CHAPTER ONE

How Can Great Firms Fail? Insights from the Hard Disk Drive Industry

When I began my search for an answer to the puzzle of why the best firms can fail, a friend offered some sage advice. “Those who study genetics avoid studying humans,” he noted. “Because new generations come along only every thirty years or so, it takes a long time to understand the cause and effect of any changes. Instead, they study fruit flies, because they are conceived, born, mature, and die all within a single day. If you want to understand why something happens in business, study the disk drive industry. Those companies are the closest things to fruit flies that the business world will ever see.”

Indeed, nowhere in the history of business has there been an industry like disk drives, where changes in technology, market structure, global scope, and vertical integration have been so pervasive, rapid, and unrelenting. While this pace and complexity might be a nightmare for managers, my friend was right about its being fertile ground for research. Few industries offer researchers the same opportunities for developing theories about how different types of change cause certain types of firms to succeed or fail or for testing those theories as the industry repeats its cycles of change.

This chapter summarizes the history of the disk drive industry in all its complexity. Some readers will be interested in it for the sake of history itself. [1] But the value of understanding this history is that out of its complexity emerge a few stunningly simple and consistent factors that have repeatedly determined the success and failure of the industry’s best firms. Simply put, when the best firms succeeded, they did so because they listened responsively to their customers and invested aggressively in the technology, products, and manufacturing capabilities that satisfied their customers' next-generation needs. But, paradoxically, when the best firms subsequently failed, it was for the same reasons—they listened responsively to their customers and invested aggressively in the technology, products, and manufacturing capabilities that satisfied their customers' next-generation needs. This is one of the innovator's dilemmas: Blindly following the maxim that good managers should keep close to their customers can sometimes be a fatal mistake.

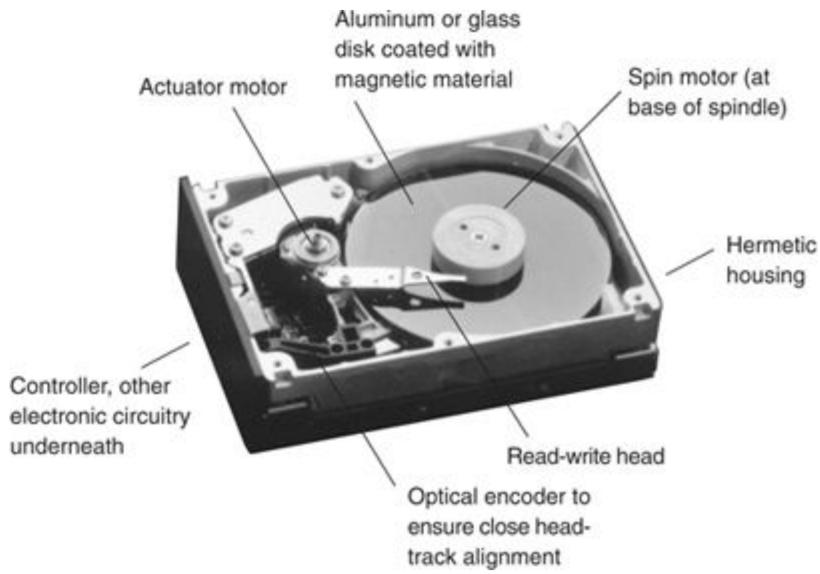
The history of the disk drive industry provides a framework for understanding when "keeping close to your customers" is good advice —and when it is not. The robustness of this framework could only be explored by researching the industry's history in careful detail. Some of that detail is recounted here, and elsewhere in this book, in the hope that readers who are immersed in the detail of their own industries will be better able to recognize how similar patterns have affected their own fortunes and those of their competitors.

HOW DISK DRIVES WORK

Disk drives write and read information that computers use. They comprise read-write heads mounted at the end of an arm that swings over the surface of a rotating disk in much the same way that a phonograph needle and arm reach over a record; aluminum or glass disks coated with magnetic material; at least two electric motors, a spin motor that drives the rotation of the disks and an actuator motor that moves the head to the desired position over the disk; and a variety of electronic circuits that control the drive's operation and its interface with the computer. See Figure 1.1 for an illustration of a typical disk drive.

The read-write head is a tiny electromagnet whose polarity changes whenever the direction of the electrical current running through it changes. Because opposite magnetic poles attract, when the polarity of the head becomes positive, the polarity of the area on the disk beneath the head switches to negative, and vice versa. By rapidly changing the direction of current flowing through the head's electromagnet as the disk spins beneath the head, a sequence of positively and negatively oriented magnetic domains are created in concentric tracks on the disk's surface. Disk drives can use the positive and negative domains on the disk as a binary numeric system—*1* and *0*—to "write" information onto disks. Drives read information from disks in essentially the opposite process: Changes in the magnetic flux fields on the disk surface induce changes in the micro current flowing through the head.

Figure 1.1 Primary Components of a Typical Disk Drive

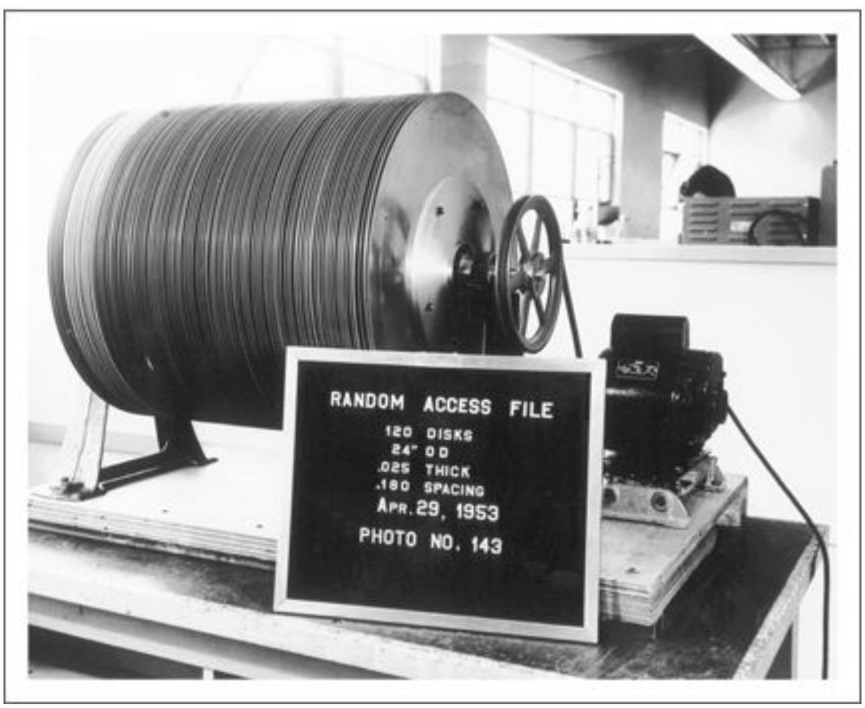


Aluminum or glass
disk coated with
magnetic material
Actuator motor
Spin motor (at
base of spindle)
Hermetic
housing
Controller, other
electronic circuitry
underneath
Read-write head
Optical encoder to
ensure close head-
track alignment

