectations, which can lead to overly pessimistic assessments of opportunities (e.g., hard disk manufacturers like Seagate and Quantum, by relying on the early assessments of desktop computer users, missed enormous opportunities in small, light, but low capacity disk drives (Christensen, 1997); similarly, incumbent telecommunication equipment providers like Lucent and Siemens followed their lead users and chose to limit their early involvement in packet based switching equipment). Such false generalizations may also lead to overly optimistic assessments of opportunities (e.g., satellite based mobile telephony operators like Iridium and Globalstar who extrapolated the preferences of a small set of globe-trotting executives to the broader market). Learning and adaptation are feedback-driven processes (March and Simon, 1958; Nelson and Winter, 1982); as a result, decisions regarding the sources of feedback have significant implications for learning and directing change.

- **Learn by doing:** Engage in exploration through exploitation. By engaging the market, firms not only sell product and create revenues, they also gain information on market size, preferences and requirements. Flexibility in market focus allows for a broad set of alternative bases of market support, customer feedback, production experience, and accompanying these, the increased capacity to learn and improve in subsequent development attempts. Learning requires action. Arguably, in mature markets, firms can learn about market preferences by observing consumer responses to other firms' products. However, for emerging technologies that offer new functionalities and functionality bundles, understanding consumer preferences strictly on the basis of this kind of vicarious learning is less effective.

- **Mainstreaming niche technologies:** Given the pattern of evolution shown in Figure 3, managers can look for opportunities to accelerate this evolution. One approach is to target niches whose qualitative selection criteria overlap with the mass market's but whose absolute requirements are more accommodating along some dimension. Selecting early niches on the basis of such preference overlap allows firms to transfer experience acquired in the incubating niche to other market segments. Such overlap characterized the early evolution of the United State's semiconductor industry for whom the early requirements of government sponsors, particularly the Department of Defense, for smaller, lighter, and more reliable digital integrated circuits mapped well onto the selection criteria employed in the emerging market for industrial computers and, ultimately (in step with lower prices) to the mass market that was created by the microprocessor. In Europe, by contrast, semiconductor firms were initially focused on consumer electronics markets (stereos, televisions, and automobiles) and, to this end, pursued analog integrated circuit technology which proved much more difficult to port to other niches. Indeed, as the applicability of digital integrated circuits has expanded, analog circuits have been displaced even from their home niches (Malerba, 1985).

In evaluating technology opportunities, managers can examine whether there are relatively small technological changes or complementary technologies that will open the technology to a whole new level of development, such as Web browsers that opened up the latent opportunity of the already existing Internet protocols (Berners-Lee, 1999). Indeed, just as Marconni's reapplication of Hertz's discoveries to wireless telegraphic communication unleashed a wave of resources which served to accelerate the evolution of wireless radio technology, the introduction of internet technology to the mass market fueled a simultaneous boom in investment and innovation which would have been impossible had the internet remained in the exclusive domain of government labs and research institutions.

Clearly, the market feedback based approach suggested here raises important questions as to the relationship between the sequencing of expenditures and the timing of feedback. An investment process based on feedback is implicitly making assumptions about the level of initial commitments relative to subsequent commitments and about the speed of feedback relative to the pace at which these commitments must be made. To the extent that there are large fixed investments that must be made prior to the realization of any market feedback, then the process suggested here is not appropriate.

A further organizational challenge is raised by attempting a feedback-based approach to technology management in the face of multiple application domains. In a heterogeneous demand environment market rejection signals are not definitive – an innovation that is rejected in one application domain may nonetheless find acceptance in another domain; an innovation that is rejected at a certain state of development may find acceptance after further refinement. The open-ended nature of this feedback can make abandoning projects quite difficult. Exploiting the inherent flexibility of a sequential development process, however, requires that firms be able to exit opportunity paths in a timely and efficient manner. Adopting efficient resource (re)allocation processes is thus a critical component to implementing a feedback based approach.

Given these boundary conditions, one is left with the empirical question as to how constraining the boundaries are. The development histories of such disparate innovations as xerography (Dessauer, 1971; Pell, 1998), video recording (Rosenbloom and Freeze, 1985, machine tools (Rosenberg, 1976), electric power utility (Hughes, 1983), speech recognition technology (Forrester, 2000), and internet telephony (Mines and Delhagen, 1998) provide evidence that development through sequential entry into markets is not an uncommon mode of technology evolution.

