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# Explaining the attacker's advantage: technological paradigms, organizational dynamics, and the value network [1]

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**Abstract**

Understanding when entrants might have an advantage over an industry's incumbent firms in developing and adopting new technologies is a question which several scholars have explained in terms of technological capabilities or organizational dynamics. This paper proposes that the value network—the context within which a firm competes and solves customers' problems—is an important factor affecting whether incumbent or entrant firms will most successfully innovate. In a study of technology development in the disk drive industry, the authors found that incumbents led the industry in developing and adopting new technologies of every sort identified by earlier scholars —at component and architectural levels; competency-enhancing and competency-destroying; incremental and radical—as long as the technology addressed customers' needs within the value network in which the incumbents competed. Entrants led in developing and adopting technologies which addressed user needs in different, emerging value networks. It is in these innovations, which disrupted established trajectories of technological progress in established markets, that attackers proved to have an advantage. The rate of improvement in product performance which technologists provide may exceed the rate of improvement demanded in established markets. This mismatch between trajectories enables firms entering emerging value networks subsequently to attack the industry's established markets as well.

## 1. Introduction

From the earliest studies of innovation, scholars exploring factors influencing the rate and direction of technological change have sought to distinguish between innovations launching new directions in technology—'radical' change—and those making progress along established paths—often called 'incremental' innovations. In an empirical study of a series of novel processes in petroleum refining, for example, John Enos [19, p. 299] found that half of the economic benefits of new technology came from process improvements introduced after a new technology was commercially established. Continuing this pattern, and borrowing Thomas Kuhn's [26] notion of scientific 'paradigms', Giovanni Dosi [17, p. 147] distinguished between 'normal' modes of technological progress—which propel a product's progress along a defined, established path—and the introduction of new 'technological paradigms'.

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Dosi characterizes a technological paradigm as a 'pattern of solution of selected technological problems, based on selected principles derived from natural sciences and on selected material technologies' (p. 152). New paradigms represent discontinuities in trajectories of progress which were defined within earlier paradigms. They tend to redefine the very meaning of 'progress', and point technologists toward new classes of problems as the targets of ensuing 'normal' technology development.

The question examined by Dosi—how new technologies are selected and retained—is closely related to the question of why firms succeed or fail as beneficiaries of such changes. Chandler [7, p. 79] has shown that, in a variety of industries, leading firms have prospered for extended periods by exploiting a series of incremental technological innovations built upon their established organizational and technical capabilities. When challenged by radically different technologies, however, dominant incumbents frequently lag behind aggressive entrants, sometimes with fatal consequences to their established businesses. Students of innovation have long sought to understand the circumstances that will determine the outcomes under such conditions [13]. Richard Foster [20] argues that there is an 'attacker's advantage' in bringing new technologies to market, which incumbents must act to offset.

To explain that advantage, most studies have focused on two sets of factors: (1) the characteristics or magnitude of the technological change relative to the capabilities of incumbent and entrant firms, and (2) the managerial processes and organizational dynamics through which entrant and incumbent firms respond to such changes. We undertake to expand those explanations by arguing that the success and failure of entrants and incumbents with respect to strategic technological innovations is largely shaped by three interlocking sets of forces. To the two identified above we add a third, which we call the value network—the context within which the firm identifies and responds to customers' needs, procures inputs and reacts to competitors. Building on Christensen's [8] notion of a nested system of product architectures, we argue that the firm's competitive strategy, and particularly its past choices of markets to serve, determines its perceptions of economic value in new technology that in turn shape the rewards it will expect to obtain through innovation.

The first two sections of this paper review the two perspectives on innovation mentioned above, and the third presents the concept of nested systems and the value network. In the fourth section, we develop these ideas further by analyzing the series of technological innovations that have underpinned frequent and substantial changes in the market position of leading firms throughout the history of the disk drive industry. The final section summarizes the paper and describes the sorts of innovations in which incumbents or attackers might be expected to enjoy an advantage.

## 2. Studies focused on the characteristics of a technology in relation to technological capabilities

Upon the emergence of some new technological paradigms, the inability of incumbent practitioners of the prior technology to acquire the capabilities required to compete within the new paradigm is a clear cause of some incumbents' decline. For example, cotton spinners simply lacked the financial, human and technical resources required to compete in synthetic fibers when that radically different technology was brought into the apparel industry by Dupont. Tushman and Anderson [40, p. 439] label such innovations 'competence-destroying', because they destroy the value of the competencies an organization has developed. The relationship between firms' capabilities and different types of technological change has been clarified by Henderson and Clark [24, p. 9]. They note that the core technologies upon which products are generally built are manifest in the components used in a product. Differences between analog and digital circuitry, optical and magnetic recording, and autos powered by electric motors instead of internal combustion engines are reflected in fundamentally different technological concepts embodied in componentry. A product's design architecture defines the patterns through which components interact with each other. For example, both front-wheel-drive cars and rear-wheel-drive cars employ similar component technologies, but the components interact within the two automobile architectures in quite different ways.

Henderson and Clark propose a four-fold classification of innovations, shown in Fig. 1, according to the degree to which innovations reinforce or diminish the value of a firm's expertise in two respects—componentry and architecture. Incremental changes build upon and reinforce the producer's expertise in both product architecture and component technologies. Modular innovation denotes the introduction of new component technology inserted within an essentially unchanged product architecture, as when an antilock braking system is added to automobile design. Architectural innovation alters the ways that components work together. In the fourth category, radical innovation, a new core technology—for example, using optical fiber instead of metal for communications cables—leads to significant changes in both components and architecture.

The use of a given set of core technologies in a given architecture can be said to constitute the technological paradigm for the class of products. The cost and capabilities of products within a given technological paradigm evolve along a certain trajectory of improvement, generally building upon prior innovations. Within an established paradigm, innovation may either alter the particular materials and components employed, or the detailed design thereof. The higher in the design hierarchy these changes occur, the more trenchant the consequences [11, p. 235]. A shift to a new technological regime throughout the system (e.g. from electro-mechanical to electronic cash registers) is more profound than a similar shift in a single component (e.g. from LED to liquid crystal display) because new capabilities are required, and the value of established ones may be diminished or eliminated [40, p. 439]. These concepts suggest an ordering of difficulty of technological change to individual incumbent and entrant firms.

The early stages of the emergence of a new technological paradigm are characterized by diverse technical approaches and fluid designs, but once a dominant design has been established [1, p. 40] incumbent firms strengthen their positions by pursuing normal modes of innovation. Henderson and Clark [24, p. 9] predict that in this process, incumbent firms' abilities to develop and employ new component technologies and refine established product architectures will be strengthened and refined, but that their abilities to create novel product architectures will atrophy. Abernathy and Utterback [1] propose that the focus of incumbents' innovative efforts will shift from product to process innovations. Such evolution to normal modes of innovation ill equips successful incumbent firms to succeed when newer technological paradigms emerge—thus giving certain attackers an advantage.

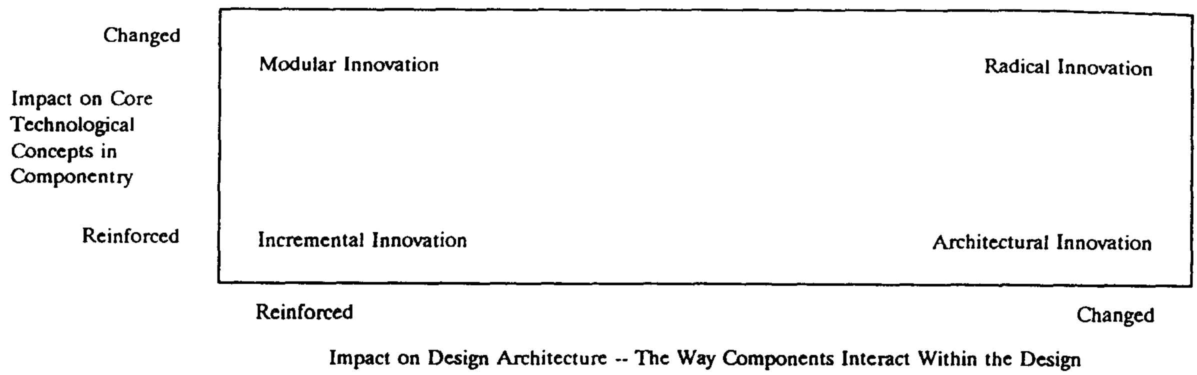


Fig. 1. Types of technological innovation identified by Henderson and Clark [24].

Foster [20] characterized technological change in relation to the trajectory over time of salient attributes (performance, cost, etc.) rather than in terms of technological hierarchies and architectures. He argued that performance, mapped in relation to cumulative engineering effort, follows an S-shaped path as initial exponential improvement encounters diminishing returns. In the terms used above, this improvement path is driven by modular and incremental innovation—generally the result of learning by both producers [25] and users [34]. Foster notes that new paradigms, drawing on different core technologies or employing innovative architectures, may then emerge to challenge established techniques. When viewed in terms of the preferences of established markets, these challenging technologies often display inferior characteristics, and therefore find their earliest application in new or remote market segments where preferences are more closely aligned with the capabilities of the new technology. As normal advances are made in the new technology in its initial market, the new paradigm may return to overtake and surpass established paradigms in the original market as well [9].

The new competencies intrinsically required by new technological paradigms clearly provide part of the explanation for why once-successful firms may fail at such technological transitions. There are, however, innovative phenomena for which a technology-centered perspective cannot account —phenomena in which the experiences of leading incumbent firms facing the same technological transition have been shown to be very different. For example, the advent of radial tires brought opportunity to some tire-makers and disaster to others [15], and when electronics transformed office information equipment, Burroughs prospered, National Cash Register struggled and eventually triumphed, and Addressograph was destroyed [36]. In these and many other examples, some incumbent firms were able to muster the resources and skills to develop competitive capability in the new technology in question, while competing firms were unable to do so.