EMERGENCE OF THE EARLIEST DISK DRIVES

A team of researchers at IBM's San Jose research laboratories developed the first disk drive between 1952 and 1956. Named RAMAC (for Random Access Method for Accounting and Control), this drive was the size of a large refrigerator, incorporated fifty twenty-four-inch disks, and could store 5 megabytes (MB) of information (see Figure 1.2). Most of the fundamental architectural concepts and component technologies that defined today's dominant disk drive design were also developed at IBM. These include its removable packs of rigid disks (introduced in 1961); the floppy disk drive (1971); and the Winchester architecture (1973). All had a powerful, defining influence on the way engineers in the rest of the industry defined what disk drives were and what they could do.

Figure 1.2 The First Disk Drive, Developed by IBM



Source: Courtesy of International Business Machines Corporation.

As IBM produced drives to meet its own needs, an independent disk drive industry emerged serving two distinct markets. A few firms developed the plug-compatible market (PCM) in the 1960s, selling souped-up copies of IBM drives directly to IBM customers at discount prices. Although most of IBM's competitors in computers (for example, Control Data, Burroughs, and Univac) were integrated vertically into the manufacture of their own disk drives, the emergence in the 1970s of smaller, nonintegrated computer makers such as Nixdorf, Wang, and Prime spawned an original equipment market (OEM) for disk drives as well. By 1976 about $1 billion worth of disk drives were produced, of which captive production accounted for 50 percent and PCM and OEM for about 25 percent each.

The next dozen years unfolded a remarkable story of rapid growth, market turbulence, and technology-driven performance improvements. The value of drives produced rose to about $18 billion by 1995. By the mid-1980s the PCM market had become insignificant, while OEM output grew to represent about three-fourths of world production. Of the seventeen firms populating the industry in 1976—all of which were relatively large, diversified corporations such as Diablo, Ampex, Memorex, EMM, and Control Data—all except IBM's disk drive operation had failed or had been acquired by 1995. During this period an additional 129 firms entered the industry, and 109 of those also failed. Aside from IBM, Fujitsu, Hitachi, and NEC, all of the producers remaining by 1996 had entered the industry as start-ups after 1976.

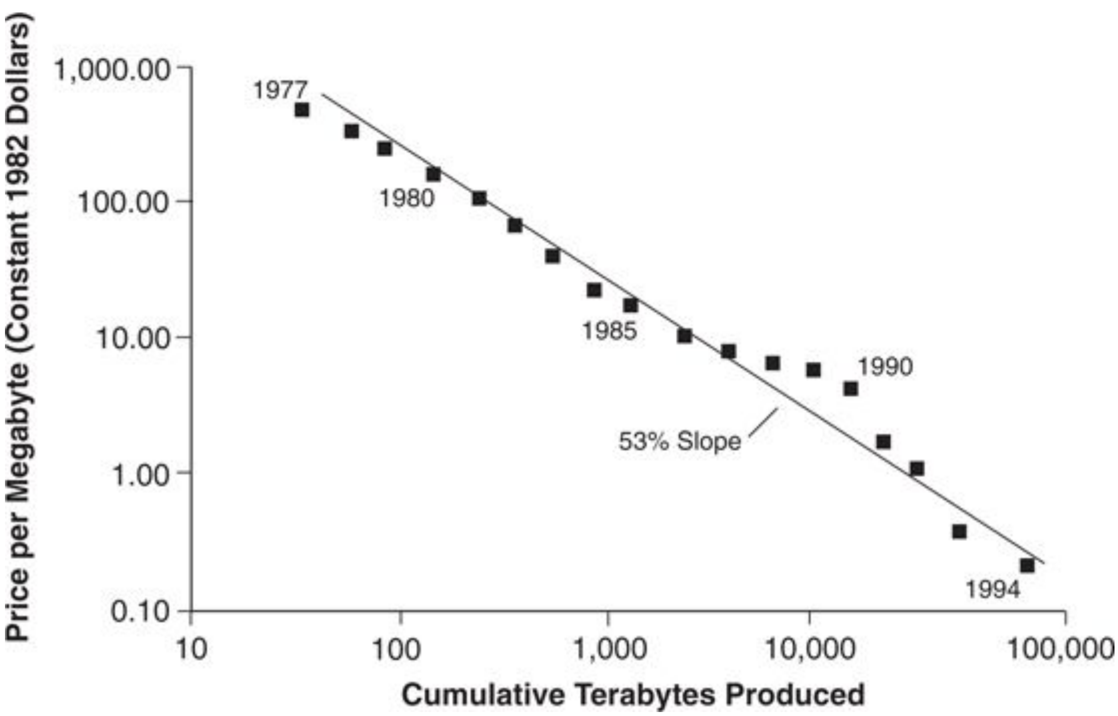
Some have attributed the high mortality rate among the integrated firms that created the industry to its nearly unfathomable pace of technological change. Indeed, the pace of change has been breathtaking. The number of megabits (Mb) of information that the industry's engineers have been able to pack into a square inch of disk surface has increased by 35 percent per year, on average, from 50 Kb in 1967 to 1.7 Mb in 1973, 12 Mb in 1981, and 1100 Mb by 1995. The physical size of the drives was reduced at a similar pace: The smallest available 20 MB drive shrank from 800 cubic inches (in. 3) in 1978 to 1.4 in. 3 by 1993—a 35 percent annual rate of reduction.

Figure 1.3 shows that the slope of the industry's experience curve (which correlates the cumulative number of terabytes (one thousand gigabytes) of disk storage capacity shipped in the industry's history to the constant-dollar price per megabyte of memory) was 53 percent—meaning that with each doubling of cumulative terabytes shipped, cost per megabyte fell to 53 percent of its former level. This is a much steeper rate of price decline than the 70 percent slope observed in the markets for most other microelectronics products. The price per megabyte has declined at about 5 percent per *quarter* for more than twenty years.