While technologies may require a significant incubation period, the investments required during the incubation stage are rather modest; the large scale investments associated with technology ventures are related to scaling up for mass production and establishing distribution and support systems (Rosenberg, 1976). The costs associated with mass production are indeed high, but that does not negate the possibility and benefit of engaging intermediate markets before committing to the pursuit of the mass market. The example of Sony, which produced its first Betamax machines at a U-Matic plant which was producing video tape machines targeted at corporate and institutional users, suggests that that even production capacity can be built incrementally in parallel with activity in intermediate markets (Lyons, 1976).

The pattern of exploration through exploitation is borne out time and again in the evolution of technology. At times it is a matter of deliberate strategy, in which firms actively direct development through intermediate markets in their quest to reach their target market. This was the case in the development of video technology, where a market for home video was suggested in 1956, twenty years before a video machine was successfully introduced to the home market (Rosenbloom and Cusumano, 1987). At other times, the market niche which propels an innovation to success emerges through a relatively undirected stream of market experiments, such as Dupont's discovery of ballistic applications for Kevlar after failed initial attempts at serving tire and airframe manufacturers (Rosenbloom and Hounshell, 1992).

**Conclusions**

Managerial interest in emerging technologies hinges on the promise these technologies hold for their mature states. However, the path to technological maturity holds great uncertainty. As a result, a primary challenge in managing technological emergence is how to structure development activities before the full character of the technology and of its market relevance is established

The challenge of identifying applications in the early stage is driven not only by the limitations in technology performance, but also by the fact that attention focused on a search for market application is attention diverted from immediate development. Therefore, firms have incentives to develop technologies in-house rather than attempt to exploit their possibilities in an elusive market. This is, in a sense, the reverse of the more common criticism leveled at managers that a lack of research focus is attributed to concern with the short term over the long term (Dertouzos, Lester, and Solow, 1989). Early on, the market search process is likely to lead to blind alleys and, because 'negative knowledge' is not highly regarded, the outcomes of such search are not seen as being of high value. As such, in the case of emerging technologies, short-term results are easier to show for research and development activity than for market activity.

New technologies, like new genetic species, undergo periods of evolution and revolution. They involve technological development and the transfer of the technology to new domains of application. Beneath the revolutionary emergence of new technologies is often a process of shifting application domains and rapid subsequent growth in the new domain. By understanding this process, managers can better use it to their advantage.