Attempts to explain these phenomena have elicited a second line of research, in which another set of scholars have used the dynamics and culture of the organization as their root cause explanatory variable. Rather than asking what types of technological changes are most difficult for incumbent firms to manage, these scholars take a given technology and examine the organizational dynamics which may explain why some incumbent firms successfully develop the capabilities required in the new technology, while other, similar organizations seem unable to do so.

## 3. Studies of the organizational dynamics of technological innovation

Clark [12] and Henderson and Clark [24, p. 9] have each postulated that once a new technological paradigm has become established, an organization's attention tends to shift to the sorts of incremental and modular innovations which drive performance and cost improvement within that paradigm. Groups within the engineering organization are chartered to focus on improvements to particular components, and the pattern of interactions amongst these groups tends to mirror the way the components themselves interact within the product's architecture. The organizational structure facilitates improvements at the component level and refinements in the interaction amongst components within the architectural paradigm. Conversely, such organizations can lose their capabilities to develop new architectural technologies because their positions in maturing markets do not require such capabilities to be exercised and honed. For example, RCA and Ampex had access to capabilities that would have made them contenders in VCR manufacture, but strongly held beliefs and inappropriate organizational structures frustrated their strategic commitments to do so [38,22]. Other detailed case studies of paradigmatic industry transitions in photolithographic equipment [23], video recording [37] and medical imaging [29] demonstrate that the structure, culture and dynamics of the incumbent's organization can modulate its engagement with a new technological paradigm.

Schein [39] argues that a work group's success in problem-solving contributes to the consensus about the best approach to problem-solving. Repeated success strengthens such beliefs until it is no longer necessary to explicitly decide on the approach; the decision is made by cultural fiat. The stronger and more sustained the firm's success, the stronger these culturally embedded, 'pre-determined' decisions will become. When key choices are made by culture rather than by explicit decision, an organization's ability to respond to new technologies becomes circumscribed: it becomes difficult for insiders to perceive that such decisions are even being made—and they therefore become very difficult to alter. For example, Henderson [23] found that engineers of photolithographic aligners steeped in one particular architectural technology perspective were not even able to see what was different about a superior competitive machine when they examined it. Also in a study of development projects in a single firm, Maidique and Zirger [27] found that technical teams tended to apply historically successful approaches to new problems until they failed badly. Failure forced reappraisal and development of new approaches which, when successful, became incorporated in the culture.

Another factor affecting an organization's perceptions of the returns obtainable through different sorts of innovations is its economic structure, which becomes shaped and hardened through its competitive experience. This is often reflected in its patterns of integration [21,33]. For example, for more than half a century, National Cash Register (NCR) produced a wide variety of electromechanical cash registers and accounting machines—some models containing as many as 10 000 parts—at its huge Dayton, Ohio, headquarters complex. To assure adequate, cost-effective and timely supply of necessary components, NCR created an extensive vertically integrated manufacturing organization. It took these products to market through a direct sales force, and supported its vast customer base with a highly effective field service organization. When emerging microelectronics technologies rendered NCR's mechanical calculating technologies obsolete, acquiring the requisite electrical engineering expertise was the simplest of the barriers to innovation NCR faced: engineers could be hired. Much more difficult were the tasks of dismantling large and powerful organizational units which had once been keys to NCR's competitive success, and of terminating old patterns of organizational interaction and communication which had once been effective and efficient, and forging new patterns in their stead [36].

These phenomena support the widespread observation that technical progress is largely path dependent—that established firms are more likely to "search in zones that are closely related to their existing skills and technologies" [30]. It is not just that a firm's technological expertise is shaped through its experience. The technological capabilities its engineers are able to perceive, pursue and develop can be limited by its culture and its organizational structure, even though the technological expertise per se may not be beyond the reach of the firm's human and financial resources.

So far, we have identified two broad classes of explanations for why attackers may hold the upper hand at points of paradigmatic technological change. Both relate to capabilities. At the first level, the nature or sheer magnitude of a new technology may make it impossible for incumbents to succeed. At a deeper level, we see that the structure and dynamics of an organization may facilitate or impede a firm's efforts to overcome the technological barriers which scholars using the first perspective cite as the driver of incumbents' fortunes.

Christensen's [8] research into the history of technological innovations in the rigid disk drive industry, however, indicates that just as organizational dynamics can affect an organization's ability to develop the requisite technological capabilities, its position in the marketplace may profoundly affect its organizational dynamics—which in turn drives the sorts of technologies a firm can and cannot develop successfully. This research suggests that successful incumbents' engagements in the marketplace and the influence of those engagements in creating informational asymmetries may determine their relative willingness to make strategic commitments to the development and commercialization of new technology. This mechanism is described conceptually in the following section. The history of the disk drive industry, in which the following framework is grounded, is then summarized.

## 4. Nested hierarchies and value networks

The viewpoint that differences in firms' market positions drive differences in how they assess the economics of alternative technological investments is rooted in the notion that products are systems comprised of components which relate to each other in a designed architecture. This is an established concept in studies of innovation [28,2]. It is important to note, however, that each component can also be viewed as a system, comprising sub-components whose relationships to each other are also defined by a design architecture. Furthermore, the end-product may also be viewed as a component within a system-of-use, relating to other components within an architecture defined by the user. In other words, products which at one level can be viewed as complex architected systems act as components in systems at a higher level. Viewed in these terms, a given system-of-use comprised a hierarchically nested set of constituent systems and components.

This is illustrated in Fig. 2 by the example of a typical management information system (MIS) for a large organization. The architecture of the MIS ties together various 'components'—a mainframe computer; peripheral equipment such as line printers, tape and disk drives; software; a large,

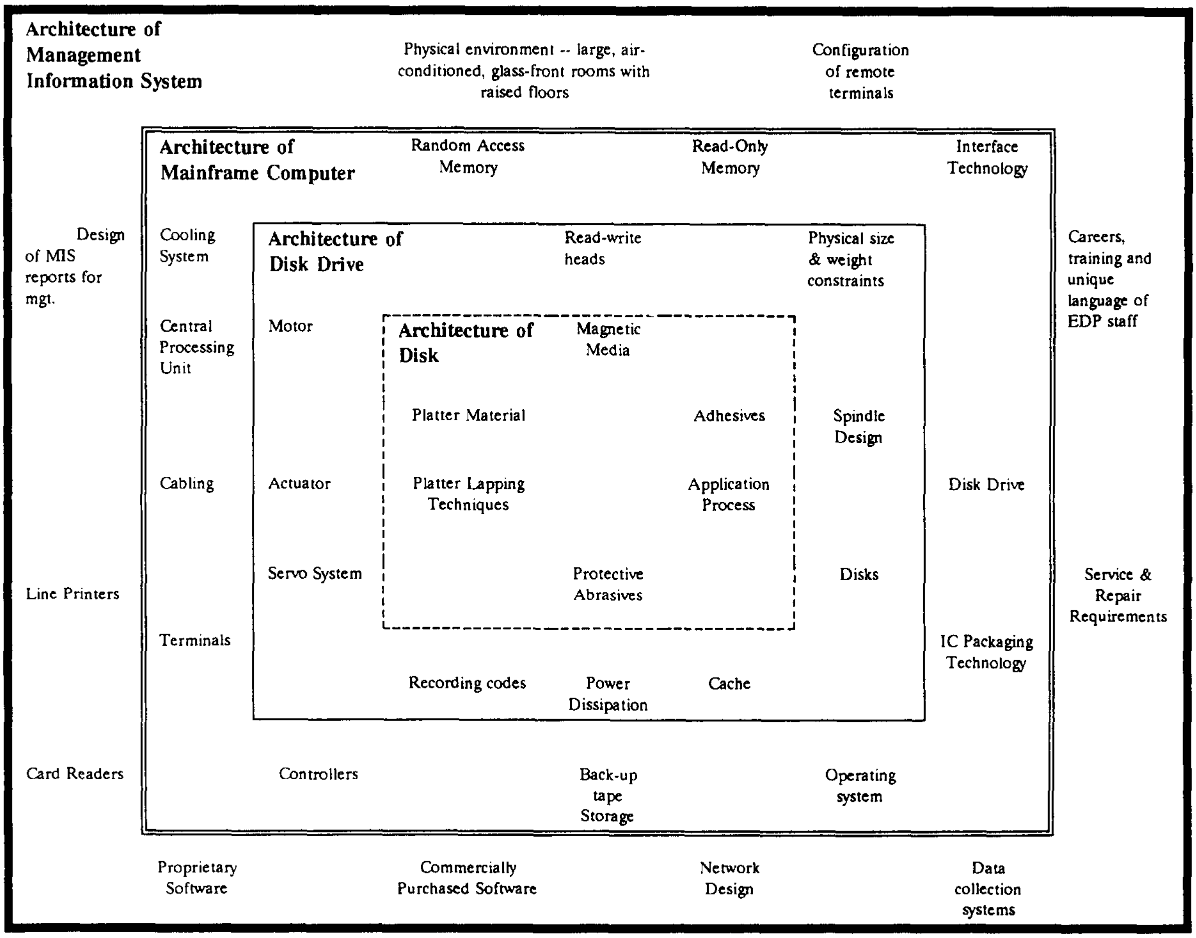


Fig. 2. A nested hierarchy of product architectures.

air-conditioned room with cables running under a raised floor; a staff of data processing professionals whose training and language are unique. At the next level, the mainframe computer is itself an architected system, comprising components such as a central processing unit, multi-chip pack-