THE IMPACT OF TECHNOLOGICAL CHANGE

My investigation into why leading firms found it so difficult to stay atop the disk drive industry led me to develop the "technology mudslide hypothesis": Coping with the relentless onslaught of technology change was akin to trying to climb a mudslide raging down a hill. You have to scramble with everything you've got to stay on top of it, and if you ever once stop to catch your breath, you get buried.

Figure 1.3 Disk Drive Price Experience Curve



Source: Data are from various issues of *Disk/Trend Report.*

To test this hypothesis, I assembled and analyzed a database consisting of the technical and performance specifications of every model of disk drive introduced by every company in the world disk drive industry for each of the years between 1975 and 1994. [2] This database enabled me to identify the firms that led in introducing each new technology; to trace how new technologies were diffused through the industry over time; to see which firms led and which lagged; and to measure the impact each technological innovation had on capacity, speed, and other parameters of disk drive performance. By carefully reconstructing the history of each technological change in the industry, the changes that catapulted entrants to success or that precipitated the failure of established leaders could be identified.

This study led me to a very different view of technology change than the work of prior scholars on this question had led me to expect. Essentially, it revealed that neither the pace nor the difficulty of technological change lay at the root of the leading firms' failures. The technology mudslide hypothesis was wrong.

The manufacturers of most products have established a trajectory of performance improvement over time. [3] Intel, for example, pushed the speed of its microprocessors ahead by about 20 percent per year, from its 8 megahertz (MHz) 8088 processor in 1979 to its 133 MHz Pentium chip in 1994. Eli Lilly and Company improved the purity of its insulin from 50,000 impure parts per million (ppm) in 1925 to 10 ppm in 1980, a 14 percent annual rate of improvement. When a measurable trajectory of improvement has been established, determining whether a new technology is likely to improve a product's performance relative to earlier products is an unambiguous question.

But in other cases, the impact of technological change is quite different. For instance, is a notebook computer better than a mainframe? This is an ambiguous question because the notebook computer established a completely new performance trajectory, with a definition of performance that differs substantially from the way mainframe performance is measured. Notebooks, as a consequence, are generally sold for very different uses.

This study of technological change over the history of the disk drive industry revealed two types of technology change, each with very different effects on the industry's leaders. Technologies of the first sort *sustained* the industry's rate of improvement in product performance (total capacity and recording density were the two most common measures) and ranged in difficulty from incremental to radical. The industry's dominant firms always led in developing and adopting these technologies. By contrast, innovations of the second sort *disrupted* or redefined performance trajectories—and consistently resulted in the failure of the industry's leading firms. [4]

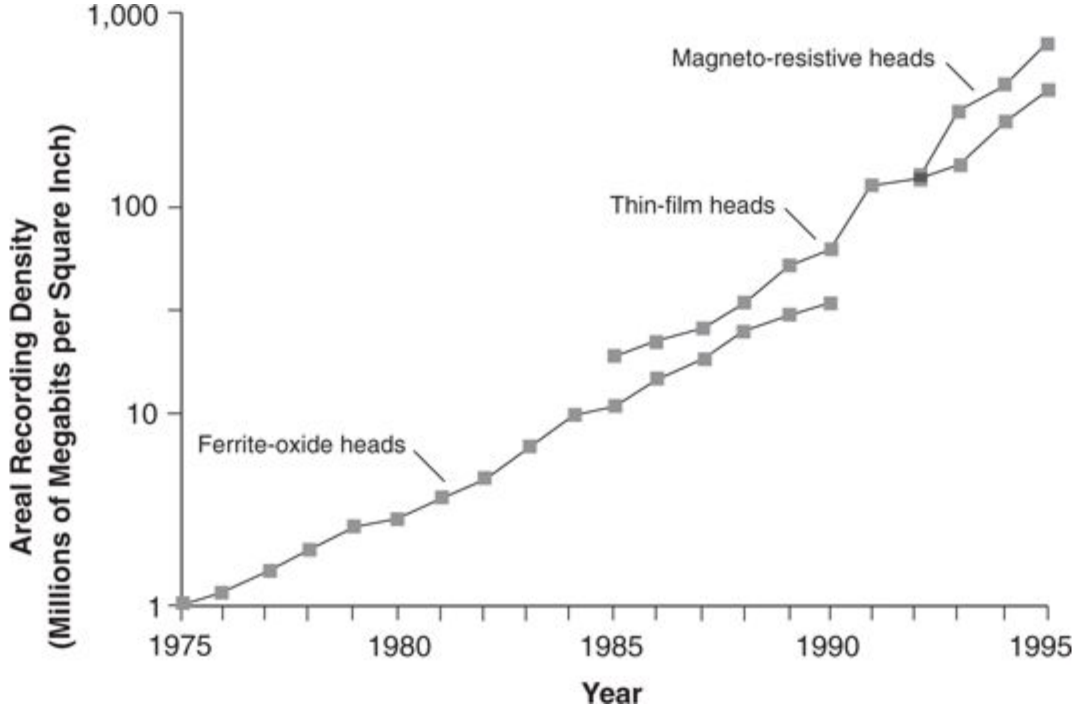
The remainder of this chapter illustrates the distinction between sustaining and disruptive technologies by describing prominent examples of each and summarizing the role these played in the industry's development. This discussion focuses on differences in how established firms came to lead or lag in developing and adopting new technologies, compared with entrant firms. To arrive at these examples, each new technology in the industry was examined. In analyzing which firms led and lagged at each of these points of change, I defined *established firms* to be those that had been established in the industry prior to the advent of the technology in question, practicing the prior technology. I defined *entrant firms* as those that were new to the industry at that point of technology change. Hence, a given firm would be considered an entrant at one specific point in the industry's history, for example, at the emergence of the 8-inch drive. Yet the same firm would be considered an established firm when technologies that emerged subsequent to the firm's entry were studied.