Figure 1: Speciation in the Development of Technology

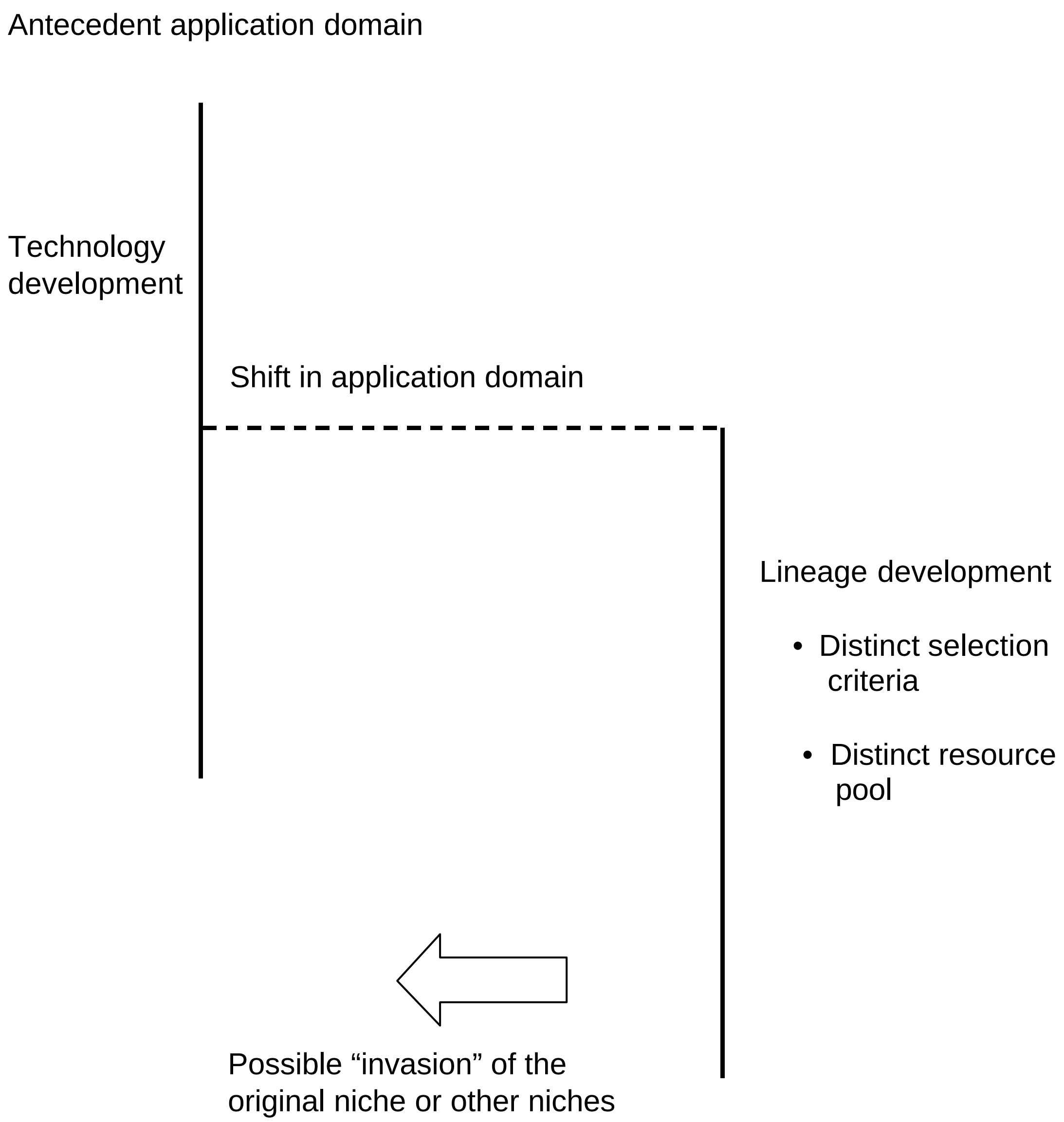


Figure 2: Technological Convergence in CAT Scanning

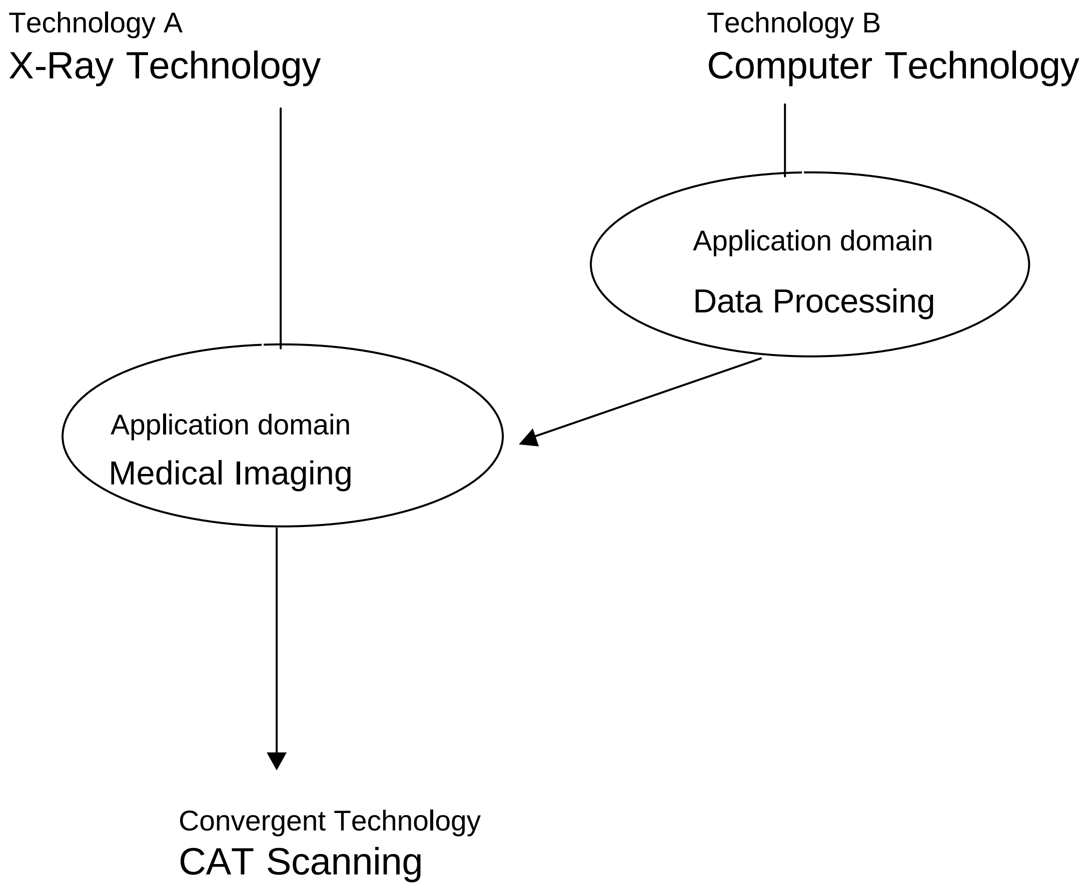