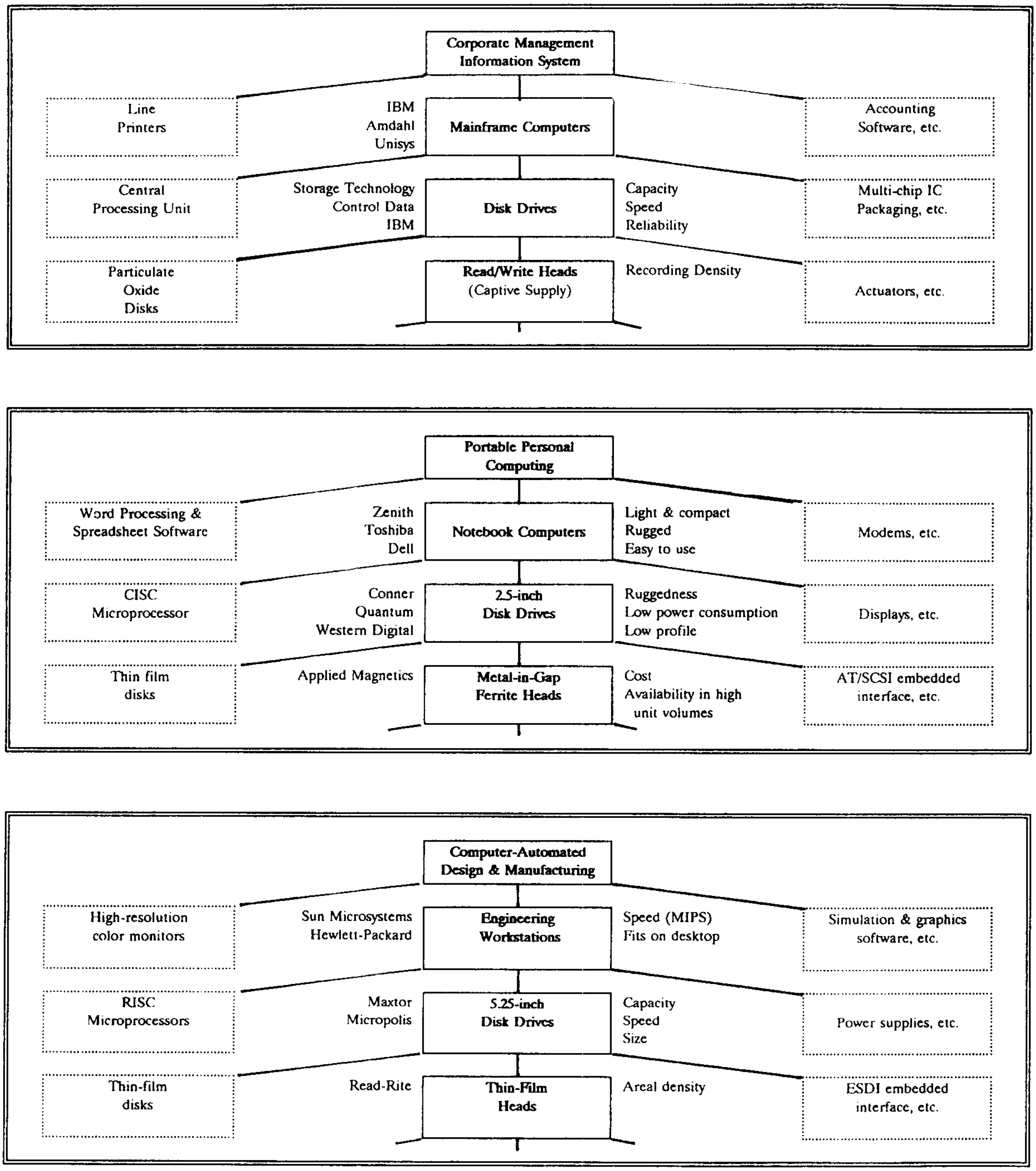


Fig. 3. Examples of three value networks: a corporate MIS system, portable personal computing, and CAD/CAM (dated approximately 1989).

ages and circuit boards, RAM circuits, terminals, controllers, disk drives and other peripherals, and telescoping down still further, the disk drive is a system whose components include a motor, actuator, spindle, disks, heads and controller. In turn, the disk itself can be analyzed as a system composed of an aluminum platter, magnetic material, adhesives, abrasives, lubricants and coatings.

Although the goods and services which constitute the system of use illustrated in Fig. 2 may all be made or provided within a single, extensively integrated corporation such as AT&T or IBM, most of these goods and services are tradeable—especially in more mature markets. This means that, while Fig. 2 is drawn to describe the nested physical architecture of a product system, it also implies the existence of a nested network of producers and markets through which the tradeable architected components at each level are made and sold to integrators at the next higher level in the system. For example, firms which are the architects and assemblers of disk drives—such as Quantum, Conner Peripherals and Maxtor—procure read-write heads from a group of firms which specialize in the manufacture of those heads, disks from a different set of disk manufacturing firms, and spin motors, actuator motors and cache circuitry from different, unique sets of firms. Firms which design and assemble computers at the next higher level may buy their integrated circuits, terminals, disk drives, IC packaging and power supplies from unique sets of firms focused upon manufacturing and supplying those particular products. We call this nested commercial system a value network. Three illustrative value networks for computing applications are shown in Fig. 3. The top network depicts the commercial infrastructure which creates the corporate MIS system-of-use depicted in Fig. 2. The middle network depicts a portable personal computing value network, while the bottom one represents a computer automated design/computer automated manufacturing (CAD/CAM) value network. These depictions are drawn only to convey the concept of how networks are bounded and may differ from each other, and are not meant to represent their complete structure.

The scope and boundaries of a value network are defined by the dominant technological paradigm and the corresponding technological trajectory [17, p. 147] employed at the higher levels of the network. As Dosi suggests, the very definition of value is a function of the dominant technological paradigm in the ultimate system of use in the value network. The metrics by which value is assessed will therefore differ across networks. Specifically, associated with each network is a unique rank-ordering of the importance of various performance attributes, which rank-ordering differs from that employed in other value networks. As illustrated in Fig. 3, this means that parallel value networks, each built around a different technological paradigm and trajectory, may exist within the same broadly defined industry. Note how each value network exhibits a very different rank ordering of important product attributes, as shown at the right of the center column of component boxes. In the top-most value network, performance of disk drives is measured in terms of capacity, speed and reliability. In the portable computing value network depicted beneath it, important performance attributes are ruggedness, power consumption and physical size.

Although many of the constituent architected components in these different systems-of-use carry the same labels (each network involves read-write heads, disk drives, RAM circuits, printers, software, etc.), the nature of components used in the three networks is quite different. Generally, there is a set of competing firms, each of which has its own value chain [32], associated with each box in the network diagram. Often, the firms which supply the products and services used in each network are different, as illustrated by the listings of firms to the left of the center column of component boxes in Fig. 3.

Finally, we note that the juxtaposed depiction of value networks in Fig. 3 represents their structure at a given moment. As will be shown below, the value network is not a static structure—it can be highly dynamic. The rates of performance improvement which manufacturers of the constituent components are able to achieve may exceed the rate of improvement in performance demanded by downstream users within a value network. This enables technologies which may initially have been confined to one value network to migrate into other networks as well. In addition, the rank orderings of performance attributes which define the boundaries of a network may change over time.

The position of a given established producer within a value network—the pathways it is supplying through downstream markets and producers to ultimate users, and its upstream supply network—therefore influences, and even defines to a considerable degree, the nature of the incentives associated with different opportunities for technological innovation which are perceived by the firm's managers. For example, the value placed on certain attributes of an automotive engine will differ depending upon whether the engine is destined for a delivery van, a family sedan, or an Indy 500 racing car. Since value and product performance are defined differently in these instances, we suggest that each of these vehicles is associated with a unique value network.

In another example, throughout the 1970s, Xerox Corporation's product and customer base was dominated by large, high-speed plain paper copiers used in large, central copying centers. It sold products direct to its customers, and supported them through an extensive, capable field service organization. Speed (pages per minute), resolution and cost per copy were among the most important of the performance attributes in that market. Technological improvements which enhanced these aspects of performance were of great value to Xerox, because they helped defend an established, profitable business. In general, few infrastructural investments were required to realize value from such innovations. Products embodying these innovations could be sold and serviced through established capabilities without having to build a different customer base. Often they could be produced in existing facilities.

On the other hand, simplicity, low machine cost, small size and relative ease of self-service are attributes which, though of great potential value in other value networks dominated by alternative technological paradigms, were accorded less worth within Xerox's value network. From an engineering standpoint, they could generally be obtained only by sacrificing along other, more important performance dimensions like speed and per-copy costs, and therefore were not viewed as improvements by Xerox's most important customers. Furthermore, they did not enhance the value of the company's downstream investments in direct sales, service and financing. Commercializing the sorts of component and architectural technologies associated with these attributes would have entailed for Xerox the expense in time and money of creating new market applications for photocopying, and new channels of distribution. In other works, Xerox's position in its value network, skewed its perceptions of return and risk associated with a marginal dollar of investment toward those technologies which addressed downstream needs in its own value network.

The position of a potential entrant to the photocopying value network could bias its perception of risks and rewards in just the opposite fashion. The costs and risks of replicating parallel and competitive capabilities throughout Xerox's large/fast copier value network made development of technologies for small copiers, and the creation of a new small business and office-based copying value network, a much more attractive option for entrants like Canon.

In this example of two photocopying value networks, note that the boundaries of such networks may not coincide with what marketers call 'market segments'. For example, one might well regard small businesses as a different market segment than large corporations, but some of the former will buy high-performance copiers for particular needs, while the latter may buy smaller copiers for distributed use in office areas throughout their facilities. The rank-ordering of preferred attributes (the definition of what constitutes improved product performance) will differ according to the application sought by each type of buyer, thus giving rise to two distinct systems of use, and hence two value networks.

We argue that both the perceived attractiveness of a technological opportunity and the degree of difficulty a producer will encounter in exploiting it are determined, among other factors, by the firm's position in the relevant value network. As firms gain experience within a given network, they are likely to develop their capabilities, structures and cultures to 'fit' that position better by meeting that network's distinctive requirements. Manufacturing volumes, the slope of ramps to volume production, product development cycle times and organizational consensus about who the customer is, and what the customer needs, may differ substantially from one value network to the next. Competitors may therefore become progressively less well suited to compete in other networks. Their abilities and the incentives to create new market applications for their technology—giving rise to new value networks—may atrophy. While successful incumbents will become more cognizant of relevant information pertaining to the networks in which they compete, they will have greater difficulty acquiring and assessing information about others. The longer the firm has been in a given position, and the more successful it has been, the stronger these effects are likely to be. Hence it faces significant barriers to mobility [6]—barriers to those innovations whose intrinsic value is greatest within networks other than those with which it is already engaged.