SUSTAINING TECHNOLOGICAL CHANGES

In the history of the disk drive industry, most technology changes have sustained or reinforced established trajectories of product performance improvement. Figure 1.4, which compares the average recording density of drives that employed successive generations of head and disk technologies, maps an example of this. The first curve plots the density of drives that used conventional particulate oxide disk technology and ferrite head technology; the second charts the average density of drives that used new-technology thin-film heads and disks; the third marks the improvements in density achievable with the latest head technology, magneto-resistive heads. [5]

The way such new technologies as these emerge to surpass the performance of the old resembles a series of intersecting technology S-curves. [6] Movement along a given S-curve is generally the result of incremental improvements within an existing technological approach, whereas jumping onto the next technology curve implies adopting a radically new technology. In the cases measured in Figure 1.4, incremental advances, such as grinding the ferrite heads to finer, more precise dimensions and using smaller and more finely dispersed oxide particles on the disk's surface, led to the improvements in density from 1 to 20 megabits per square inch (Mbpsi) between 1976 and 1989. As S-curve theory would predict, the improvement in recording density obtainable with ferrite/ oxide technology began to level off toward the end of the period, suggesting a maturing technology. The thin-film head and disk technologies' effect on the industry sustained performance improvement at its historical rate. Thin-film heads were barely established in the early 1990s, when even more advanced magneto-resistive head technology emerged. The impact of magneto-resistive technology sustained, or even accelerated, the rate of performance improvement.

Figure 1.4 Impact of New Read-Write Head Technologies in Sustaining the Trajectory of Improvement in Recording Density



Source: Data are from various issues of *Disk/Trend Report.*

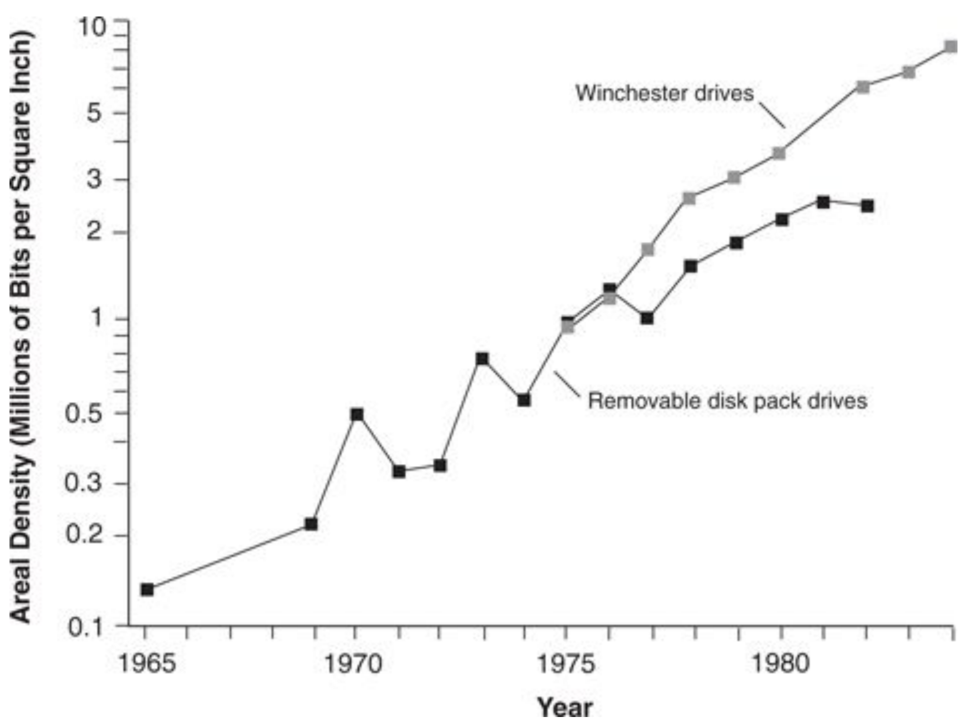
Figure 1.5 describes a sustaining technological change of a very different character: an innovation in product architecture, in which the 14-inch Winchester drive is substituted for removable disk packs, which had been the dominant design between 1962 and 1978. Just as in the thin-film for ferrite/oxide substitution, the impact of Winchester technology sustained the historically established rate of performance improvement. Similar graphs could be constructed for most other technological innovations in the industry, such as embedded servo systems, RLL and PRML recording codes, higher RPM motors, and embedded interfaces. Some of these were straightforward technology improvements; others were radical departures. But all had a similar impact on the industry: They helped manufacturers to sustain the rate of historical performance improvement that their customers had come to expect. [7]

In literally every case of sustaining technology change in the disk drive industry, established firms led in development and commercialization.

The emergence of new disk and head technologies illustrates this.

In the 1970s, some manufacturers sensed that they were reaching the limit on the number of bits of information they could pack onto oxide disks. In response, disk drive manufacturers began studying ways of applying super-thin films of magnetic metal on aluminum to sustain the historical rate of improvements in recording density. The use of thin-film coatings was then highly developed in the integrated circuit industry, but its application to magnetic disks still presented substantial challenges. Experts estimate that the pioneers of thin-film disk technology—IBM, Control Data, Digital Equipment, Storage Technology, and Ampex—each took more than eight years and spent more than $50 million in that effort. Between 1984 and 1986, about two-thirds of the producers active in 1984 introduced drives with thin-film disks. The overwhelming majority of these were established industry incumbents. Only a few entrant firms attempted to use thin-film disks in their initial products, and most of those folded shortly after entry.

Figure 1.5 Sustaining Impact of the Winchester Architecture on the Recording Density of 14-inch Disk Drives