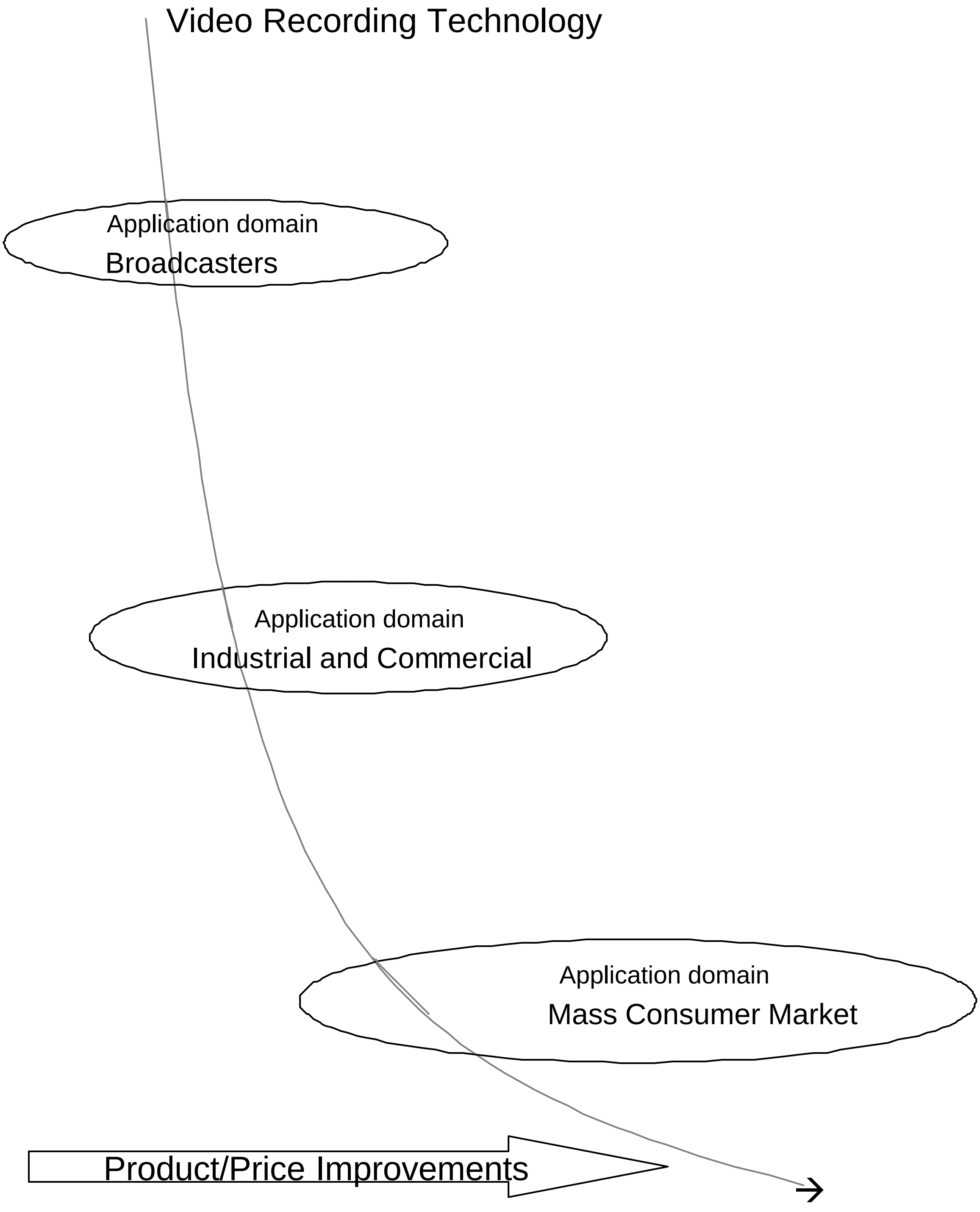


Figure 3: Technology Evolution and Penetration of Application Domains by Video Recorders



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