These considerations provide a third dimension for analyzing technological innovation. In addition to required capabilities inherent in the technology and in the innovating organization, we argue that one should examine the innovation's implications for the relevant value network. The key consideration is whether the performance attributes implicit in the innovation will be valued within networks already served by the innovator, or whether other networks must be addressed or new ones created in order to realize value for the innovation.

In the case of the disk drive industry to date, one observes that most architectural innovations have imparted attributes to products which appealed to different intermediate buyers and end users from the ones which established firms were already serving. In other words, they constituted new technological paradigms, which were initially rejected within established value networks, but enabled the emergence of new ones. Component innovations, on the other hand, have generally addressed the needs of existing customers and downstream users. Established firms have historically excelled at component-level innovations, while new entrants generally succeeded at architectural innovations. We contend that the manifest strength of established firms in component innovation and their weakness in architectural innovation—and the opposite manifest strengths and weaknesses of entrant firms—are consequences not of differences in technological or organizational capabilities between incumbent and entrant firms, but of their positions in the industry's different value networks. Indeed, established disk drive manufacturers were the industry leaders in every sort of innovation—incremental, modular and architectural; competency-enhancing and competency-destroying—which addressed the needs of downstream actors in their value network, and they lagged behind the industry, in developing (or often failed to develop altogether) those technologies which addressed performance needs in other value networks. Details of this history of incumbent and entrant firms' successes and failures in the face of different types technological changes in the disk drive industry are recounted in the following section.

## 5. Technological history of the rigid disk drive industry [1]

Disk drives are magnetic information storage and retrieval devices used with most types of computers and a range of other products, such as high speed digital reprographic devices and medical imaging equipment. The principal components of most disk drives are: the disk, which is a substrate coated with magnetic material format-

[1] The following section draws upon a recent study of the industry by one of the authors (Christensen, 1992, [8]). The database rests on field-based studies of six leading disk drive manufacturers, which historically have accounted for over 70% of industry revenues, and detailed technical specifications of every disk drive model announced in the world between 1975 and 1990. Technical data come from *Disk / Trend Report*, *Electronic Business Magazine*, and manufacturers' product specification sheets.

ted to store information in concentric tracks; the read–write head, which is a tiny electromagnet positioned over the spinning disk which, when energized, orients the polarity of the magnetic material on the disk immediately beneath it; a motor which drives the rotation of the disk; an actuator mechanism which positions the head precisely over the track on which data is to be read or written; electronic circuitry and software, which control the drive's operation and enable it to communicate with the computer. These components work together within a particular product architecture. From the industry's inception there have been significant technological changes both within each component and in the architecture.

Magnetic recording and storage of digital information was pioneered with the earliest commercial computer systems, which used reels of coated mylar tape. IBM introduced the use of rigid rotating disks in 1956 and flexible ('floppy') disks in 1971. The dominant design for what are now called 'hard' drives was provided by the IBM 'Winchester' project, introduced as the Model 3340 in 1973.

While IBM pioneered in disk drive technology and produced drives to meet its own needs, an independent disc drive industry grew to serve two distinct markets. A few firms developed the plug-compatible market [PCM] in the 1960s, selling to IBM customers. Although most of IBM's initial rivals in the computer market were vertically integrated, the emergence in the 1970s of smaller, non-integrated computer makers spawned an OEM market for disk drives as well. By 1976 the output of rigid disk drives was valued at about $1 billion, in which captive production accounted for 50% of unit production, and PCM and OEM segments each accounted for about 25%.

The next dozen years tell a remarkable story of rapid growth, market turbulence, and technology-driven 'creative destruction'. The value of drives produced rose to more than $13 billion by 1989. By the mid-1980s the PCM market had become insignificant, while OEM output grew to represent two-thirds of world production. Of the 17 firms which populated the industry in 1976—all of which were relatively large, diversified corporations—fourteen had failed and exited or had been acquired by 1989. During this period an additional 124 firms entered the industry, and exactly 100 of those also failed. Some 60% of the producers remaining by 1989 had entered the industry as de novo start-ups since 1976. All this took place within the context of the established core technology, i.e. magnetic digital recording. [2] However, components changed, and so did architectures, and therein lies the story.

Successive waves of technological change permitted dramatic improvements in performance at constantly decreasing cost. The impact on the industry of innovations in componentry and architecture was very different. In general, component innovations, such as thin-film heads, embedded servo systems and run length limited [RLL] recording codes, were developed and introduced by well-established incumbents. Component innovations sustained established trajectories of performance improvement within each architecture —an annual increase in capacity per drive which often approached 50%. Several waves of architectural innovation swept through the industry in this period, usually introduced by entrant firms. In contrast to the role played by component innovation, these new architectures often disrupted established trajectories of performance improvement, and redefined the parameters along which performance was assessed. For example, in the architecture used for portable computers, size, weight, ruggedness and power consumption, were all important attributes of performance. None of these attributes were critical in the architectures used in mainframe or minicomputers. These parallel streams of component and architectural innovation were symmetrical in one respect: new components were first introduced in the context of established architectures, while new architectures generally embodied proven componentry.

Both types of innovation were important to the growth and development of the industry in the

[2] An alternative core technology, digital optical recording, was widely perceived as a potential substitute through the 1980s, but by 1992 had made few substantial inroads.

1980s, but it is only in architectural innovation—and a particular class of architectural innovation at that—that attackers proved to have any advantage. Entrants rarely tried to pioneer innovative components, and most that did failed. In contrast, the predominant pattern for new architectures was for the innovation—and subsequent market leadership in the next generation—to belong to an entrant firm.

Until the late 1970s, 14-inch drives were the only rigid drive architectures available, and nearly all were sold to mainframe computer manufacturers. The hard disk capacity provided in the median priced, typically configured mainframe computer system in 1976 was about 170 megabytes (Mb) per computer. The hard disk capacity supplied with the typical mainframe increased at a 15% annual rate over the next 15 years. At the

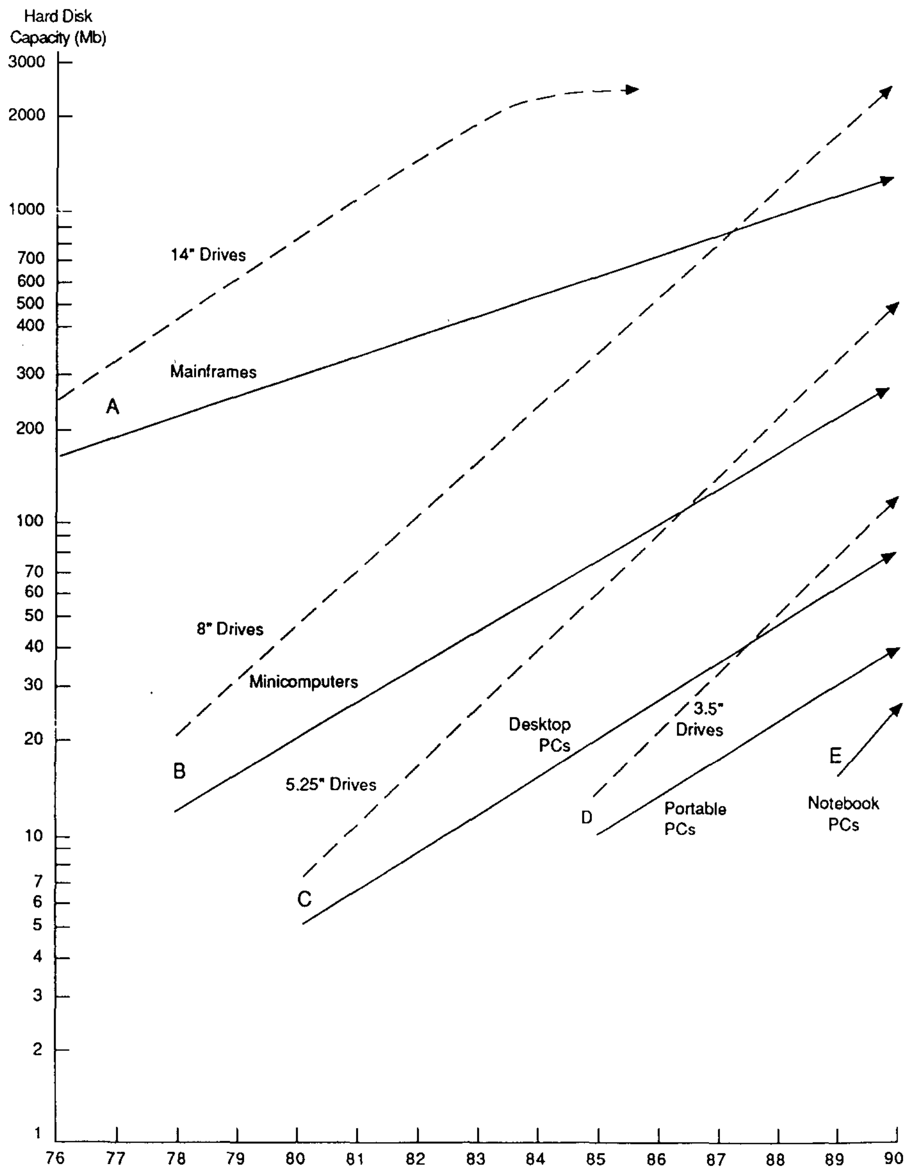


Fig. 4. A comparison of the trajectories of disk capacity demanded per computer, vs. capacity provided in each architecture.