Source: Data are from various issues of *Disk/Trend Report.*

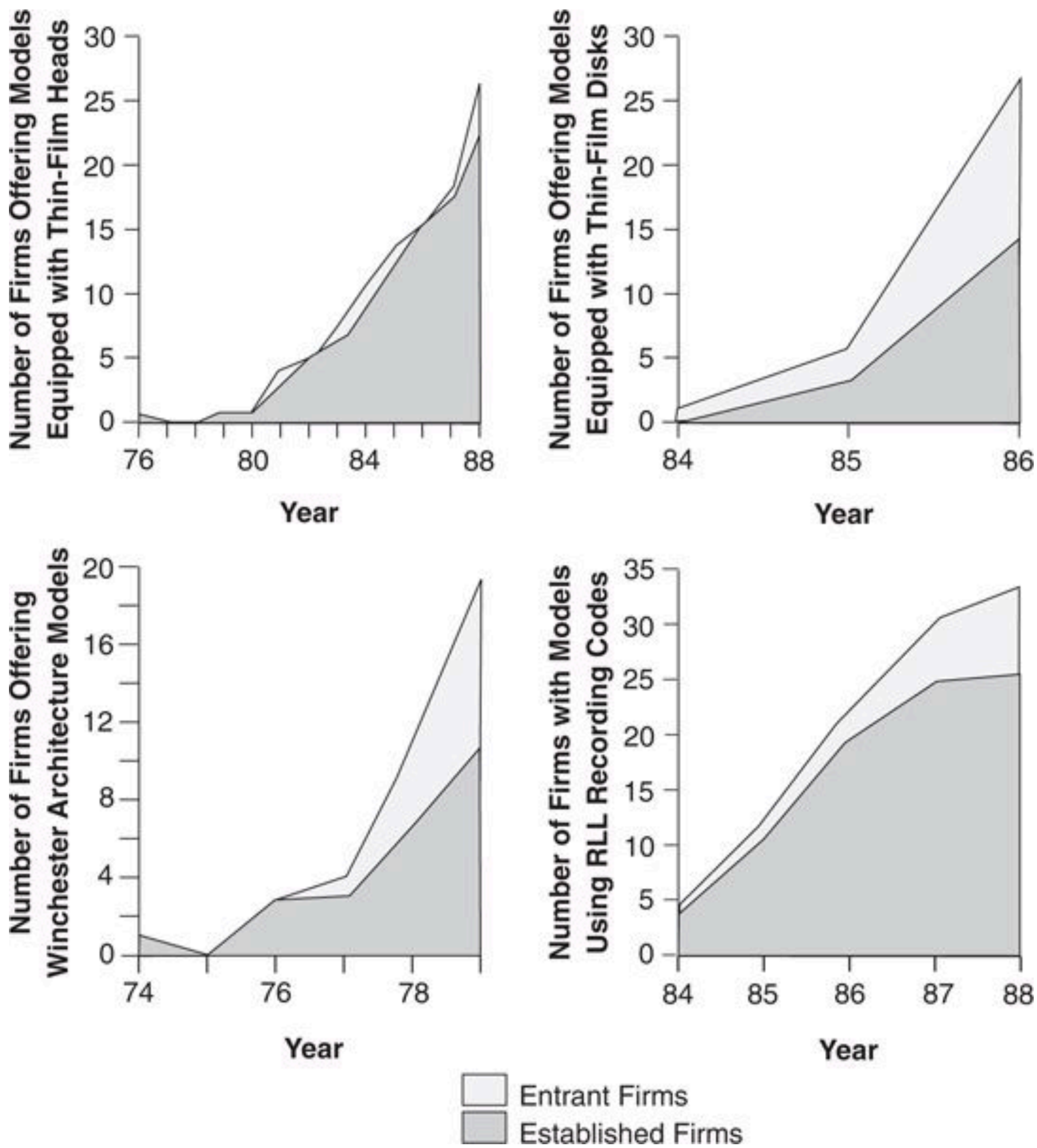
The same pattern was apparent in the emergence of thin-film heads. Manufacturers of ferrite heads saw as early as 1965 the approaching limit to improvements in this technology; by 1981 many believed that the limits of precision would soon be reached. Researchers turned to thin-film technology, produced by sputtering thin films of metal on the recording head and then using photolithography to etch much finer electromagnets than could be attained with ferrite technology. Again, this proved extraordinarily difficult. Burroughs in 1976, IBM in 1979, and other established firms first successfully incorporated thin-film heads in disk drives. In the period between 1982 and 1986, during which some sixty firms entered the rigid disk drive industry, only four (all commercial failures) attempted to do so using thin-film heads in their initial products as a source of performance advantage. All other entrant firms—even aggressively performance-oriented firms such as Maxtor and Conner Peripherals—found it preferable to learn their way using conventional ferrite heads first, before tackling thin-film technology.

As was the case with thin-film disks, the introduction of thin-film heads entailed the sort of sustained investment that only established firms could handle. IBM and its rivals each spent more than $100 million developing thin-film heads. The pattern was repeated in the next-generation magneto-resistive head technology: The industry's largest firms—IBM, Seagate, and Quantum—led the race.

The established firms were the leading innovators not just in developing risky, complex, and expensive component technologies such as thin-film heads and disks, but in *literally every other one of the sustaining innovations in the industry's history.* Even in relatively simple innovations, such as RLL recording codes (which took the industry from double-to triple-density disks), established firms were the successful pioneers, and entrant firms were the technology followers. This was also true for those architectural innovations—for example, 14-inch and 2.5-inch Winchester drives— whose impact was to sustain established improvement trajectories. Established firms beat out the entrants.

Figure 1.6 summarizes this pattern of technology leadership among established and entrant firms offering products based on new sustaining technologies during the years when those technologies were emerging. The pattern is stunningly consistent. Whether the technology was radical or incremental, expensive or cheap, software or hardware, component or architecture, competence-enhancing or competence-destroying, the pattern was the same. When faced with sustaining technology change that gave existing customers something more and better in what they wanted, the leading practitioners of the prior technology led the industry in the development and adoption of the new. Clearly, the leaders in this industry did not fail because they became passive, arrogant, or risk-averse or because they couldn't keep up with the stunning rate of technological change. My technology mudslide hypothesis wasn't correct.

Figure 1.6 Leadership of Established Firms in Sustaining Technologies



Source: Data are from various issues of *Disk/Trend Report.*

FAILURE IN THE FACE OF DISRUPTIVE TECHNOLOGICAL CHANGES

Most technological change in the disk drive industry has consisted of sustaining innovations of the sort described above. In contrast, there have been only a few of the other sort of technological change, called disruptive technologies. These were the changes that toppled the industry's leaders.

The most important disruptive technologies were the architectural innovations that shrunk the size of the drives—from 14-inch diameter disks to diameters of 8, 5.25, and 3.5-inches and then from 2.5 to 1.8 inches. Table 1.1 illustrates the ways these innovations were disruptive. Based on 1981 data, it compares the attributes of a typical 5.25-inch drive, a new architecture that had been in the market for less than a year, with those of a typical 8-inch drive, which at that time was the standard drive used by minicomputer manufacturers. Along the dimensions of performance important to established minicomputer manufacturers—capacity, cost per megabyte, and access time—the 8-inch product was vastly superior. The 5.25-inch architecture did not address the perceived needs of minicomputer manufacturers at that time. On the other hand, the 5.25-inch drive had features that appealed to the desktop personal computer market segment just emerging in the period between 1980 and 1982. It was small and lightweight, and, priced at around $2,000, it could be incorporated into desktop machines economically.

Generally disruptive innovations were technologically straightforward, consisting of off-the-shelf components put together in a product architecture that was often simpler than prior approaches. [8] They offered less of what customers in established markets wanted and so could rarely be initially employed there. They offered a different package of attributes valued only in emerging markets remote from, and unimportant to, the mainstream.