Table 1
A comparison of the average attributes of 8-inch drives introduced in 1981 by established vs. entrant firms

| Attributes | Level of performance | | Annual rate of performance improvement (%) | |
|---|---|---|---|---|
| | Established firms | Entrant firms | Established firms | Entrant firms |
| Capacity (Mb) | 19.2 | 19.1 | 61.2 | 57.4 |
| Areal density (Mb sq in.) | 3.213 | 3.104 | 35.5 | 36.7 |
| Access time (milliseconds) | 46.1 | 51.6 | −8.1 | −9.1 |
| Price per megabyte | $143.03 | $147.73 | −58.8 | −61.9 |

*Source:* Analysis of *Disk / Trend Report* data, from Christensen (1992, [8]).

same time, the capacity of the average 14-inch drives introduced for sale each year increased at a faster 22% rate, reaching beyond the mainframe market to the large scientific and supercomputer markets. This is shown in Fig. 4 [3].

Between 1978 and 1980, several entrant firms —Shugart Associates, Micropolis, Priam and Quantum—developed new architectural families of 8-inch drives with 10, 20, 30 and 40 Mb capacity. These drives were of no interest to mainframe computer manufacturers, who at that time were demanding drives with 300–400 Mb capacity. These 8-inch entrants therefore sold their small, low-capacity drives into a new application—minicomputers. [4] The customers—Wang, DEC, Data General, Prime and Hewlett Packard—were not the firms which manufactured mainframes, and their customers often used software which was substantially different from programs used by mainframe computer users. In other words, 8-inch drives found their way into a different value network, leading to a different system-of-use. Although initially the cost per megabyte of capacity of 8-inch drives was higher than that of 14-inch products, these new customers were willing to pay a premium for other attributes of the 8-inch drive which were important to them—especially its smaller size. This attribute had little value to mainframe users.

Once the use of 8-inch drives became established in minicomputers, the hard disk capacity shipped with the median-priced minicomputer grew about 25% per year—a trajectory driven by the ways in which minicomputers came to be used in their value networks. At the same time, however, the 8-inch drivemakers found they could increase the capacity of their products at over 40% per year—nearly double the rate demanded by their original 'home' minicomputer market. In consequence, by the mid-1980s, 8-inch drive makers were able to provide the capacities required for lower-end mainframe computers, and by that point, unit volumes had grown significantly so that the cost per megabyte of 8-inch drives had declined below that of 14-inch products. Other advantages of 8-inch drives also become apparent. For example, the same percentage mechanical vibration in an 8-inch drive caused the head to vary its absolute position over the disk much less than it would in a 14-inch product. Within a 3–4 year period, therefore, 8-inch drives began to invade an adjacent, established value network, substituting for 14-inch drives in the lower-end mainframe computer market.

When 8-inch products began to penetrate the mainframe computer market, most of the established manufacturers of 14-inch drives began to fail. Two thirds of these manufacturers never introduced an 8-inch model. The one-third of the 14-inch drive manufacturers which did introduce 8-inch drives did so with about a 2-year lag behind the 8-inch entrant manufacturers.

Interviews with industry participants and analysis of product data suggest that destruction of engineering capabilities by the new architecture, as posited by Henderson and Clark [24, p. 9] and Tushman and Anderson [40, p. 439], does not explain the failure of the established producers.

[3] A summary of the data and procedures used to generate Fig. 4 is included in the Appendix.

[4] The minicomputer market was not new in 1978, but it was a new application for Winchester-technology disk drives.

Table 1, for example, shows that the population of 8-inch models introduced by the established firms in 1981 possessed performance attributes which, on average, were nearly identical to the average of those introduced that year by the entrant firms. In addition, the rates of improvement (measured between 1979 and 1983) in those attributes were stunningly similar between established and entrant firms. [5] This evidence supports the view that the 14-inch drive manufacturers were fully capable of producing the new architecture; their failure resulted from delay in making the necessary strategic commitments. By 1981 the entrants had already created barriers to entry around their new value network, and were surmounting the barriers which had protected the old one.

What explains the incumbents' strategic lag? Interviews with marketing and engineering executives close to these companies suggest that the established 14-inch drive manufacturers were held captive by customers within their value network. Mainframe computer manufacturers did not need an 8-inch drive. In fact, they explicitly did not want it—wanting instead drives with increased capacity at a lower cost per megabyte. The 14-inch drive manufacturers were listening and responding to their established customers, and their customers—in a way that was not apparent either to the disk drive manufacturers or their customers—were pulling them along a trajectory (22% capacity growth in a 14-inch platform) which would ultimately prove fatal.

This finding is similar to the phenomena observed by Bower (1970, [3], p. 254), who saw that explicit customer demands have tremendous power as a source of impetus in the resource allocation process. 'When the discrepancy (the problem to be solved by a proposed investment) was defined in terms of cost and quality, the projects languished. In all four cases, the definition process moved toward completion when capacity to meet sales was perceived to be inadequate .... In short, pressure from the market reduces both the probability and the cost of being wrong'. Although Bower's specific reference is to manufacturing capacity, we believe that we observed the same fundamental phenomenon which he saw: the power of the known needs of known customers in marshalling and directing the investments of a firm.

Figure 4 also maps the disparate trajectories of performance improvement demanded in the subsequent, sequentially-emerging computer product categories which defined market segments for the disk drive suppliers, versus the performance made available within each successive architecture by changes in component technology and refinements in system design. Again, the solid lines emanating from points A, B, C, D and E measure the disk drive capacity provided with the median-priced computer in each category, while the dotted lines emanating from the same points measure the average capacity of all disk drives introduced for sale in each architecture for each year. Brief accounts of these transitions are presented below.

### *5.1. The advent of 5.25-inch drives*

In 1980, Seagate Technology introduced the next architectural generation, 5.25-inch drives, as shown in Fig. 4. Their capacities of 5 and 10 Mb were of no interest to minicomputer manufacturers, who were demanding drives of 40 and 60 Mb from their suppliers. Seagate and other firms which entered with 5.25-inch drives in the 1980–1983 period (such as Miniscribe, Computer Memories and International Memories) had to pioneer new applications for their products—primarily desktop personal computers. Once the use of hard drives was established in the desktop PC application, the disk capacity shipped with the

[5] This result is very different from that observed by Henderson (1988, [23]), where the new-architecture aligners produced by the established manufacturers were inferior on a performance basis to those produced by the entrant firms. One possible reason for these different results is that the successful entrants in the photolithographic aligner industry which Henderson studied brought with them a well-developed body of technological knowledge and experience which had been developed and refined in other markets. In the case studied here, none of the entrants brought such well-developed knowledge with them. Most, in fact, were de novo start-ups comprised of managers and engineers who had defected from established drive manufacturing firms.

median-priced desktop PC increased about 25% per year. Again, the technology improved at nearly twice the rate demanded in the new market—the capacity of new 5.25-inch drives increased about 50% per year between 1980 and 1990. As in the 8- for 14-inch substitution, the first firms to produce 5.25-inch drives were entrants; on average, the established firms lagged the entrants by 2 years. By 1985, 50% of the firms which had produced 8-inch drives had introduced 5.25-inch models. The other 50% never made the transition. Growth in 5.25-inch drives occurred in two waves. The first was in the establishment of a new application for rigid disk drives—desktop computing, where product attributes which had been relatively unimportant in established applications were highly valued. The second wave was in substituting for the use of larger drives in established minicomputer and mainframe computer markets, as the rapidly increasing capacity of 5.25-inch drives intersected the more slowly-growing trajectories of capacity demanded in these markets. Of the four leading 8-inch drivemakers listed above, only Micropolis survived to become a significant manufacturer of 5.25-inch drives, and that was accomplished only with Herculean managerial effort.

### *5.2. The pattern is repeated: the emergence of the 3.5-inch drive*

The 3.5-inch drive was first developed in 1984 by Rodime, a Scottish entrant. Sales of this architecture were not significant, however, until Conner Peripherals, a Seagate/Miniscribe spin-off, started shipping product in 1987. Conner had developed a small, lightweight drive architecture, which was much more rugged than its 5.25-inch ancestors, by handling functions electronically which had previously been managed with mechanical parts, and by using microcode to replace functions which had previously been addressed electronically. Nearly all of Conner's record first-year revenues of $113 million came from Compaq Computer, which had funded most of Conner's start-up with a $30 million investment. The Conner drives were used primarily in a new application—portable and laptop machines, in addition to 'small footprint' desktop models—where customers were willing to accept lower capacities and higher costs per megabyte in order to get the lighter weight, greater ruggedness and lower power consumption which 3.5-inch drives offered.

Seagate engineers were not oblivious to the coming of the 3.5-inch architecture. [6] By early 1985, less than 1 year after the first 3.5-inch drive was introduced by Rodime and 2 years before Conner Peripherals started shipping its product, Seagate personnel had shown working 3.5-inch prototype drives to customers for evaluation. The initiative for the new drives came from Seagate's engineering organization. Opposition to the program came primarily from the marketing organization and Seagate's executive team, on the grounds that the market wanted higher capacity drives at a lower cost per megabyte and that 3.5-inch drives could never be built at a lower cost per megabyte than 5.25-inch drives.

The customers to whom the Seagate 3.5-inch drives were shown were firms within the value network already served by Seagate: they were manufacturers of full-sized desktop computer systems. Not surprisingly, they showed little interest in the smaller drive. They were looking for capacities of 40 and 60 megabytes for their next generation machines, while the 3.5-inch architecture could only provide 20 Mb—and at higher costs. [7]

In response to these lukewarm reviews from customers, Seagate's program manager lowered his 3.5-inch sales estimates, and the firm's executives canceled the 3.5-inch program. Their reasoning was that the markets for 5.25-inch products were larger, and that the sales generated by spending the engineering effort on new 5.25-inch

[6] This information was provided by former employees of Seagate Technology.

[7] This finding is consistent with what Robert Burgelman has observed. He noted that one of the greatest difficulties encountered by corporate entrepreneurs was finding the right 'beta test sites', where products could be interactively developed and refined with customers. Generally, the entrée to the customer was provided to the new venture by the salesman who sold the firm's established product lines. This helped the firm develop new products for established markets, but did not help it identify new applications for its new technology. [5, pp. 76–80].

products would generate greater revenues for the company than would efforts targeted at new 3.5-inch products.