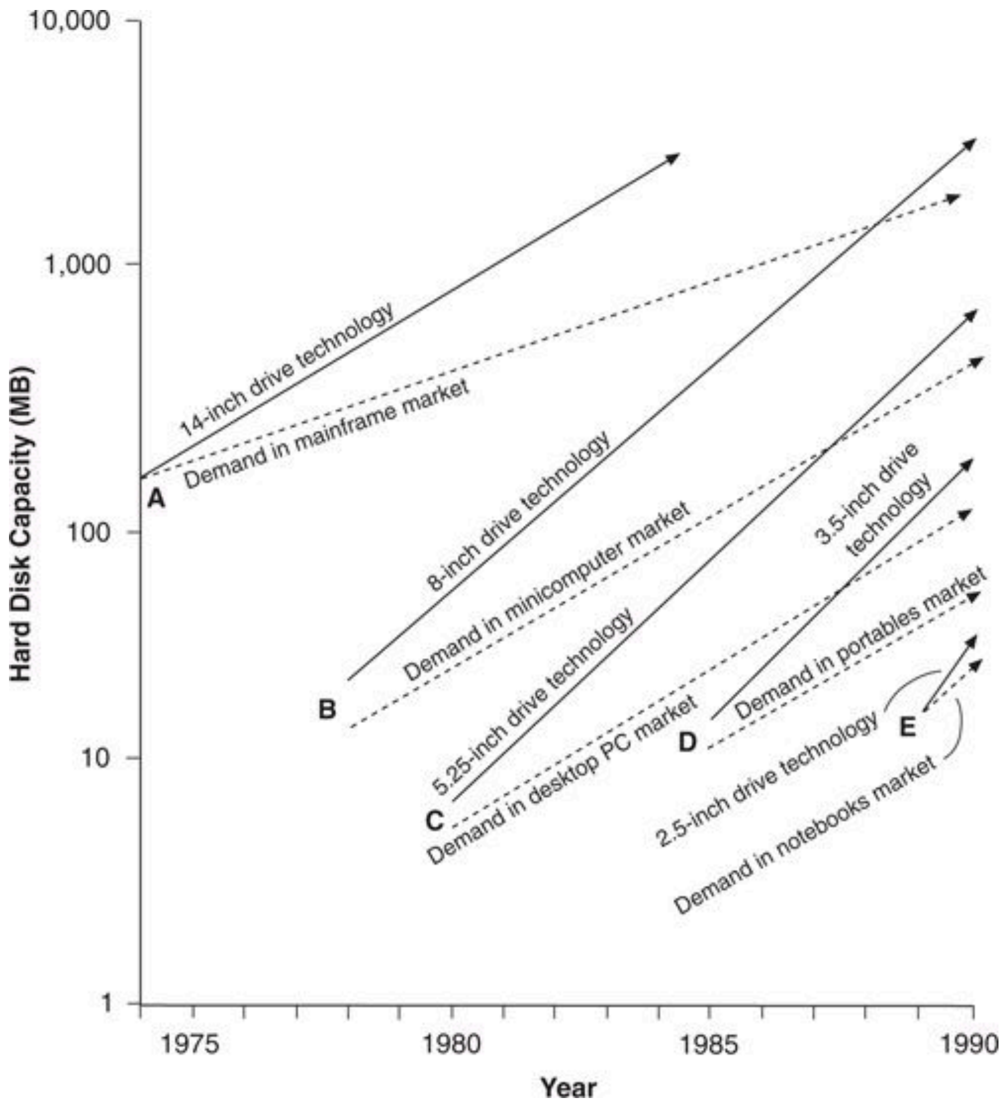
The trajectory map in Figure 1.7 shows how this series of simple but disruptive technologies proved to be the undoing of some very aggressive, astutely managed disk drive companies. Until the mid-1970s, 14-inch drives with removable packs of disks accounted for nearly all disk drive sales. The 14-inch Winchester architecture then emerged to sustain the trajectory of recording density improvement. Nearly all of these drives (removable disks and Winchesters) were sold to mainframe computer manufacturers, and the same companies that led the market in disk pack drives led the industry's transition to the Winchester technology.

Table 1.1 A Disruptive Technology Change: The 5.25-inch Winchester Disk Drive (1981)

Attribute	8-Inch Drives (Minicomputer Market)	5.25-Inch Drives (Desktop Computer Market)
Capacity (megabytes)	60	10
Physical volume (cubic inches)	566	150
Weight (pounds)	21	6
Access time (milliseconds)	30	160
Cost per megabyte	$50	$200
Unit cost	$3000	$2000

Source: Data are from various issues of *Disk/Trend Report*.

Figure 1.7 Intersecting Trajectories of Capacity Demanded versus Capacity Supplied in Rigid Disk Drives



Source: Clayton M. Christensen, "The Rigid Disk Drive Industry: A History of Commercial and Technological Turbulence," Business History Review 67, no. 4 (Winter 1993): 559. Reprinted by permission.

The trajectory map shows that the hard disk capacity provided in the median priced, typically configured mainframe computer system in 1974 was about 130 MB per computer. This increased at a 15 percent annual rate over the next fifteen years—a trajectory representing the disk capacity demanded by the typical users of new mainframe computers. At the same time, the capacity of the average 14-inch drive introduced for sale each year increased at a faster, 22 percent rate, reaching beyond the mainframe market to the large scientific and supercomputer markets. [9]

Between 1978 and 1980, several entrant firms—Shugart Associates, Micropolis, Priam, and Quantum—developed smaller 8-inch drives with 10, 20, 30, and 40 MB capacity. These drives were of no interest to mainframe computer manufacturers, which at that time were demanding drives with 300 to 400 MB capacity. These 8-inch entrants therefore sold their disruptive drives into a new application—minicomputers. [10] The customers—Wang, DEC, Data General, Prime, and Hewlett-Packard—did not manufacture mainframes, and their customers often used software substantially different from that used in mainframes. These firms hitherto had been unable to offer disk drives in their small, desk-side minicomputers because 14-inch models were too big and expensive. Although initially the cost per megabyte of capacity of 8-inch drives was higher than that of 14-inch drives, these new customers were willing to pay a premium for other attributes that were important to them—especially smaller size. Smallness 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 percent per year: a trajectory determined by the ways in which minicomputer owners learned to use their machines. At the same time, however, the 8-inch drive makers found that, by aggressively adopting sustaining innovations, they could increase the capacity of their products at a rate of more than 40 percent per year—nearly double the rate of increase 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. Unit volumes had grown significantly so that the cost per megabyte of 8-inch drives had declined below that of 14-inch drives, and other advantages became apparent: For example, the same percentage mechanical vibration in an 8-inch drive, as opposed to a 14-inch drive, caused much less variance in the absolute position of the head over the disk. Within a three-to-four-year period, therefore, 8-inch drives began to invade the market above them, substituting for 14-inch drives in the lower-end mainframe computer market.

As the 8-inch products penetrated the mainframe market, the established manufacturers of 14-inch drives began to fail. Two-thirds of them never introduced an 8-inch model. The one-third that introduced 8-inch models did so about two years behind the 8-inch entrant manufacturers. Ultimately, every 14-inch drive maker was driven from the industry. [11]

The 14-inch drive makers were not toppled by the 8-inch entrants because of technology. The 8-inch products generally incorporated standard off-the-shelf components, and when those 14-inch drive makers that did introduce 8-inch models got around to doing so, their products were very performance-competitive in capacity, areal density, access time, and price per megabyte. The 8-inch models introduced by the established firms in 1981 were nearly identical in performance to the average of those introduced that year by the entrant firms. In addition, the rates of improvement in key attributes (measured between 1979 and 1983) were stunningly similar between established and entrant firms. [12]

Held Captive by Their Customers

Why were the leading drive makers unable to launch 8-inch drives until it was too late? Clearly, they were technologically capable of producing these drives. Their failure resulted from delay in making the strategic commitment to enter the emerging market in which the 8-inch drives initially could be sold. Interviews with marketing and engineering executives close to these companies suggest that the established 14-inch drive manufacturers were held captive by customers. Mainframe computer manufacturers did not need an 8-inch drive. In fact, they explicitly did not want it: they wanted 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 to either the disk drive manufacturers or their computer-making customers—were pulling them along a trajectory of 22 percent capacity growth in a 14-inch platform that would ultimately prove fatal. [13]

Figure 1.7 maps the disparate trajectories of performance improvement demanded in the computer product segments that emerged later, compared to the capacity that changes in component technology and refinements in system design made available within each successive architecture. 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 from the same points measure the average capacity of all disk drives introduced for sale in each architecture, for each year. These transitions are briefly described below.

The Advent of the 5.25-inch Drive

In 1980, Seagate Technology introduced 5.25-inch disk drives. 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 that entered with 5.25-inch drives in the period 1980 to 1983 (for example, Miniscribe, Computer Memories, and International Memories) had to pioneer new applications for their products and turned primarily to desktop personal computer makers. By 1990, the use of hard drives in desktop computers was an obvious application for magnetic recording. It was not at all clear in 1980, however, when the market was just emerging, that many people could ever afford or use a hard drive on the desktop. The early 5.25-inch drive makers found this application (one might even say that they *enabled* it) by trial and error, selling drives to whomever would buy them.

Once the use of hard drives was established in desktop PCs, the disk capacity shipped with the median-priced machine (that is, the capacity demanded by the general PC user) increased about 25 percent 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 percent per year between 1980 and 1990. As in the 8-inch for 14-inch substitution, the first firms to produce 5.25-inch drives were entrants; on average, established firms lagged behind entrants by two years. By 1985, only half of the firms producing 8-inch drives had introduced 5.25-inch models. The other half never did.

Growth in the use of 5.25-inch drives occurred in two waves. The first followed creation of a new application for rigid disk drives: desktop computing, in which product attributes such as physical size, relatively unimportant in established applications, were highly valued. The second wave followed substitution of 5.25-inch disks for 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 drive makers—Shugart Associates, Micropolis, Priam, and Quantum—only Micropolis survived to become a significant manufacturer of 5.25-inch drives, and that was accomplished only with Herculean managerial effort, as described in chapter 5.

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 spinoff of 5.25-inch drive makers Seagate and Miniscribe, started shipping product in 1987. Conner had developed a small, lightweight drive architecture that was much more rugged than its 5.25-inch ancestors. It handled electronically functions that had previously been managed with mechanical parts, and it used microcode to replace functions that had previously been addressed electronically. Nearly all of Conner's first year revenues of $113 million [14] came from Compaq Computer, which had aided 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 to get lighter weight, greater ruggedness, and lower power consumption.

Seagate engineers were not oblivious to the coming of the 3.5-inch architecture. Indeed, in early 1985, less than one year after Rodime introduced the first 3.5-inch drive and two years *before* Conner Peripherals started shipping its product, Seagate personnel showed 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; they argued 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.

Seagate's marketers tested the 3.5-inch prototypes with customers in the desktop computing market it already served—manufacturers like IBM, and value-added resellers of full-sized desktop computer systems. Not surprisingly, they indicated 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 provide only 20 MB—and at higher costs. [15]

In response to lukewarm reviews from customers, Seagate's program manager lowered his 3.5-inch sales estimates, and the firm's executives canceled the program. Their reasoning? The markets for 5.25-inch products were larger, and the sales generated by spending the engineering effort on new 5.25-inch products would create 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. With established applications and product architectures of their own, such as the IBM XT and AT, these customers saw no value in the improved ruggedness or the reduced size, weight, and power consumption 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 Figure 1.7) intersected the trajectory of capacity demanded in desktop computers. By that time, the industry had shipped, cumulatively, nearly $750 million in 3.5-inch products. 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. In other words, Seagate's primary customers were still desktop computer manufacturers, and many of its 3.5-inch drives were shipped with frames for mounting them in computers designed for 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 enable new market applications to emerge, the introduction of new technology may not be inherently cannibalistic. But when established firms wait until a new technology has become commercially mature in its new applications 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 we have been looking at Seagate's response to the development of the 3.5-inch drive architecture, its behavior was not atypical; by 1988, only 35 percent of the drive manufacturers that had established themselves making 5.25-inch products for the desktop PC market had introduced 3.5-inch drives. Similar to earlier product architecture transitions, the barrier to development of a competitive 3.5-inch product does not appear to have been engineering-based. As in the 14-to 8-inch transition, the new-architecture drives introduced by the incumbent, established firms during the transitions from 8 to 5.25 inches and from 5.25 to 3.5 inches were fully performance-competitive with those of entrant drives. Rather, the 5.25-inch drive manufacturers seem to have been misled by their customers, notably IBM and its direct competitors and resellers, who themselves seemed as oblivious as Seagate to the potential benefits and possibilities of portable computing and the new disk drive architecture that might facilitate it.