In retrospect, it appears that Seagate executives read the market—at least their own market—very accurately. Their customers were manufacturers and value-added resellers of relatively large-footprint desktop personal computers such as the IBM XT and AT. With established applications and product architectures of their own, these customers saw no commercial value in the reduced size, weight and power consumption, and the improved ruggedness of 3.5-inch products.

Seagate finally began shipping 3.5-inch drives in early 1988—the same year in which the performance trajectory of 3.5-inch drives shown in Fig. 4 intersected the trajectory of capacity demanded in desktop computers. By that time nearly $750 million in 3.5-inch products had been shipped cumulatively in the industry. Interestingly, according to industry observers, as of 1991 almost none of Seagate's 3.5-inch products had been sold to manufacturers of portable/laptop/notebook computers. Seagate's primary customers still were desktop computer manufacturers, and many of its 3.5-inch drives were shipped with frames which permitted them to be mounted in computers which had been designed to accommodate 5.25-inch drives.

The fear of cannibalizing sales of existing products is often cited as a reason why established firms delay the introduction of new technologies. As the Seagate–Conner experience illustrates, however, if new technologies are initially deployed in new market applications, the introduction of new technology may not be an inherently cannibalistic process. When established firms wait until a new technology has become commercially mature in its new applications, however, and launch their own version of the technology only in response to an attack on their home markets, the fear of cannibalization can become a self-fulfilling prophecy.

Although the preceding discussion focused on Seagate's response to the development of the 3.5-inch drive architecture, its behavior was not atypical; by 1988, only 35% of the drive manufacturers which had established themselves making 5.25-inch products for the desktop PC market had introduced 3.5-inch drives. As in earlier product architecture transitions, the barrier to development of a competitive 3.5-inch product does not appear to have been engineering-based. As illustrated in table 1 above for the 14- to 8-inch transition, the new-architecture drives introduced by the incumbent, established firms in the 8- to 5.25 inch and 5.25- to 3.5-inch transitions were fully performance-competitive with the entrants' drives. Rather, it seems that the 5.25-inch drive manufacturers were misled by their customers, who themselves seemed as oblivious as Seagate to the potential benefits and possibilities of the new architecture. These only became apparent in the desktop market after the 3.5-inch products had been proven in a new application.

Table 2 shows that in the 1984–1989 period, when the 3.5-inch form factor was becoming firmly established in portable and laptop applications, Seagate had in no way lost its ability to innovate. It was highly responsive to its own customers. The capacity of its drives increased at about 30% per year—a perfect match with the pace of market demand and a testament to the firm's focus on the desktop computing market, rather than the markets above or below it. Seagate also introduced new models of 5.25-inch drives at an accel-

Table 2
Indicators of the pace of Seagate engineering activity within the 525-inch architecture, 1984–1987

| | No. of new models announced | No. of new models as % of No. of models offered in prior year | % of new models equipped with thin-film disks | SCSI interface introduction | RLL codes introduction |
|---|---|---|---|---|---|
| 1984 | 3 | 50 | 0 | | |
| 1985 | 4 | 57 | 25 | X | |
| 1986 | 7 | 78 | 71 | | X |
| 1987 | 15 | 115 | 100 | | |

*Source*: Analysis of *Disk / Trend Report* data, from Christensen (1992, [8]).

erated rate during this period—models which employed many of the most advanced component technologies such as thin film disks, voice-coil actuators [8], RLL codes and embedded SCSI interfaces.

Seagate's experience was an archetype of the histories of many of the disk drive industry's leading firms. Its entry strategy employed an innovative architectural design with standard, commercially available components. Its appeal was in an emerging value network—desktop computing. Once it was established in that value network, Seagate's technological attention shifted toward innovations in component technology, as the work of Henderson and Clark [24, p. 9] suggests that it would. This is because improvements in component technology and refinements in system design —that is, modular and incremental innovations (see Fig. 1)—were the primary drivers of performance improvement within its value network. They were the drivers behind each of the dotted-line technological trajectories plotted in Fig. 4, and were the means by which firms attentive to customers' demands for improved performance addressed those needs. It is not surprising, therefore, that throughout the history of the industry, the leading innovators in the development and use of component technology were the industry's established firms, as we describe in the following section.

### 5.3. *Leadership in component technology development by incumbent firms*

As in other data processing sub-systems, disk drive technology advanced rapidly through the 1970s and 1980s, increasing drive capacity and performance, and reducing size and cost, at rates that would have been astonishing in almost any other industry. One of the primary technical trends behind increasing capacity was the relentless increase in the recording density achieved—a trend which was largely driven by improvements in component technology. The earliest drives could hold only a few kilobytes of data per square inch of drive surface; by 1967 this had risen to 50 kilobytes; within 6 years, the first Winchester design held 1.7 megabytes per square inch; by 1981 the IBM 3380 boasted a density greater than 12 Mb per square inch. In 1990, densities of 50 Mb per square inch were common, marking a 3000-fold increase in 35 years. As in other applications of magnetic technology (e.g., video recording) greater density led to smaller, less expensive devices. Costs were also driven down by a constellation of incremental improvements in components and materials, by manufacturing experience, and by huge scale increases in demand.

In the 1970s, some manufacturers sensed that they were approaching the limits of recording density obtainable from conventional particulate iron oxide disk coating technology, and began studying the use of thin film metal coatings to sustain improvements in recording density. While the use of thin-film coatings was then highly developed in the integrated circuit industry, its application to magnetic disks presented substantial challenges because of the disks' greater surface area and the need to make the relatively soft metal coatings as durable as the much harder iron oxide coatings. Industry participants interviewed by Christensen estimate that development of thin film disk technology required approximately 8 years, and that the pioneers of thin film disk technology—IBM, Control Data, Digital Equipment, Storage Technology and Ampex—each spent over $50 million in that effort. Between 1984 and 1986, a total of 34 firms—roughly two to three times the number of producers active in 1984—introduced drives with thin-film coatings. The overwhelming majority of these were established industry incumbents. Nearly all new entrants which used thin film disks in their initial products failed to establish themselves in the industry.

The standard recording head design employed small coils of wire wound around gapped ferrite (iron oxide) cores. A primary factor limiting recording density was the size and precision of the gaps forming electromagnets on the head. Ferrite heads had to be ground mechanically to achieve desired tolerances, and by 1981 many believed that the limits of precision would soon

[8] These were not new to the market, but were new to Seagate.

be reached. As early as 1965, researchers had posited that smaller and more precise electromagnets could be produced by sputtering thin films of metal on the recording head and then using photolithography to etch the electromagnets, thus enabling more precise orientation of smaller magnetic domains on the disk surface. Although thin film photolithography was well-established in the semiconductor industry, its application to recording heads proved extraordinarily difficult. Read-write heads required much thicker films than did integrated circuits, and the surfaces to be coated were often at different levels, and could be inclined.

Burroughs in 1976, IBM in 1979, and other large, integrated, established firms were the first to incorporate thin-film heads successfully in disk drives. In the 1982-1986 period, when over 60 firms entered the rigid disk drive industry, only four of them (all commercial failures) attempted to do so using thin-film heads as a source of performance advantage in their initial products. All other entrant firms—even aggressively performance-oriented firms such as Maxtor and Conner Peripherals—found it preferable to learn their way with ferrite heads before tackling thin-film technology. As was the case with thin-film disks, the introduction of thin-film heads was a resource-intensive challenge which only established firms could handle. IBM spent over $100 million developing its thin film heads, and competing pioneers Control Data and Digital Equipment spent amounts of a similar order of magnitude. The rate of adoption was slow; a decade after Burroughs first established the technology's commercial feasibility, only 15 producers employed thin-film heads. Thin-film technology was costly and difficult to master.

The established firms were the leading innovators not just in undertakings to develop risky, complex and expensive component technologies such as thin film heads and disks, but in literally every component-level innovation. Even in relatively simple but important innovations—such as RLL recording codes (which took the industry from double- to triple-density disks), embedded servo systems, zone-specific recording densities and higher RPM motors—established firms were the successful pioneers, while entrant firms were the technology followers.

### *5.4. Leadership in architectural technology innovation*

As noted above, Henderson and Clark found that in the photolithographic aligner industry attackers consistently had the advantage in architectural innovation. In contrast to their unambiguous findings, and to the clear pattern of component technology leadership by established firms described above, entrant firms led the disk drive industry in the introduction of three of the five new architectural technologies, while established firms led in the other two. The industry's first architectural technology transition was the

Table 3
Number of entrant vs. established firms offering new product architectures

| | | Number of firms offering one or more models of the new product architecture | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | First year | | Second year | | Third year | | Fourth year | |
| | | No. of firms | Percent | No. of firms | Percent | No. of firms | Percent | No. of firms | Percent |
| 8-inch drives (1978) | Entrants | 1 | 100 | 4 | 67 | 6 | 55 | 8 | 62 |
| | Established | 0 | | 2 | 33 | 5 | 45 | 5 | 38 |
| | Total | 1 | 100 | 6 | 100 | 11 | 100 | 13 | 100 |
| 5.25-inch drives (1980) | Entrants | 1 | 50 | 8 | 80 | 8 | 50 | 13 | 54 |
| | Established | 1 | 50 | 2 | 20 | 8 | 50 | 11 | 46 |
| | Total | 2 | 100 | 10 | 100 | 16 | 100 | 24 | 100 |
| 3.5-inch drives (1983) | Entrants | 1 | 100 | 2 | 67 | 3 | 75 | 4 | 50 |
| | Established | 0 | | 1 | 33 | 1 | 25 | 4 | 50 |
| | Total | 1 | 100 | 3 | 100 | 4 | 100 | 8 | 100 |

*Source:* Author's analysis of *Disk / Trend Report* data, reported in Christensen (1992, [8]).

switch from removable disk packs to the fixed-disk Winchester architecture between 1973 and 1980. The subsequent four architectural transitions involved the reduction in disk diameter from 14 to 8, 5.25, 3.5 and 2.5 inches between 1978 and 1990. These four new architectures reduced size by 'shrinking' individual components, by reducing part count, and by re-arranging the way the components interacted with each other in the system design. For example, in the 8-inch drive, a 110 volt AC motor was typically positioned in the corner of the system, and drove the disks by pulleys and a belt. In reducing the size to 5.25-inches, the motor was changed to a 12 volt DC 'pancake' design and positioned beneath the spindle.

Table 3 shows that the 8-, 5.25- and 3.5-inch generations embodied the architectural technologies which entrant firms pioneered. For example, in 1978 an entrant offered the industry's first 8-inch drive. Within 2 years, six firms were offering 8-inch drives; four of them were entrants. At the end of the second year of the 5.25-inch generation, eight of the ten producers were entrants. A similar pattern characterized the early population of firms offering 3.5-inch drives. Note that these transitions correspond to the movements from point A to points B, C and D in Fig. 4.

There were two significant architectural innovations in the industry's history in which the incumbent firms, and not entrants, were the leading innovators. The first was the substitution of sealed, fixed-disk Winchester-technology 14-inch drives for removable disk-pack drives, which was the first architectural transition after the emergence of a group of independent disk drive manu-

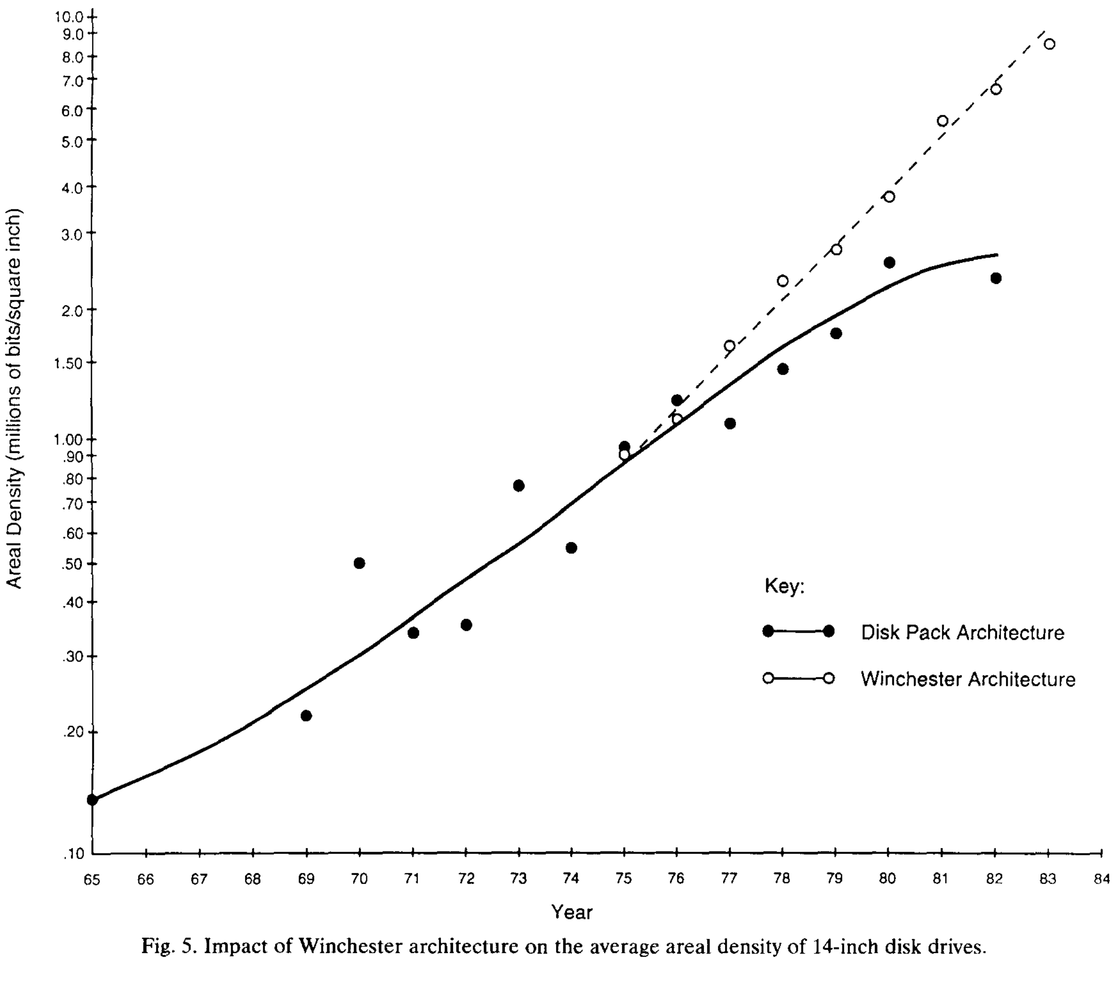


Fig. 5. Impact of Winchester architecture on the average areal density of 14-inch disk drives.

facturers in the 1960s. The first Winchester model was introduced by IBM, an established manufacturer of disk-pack drives, in 1973. The second and third firms to introduce a Winchester-architecture drive were Control Data and Microdata—also established firms—in 1975. Seven of the first eight firms to introduce 14-inch Winchester drives were established manufacturers of the prior architectural generation of disk-pack drives. Entrant firms were the followers in this transition. An indication of why the incumbent leaders successfully maneuvered across this architectural transition is found in Fig. 5, which plots the average recording density for all disk-pack models introduced in the industry each year (the solid black points), and the average density of Winchester-technology drives introduced in the same years (the open circles). Note the contrast between this architectural change and the transitions to 8-, 5.25- and 3.5-inch drives charted in Fig. 4. Whereas those architectural approaches disrupted established trajectories of performance improvement, the 14-inch Winchester architecture sustained the trajectory of improvement which had been established within the disk pack architecture. As a consequence, this new architecture was valued within the same value network as had used the prior-architecture products—in this case, mainframe computers. By listening to their customers, the leading incumbent manufacturers of disk pack drives seem to have been led, rather than misled, in the development of the 14-inch Winchester technology.

Sixteen years later, in 1989, Prairietek Corporation, a spin-off of Miniscribe, introduced a 2.5-inch drive as its first product. Its customers were almost exclusively manufacturers of notebook computers. Conner Peripherals, the leader of the 3.5-inch generation, introduced its own 2.5-inch product in 1990, however, and by 1991 it controlled over 85% of the worldwide 2.5-inch market. [9] Did Conner somehow manage its product development and deployment process differently from its predecessors to help it stay atop this industry?

[9] Miniscribe was in bankruptcy proceedings in 1989, and Prairietek declared bankruptcy and ceased operations in 1991.

Again, our interpretation is that it did not. In the three preceding architectural transitions, the new, smaller drives were sold to new customers in new applications—in new value networks. In the transition from 3.5-inch drives sold to laptop computer applications to 2.5-inch drives sold in notebook computers, however, the leading customers were largely the same firms. Toshiba, Zenith, Compaq and Sharp, which were the leading laptop computer manufacturers, became the leading notebook PC makers. Their customers, and the spreadsheet and word processing software they used, were the same. In other words, the system of use was the same; hence, and most importantly, the way disk drive performance was assessed—capacity per cubic inch and per ounce, ruggedness, power consumption, etc.—was unchanged. Whereas attentiveness to established customers led the leaders of earlier disk drive generations to attend belatedly to the deployment of new architectures, in this instance attentiveness to its established customers led Conner through a very smooth transition into 2.5-inch drives. Although the 2.5-inch drive represents a new engineering architecture, it was developed and deployed within the same value network as the 3.5-inch product, and Conner seems to have negotiated this development with competitive agility [10].

[10] Burgelman's account (1991, [4]) of Intel Corporation's development of Reduced Instruction Set Computing (RISC) microprocessors can be understood even more clearly in the context of the value network framework. According to those who Burgelman interviewed, chips made with the RISC architecture generally addressed the needs of "a customer base (which was) different than the companies who purchased (Intel's) 486 chips ... a lot of customers who before did not even talk to Intel." (p. 247). RISC's champion within the Intel organization, Les Kohn, had tried but failed to convince management to back the RISC technology. He had failed because "RISC was not an existing business and people were not convinced a market was there" (p. 246). Finally, Kohn decided to present the RISC chip as a coprocessor which enhanced the performance of Intel's 486 chip—as one which addressed the needs of the customers within Intel's primary value network, which was personal computing. Positioned as such, the RISC project got funding. Once it was funded, Kohn was able to begin selling the RISC chip to customers outside the 486 personal computing value network, to the customers who valued RISC's attributes most highly—engineering workstation manufacturers.

It does not seem from this evidence that the established disk drive manufacturers were constrained to prosper only within the value networks in which they were born. Firms such as Maxtor, Micropolis, Quantum and Conner proved themselves to have remarkable upward mobility, in terms of Fig. 4. Conner, for example, has moved from portable computing upwards to the desktop business computing market and the engineering workstation market. Micropolis and Maxtor are now the major suppliers of 5.25-inch drives to the mainframe market—even the large arrays employed by supercomputer manufacturers such as Thinking Machines. In other words, upward visibility and understanding towards other known, existing value networks seems not to have presented an insurmountable barrier to mobility. The differing slopes of the trajectories of technology supplied vs. performance demanded seem to be what facilitated the mobility of technologies and the firms practising them across the boundaries of value networks. Firms which led in the introduction of the 5.25-inch drive in desktop computing applications, for example, have been able to ride that technological paradigm across network boundaries into minicomputer, and now mainframe and supercomputer value networks.

In observing these firms' attacks across the boundaries of value networks, it is important to note that switching to new architectural paradigms per se was not the difficulty the incumbent firms faced which gave the attackers their advantage. When the new paradigms invaded the earlier established value networks, the leading incumbent firms at each transition quite rapidly introduced architecturally novel products which were fully performance competitive with those of the attackers. To repeat, as long as a technological innovation was valued within the incumbents' value network, they seemed perfectly competent and competitive in developing and introducing that technology—whether it was incremental, modular or architectural, competency enhancing or competency destroying, in character.

The problem established firms seem to have been unable to confront successfully is that of downward vision and mobility, in terms of Fig. 4. Finding new applications for new architectures, and aggressively entering latent value networks, which necessarily are not well understood, seem to be capabilities which each of these firms exhibited once, upon entry, and then seems to have lost.

One final point about mobility within and across value networks merits mention. It appears, from the history of disk drive manufacturers and their suppliers, that the farther removed a firm is from the ultimate system-of-use which defines the dominant performance paradigm in a value network, the greater is its mobility across networks. For example, the firms which manufacture the aluminum platters on which magnetic material is deposited seem to have been able to sell platters to disk manufacturers regardless of the ultimate value network in which the disks were destined to be used. The firms which coated platters with magnetic material, and sold those completed disks to disk drive manufacturers, seemed more aligned than were their platter suppliers to specific value networks—but not nearly as captive within specific networks as the disk drive companies themselves seem to have been.

## 6. Conclusions and propositions

The history summarized in Fig. 4 seems to be a relatively clear empirical example of the emergence of a sequence of what Dosi [17, p. 147] calls 'technological paradigms' and their associated new trajectories. At points B, C and D, product performance came to be defined differently, new trajectories were established, and engineers began to focus, within each new paradigm, on new sets of problems. For example, power consumption, ruggedness and weight simply were not on the development agendas of any practitioners of the 14- and 8-inch generations, whereas they became the dominating issues on the technology agendas of every firm competing within the 3.5- and 2.5-inch generations. Interpreting Dosi further, in the light of Henderson and Clark's [24, p. 9] framework, it would appear that in the history of disk drive technology, innovations on the left-hand side of the Fig. 1 matrix—incremental and modular technological changes—would constitute normal technological progress. Note that we would include discontinuous, competency-destroying modular innovations in component technology as elements of this normal progress—because they sustained, rather than redefined, the established technological trajectory. Some innovations on the right-hand side of the Henderson–Clark matrix would also fall within the 'normal' rubric—such as the 14- and 2.5-inch Winchester architectures. Yet in the instances of 8-, 5.25- and 3.5-inch generations, it seems that new architectural technologies alone were sufficient to herald the emergence of a new paradigm.

Each of these new technological paradigms emerged within a new value network—mainframes, minicomputers, desktop PCs and portable computers. The forces which defined the trajectories of performance demanded in each value network tended to be at the broader, higher system-of-use levels in each network—the software used, the data processed, the training level of operators, the locations of use, etc.

Dosi theorized that within an established technological paradigm, the pattern of technological change would become endogenous to the 'normal' economic mechanism. He anticipated, in other words, that there would be a strong fit between customers' demands with respect to the rate and direction of improvement in cost and performance, and producers' abilities to meet those needs. That harmony, governed by market forces, is the fundamental driver of innovation within an established paradigm, according to Dosi's theory. Figure 4 suggests, however, that there seem to be two distinct, independent trajectories at work. The first is a trajectory of product performance improvement demanded in the ultimate system-of-use in each value network—the solid lines in Fig. 4. The second is a trajectory of performance improvement which the technology is able to supply—represented by the dotted lines in Fig. 4. There seems to be no reason why the slopes of these trajectories should be identical: the first is driven by factors at higher system-of-use levels in the value network, while the latter is driven by the inventiveness and ingenuity of scientists and engineers, and the willingness of marketers and managers to make product commitments targeted at existing markets above them.

Likewise, Dosi theorized that the creation of new technological paradigms were events which occurred largely exogenously to the economic system—that institutional forces were largely responsible for their emergence. Our research suggests that although the factors governing selection of a new paradigm can be seen as 'outside' the 'normal' market mechanisms as perceived by established producers, they are nevertheless essentially economic in character.

Accordingly, in addition to classifying innovations according to their technological character and magnitude, and according to the requirements they place on an organization's culture and structure, as prior scholars have noted, we propose that innovations be categorized also by the degree of mobility they enable or require across value networks. If no mobility or change in strategic direction is required—if the innovation is valuable within a firm's established value network—the character of the innovation can be considered straightforward, regardless of its intrinsic technological difficulty or riskiness. If realization of inherent value requires the establishment of new systems of use—new value networks—the innovation is surely complex even if it is technologically simple. This is because such innovation requires far more than technological activity. It involves creating markets, and focusing on commercial opportunities which are small and poorly defined, rather than large and clear.

In summary, then, we argue that the context in which a firm competes has a profound influence on its ability to marshall and focus the resources and capabilities required to overcome the technological and organizational hurdles other scholars have identified as impediments to firms' ability to innovate. An important part of this context is the value network in which the firm competes. As we stated earlier, the boundaries of a value network are determined by a unique definition of product performance—by a rank-ordering of the importance of various performance attributes which differs from that employed in other systems-of-use in a broadly defined industry. In other words, the importance of such product attributes as size, weight, power consumption, heat generation, speed, ruggedness and ease of repair will be ranked very differently by users, and hence in the markets comprised by different networks.

This implies that a key determinant of the probability of commercial success of an innovative effort is the degree to which it addresses the well-understood needs of known actors within the value network in which an organization is positioned. Incumbent firms are likely to lead their industries in innovations of all sorts—in architecture and components—which address needs within their value network, regardless of their intrinsic technological character or difficulty. These are straightforward innovations in that their value and application are clear. Conversely, incumbent firms are likely to lag in the development of technologies—even those where the technology involved is intrinsically simple—which address customers' needs as defined in emerging value networks. Such innovative processes are complex because their value and application are uncertain, according to the criteria used by incumbent firms.

Extending Dosi's [17, p. 147] notion of a 'technological trajectory' associated with each technological paradigm, we also suggest that two distinct trajectories can be identified—one which defines the performance demanded over time within a given value network, and one which traces the performance which technologists are able to provide within a given technological paradigm. In some cases, as in the disk drive industry, the trajectory of performance improvement which a technology is able to provide may have a distinctly different slope from the trajectory of performance improvement which is demanded in the system-of-use by downstream customers within any given value network. When the slopes of the two trajectories are similar, we expect the technology to remain relatively contained within the value network in which it is initially used, but when the slopes of these trajectories differ, new technologies, which initially are performance-competitive only within emerging or commercially remote value networks, may migrate into other networks, providing a vehicle for innovators in new networks to attack established ones.

When such an attack occurs, it is because technological progress has made differences in the rank-ordering of performance attributes across different value networks less relevant. For example, size and weight are attributes of disk drives which are far more important in the desktop computing value network than they are in the mainframe and minicomputer value networks. When technological progress in 5.25-inch drives enabled manufacturers of those products to satisfy the attribute prioritization in the mainframe and minicomputer networks (which prize total capacity and high speed) as well as the attribute prioritization in the desktop network, the boundaries between those value networks ceased to be barriers to entry by 5.25-inch drive makers.

A characteristic of almost all innovations in component technology is that they are an important engine of improvement within a given technological paradigm and its corresponding value network. Component innovation, although often 'competency-destroying', rarely changes the trajectory of performance improvement. As such, the risk of commercial error in component innovation is lower relative to architectural innovations. Thus, we expect incumbent firms to be the leaders in component innovations.

No such general statement can be made about innovations in architectural technologies. Some may reinforce or sustain the trajectory of performance improvement as it is defined within an established value network, while others may disrupt or redefine that trajectory. We expect incumbent firms to lead their industries in the sorts of architectural technology changes which sustain or reinforce the trajectory of performance within an established value network.

When architectural or radical innovations redefine the level, rate and direction of progress of an established technological trajectory, entrant firms have an advantage over incumbents. This is not because of any difficulty or unique skill requirements intrinsic to the new architectural technology. It is because the new paradigm addresses a differently ordered set of performance parameters valued in a new or different value network. It is difficult for established firms to marshall resources behind innovations that do not address the needs of known, present and powerful customers. In these instances, although this 'attacker's advantage' is associated with an architectural technology change, the essence of the attacker's advantage is in its differential ability to identify and make strategic commitments to attack and develop emerging market applications, or value networks. The issue, at its core, may be the relative abilities of successful incumbent firms vs. entrant firms to change strategies, not technologies.

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## 8. Appendix: A note on the data and methods used to generate Fig. 4

The trajectories mapped in Fig. 4 were calculated as follows. Data on the capacity provided with computers was obtained from *Data Sources*, an annual publication which lists the technical specifications of all computer models available from each computer manufacturer. Where particular models were available with different features and configurations, the manufacturer provided *Data Sources* with a 'typical' system configuration with defined RAM capacity, performance specifications of peripheral equipment (including disk drives), list price, and year of introduction. In instances where a given computer model was offered for sale over a sequence of years, the hard disk capacity provided in the typical configuration typically increased. *Data Sources* divides computers into mainframe, mini/midrange, desktop personal, portable and laptop, and notebook computers. For each class of computers, all models available for sale in each year were ranked by price, and the hard disk capacity provided with the median-priced model identified for each year. The best-fit line through the resultant time series is plotted as the solid lines in Fig. 4. These single solid lines are drawn in Fig. 4 for expository simplification to indicate the trend in typical machines. In reality, of course, there is a wide band around these lines. The *frontier* of performance —the highest capacity offered with the most expensive computers—was substantially higher than the typical values shown.

The dotted lines in Fig. 4 represent the best-fit line through the unweighted average capacity of all disk drives introduced for sale in each given architecture for each year. This data was taken from *Disk / Trend Report*. Again, for expository simplification, only this average line is shown. There was a wide band of capacities introduced for sale in each year, so that the frontier or highest capacity drive introduced in each year was substantially above the average shown. Stated in another way, a distinction must be made between the full range of products available for purchase, and those in typical systems of use. The upper and lower bands around the median and average figures shown in Fig. 4 are generally parallel to the lines shown.

Because drives with higher capacities were available in the market than the capacities offered with the median-priced systems, we state in the text that the solid-line trajectories in Fig. 4 represent the capacities 'demanded' in each market. In other words, the capacity per machine was not constrained by technological availability. Rather, it represents a choice for hard disk capacity, made by computer users, given the prevailing cost.