Prairietek, Conner, and the 2.5-inch Drive

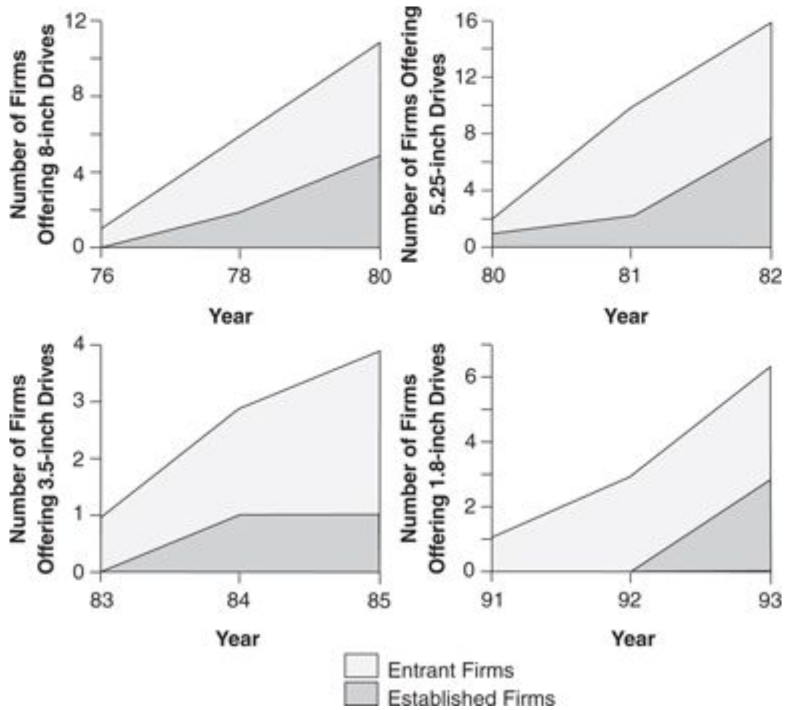
In 1989 an industry entrant in Longmont, Colorado, Prairietek, upstaged the industry by announcing a 2.5-inch drive, capturing nearly all $30 million of this nascent market. But Conner Peripherals announced its own 2.5-inch product in early 1990 and by the end of that year had claimed 95 percent of the 2.5-inch drive market. Prairietek declared bankruptcy in late 1991, by which time each of the other 3.5-inch drivemakers— Quantum, Seagate, Western Digital, and Maxtor—had introduced 2.5-inch drives of their own.

What had changed? Had the incumbent leading firms finally learned the lessons of history? Not really. Although Figure 1.7 shows the 2.5-inch drive had significantly less capacity than the 3.5-inch drives, the portable computing markets into which the smaller drives were sold valued *other* attributes: weight, ruggedness, low power consumption, small physical size, and so on. Along *these* dimensions, the 2.5-inch drive offered improved performance over that of the 3.5-inch product: It was a *sustaining* technology. In fact, the computer makers who bought Conner's 3.5-inch drive—laptop computer manufacturers such as Toshiba, Zenith, and Sharp—were the leading makers of notebook computers, and these firms needed the smaller 2.5-inch drive architecture. Hence, Conner and its competitors in the 3.5-inch market followed their customers seamlessly across the transition to 2.5-inch drives.

In 1992, however, the 1.8-inch drive emerged, with a distinctly disruptive character. Although its story will be recounted in detail later, it suffices to state here that by 1995, it was *entrant* firms that controlled 98 percent of the $130 million 1.8-inch drive market. Moreover, the largest initial market for 1.8-inch drives wasn't in computing at all. It was in portable heart monitoring devices!

Figure 1.8 summarizes this pattern of entrant firms' leadership in disruptive technology. It shows, for example, that two years after the 8-inch drive was introduced, two-thirds of the firms producing it (four of six), were entrants. And, two years after the first 5.25-inch drive was introduced, 80 percent of the firms producing these disruptive drives were entrants.

Figure 1.8 Leadership of Entrant Firms in Disruptive Technology



Source: Data are from various issues of *Disk/Trend Report.*

SUMMARY

There are several patterns in the history of innovation in the disk drive industry. The first is that the disruptive innovations were technologically straightforward. They generally packaged known technologies in a unique architecture and enabled the use of these products in applications where magnetic data storage and retrieval previously had not been technologically or economically feasible.

The second pattern is that the purpose of advanced technology development in the industry was always to *sustain* established trajectories of performance improvement: to reach the higher-performance, higher-margin domain of the upper right of the trajectory map. Many of these technologies were radically new and difficult, but they were not disruptive. The customers of the leading disk drive suppliers led them toward these achievements. Sustaining technologies, as a result, did not precipitate failure.

The third pattern shows that, despite the established firms' technological prowess in leading sustaining innovations, from the simplest to the most radical, the firms that led the industry in every instance of developing and adopting disruptive technologies were entrants to the industry, not its incumbent leaders.

This book began by posing a puzzle: Why was it that firms that could be esteemed as aggressive, innovative, customer-sensitive organizations could ignore or attend belatedly to technological innovations with enormous strategic importance? In the context of the preceding analysis of the disk drive industry, this question can be sharpened considerably. The established firms were, in fact, aggressive, innovative, and customer-sensitive in their approaches to sustaining innovations of every sort. But the problem established firms seem unable to confront successfully is that of *downward* vision and mobility, in terms of the trajectory map. Finding new applications and markets for these new products seems to be a capability that each of these firms exhibited once, upon entry, and then apparently lost. It was as if the leading firms were held captive by their customers, enabling attacking entrant firms to topple the incumbent industry leaders each time a disruptive technology emerged. [16] Why this happened, and is still happening, is the subject of the next chapter.

[illegible]~

[illegible]

- [illegible]
- [illegible]
- [illegible]

[illegible][[illegible] https://www.chenjin5.com](https://www.chenjin5.com)

- [illegible]
- [illegible]
- [illegible]

APPENDIX 1.1: A NOTE ON THE DATA AND METHOD USED TO GENERATE FIGURE 1.7

The trajectories mapped in Figure 1.7 were calculated as follows. Data on the capacity provided with computers was obtained from *Data Sources*, an annual publication listing the technical specifications of all computer models available from every computer manufacturer. For instances in which particular models were available with different features and configurations, the manufacturer provided *Data Sources* with a "typical" system configuration with defined random access memory (RAM) capacity, performance specifications of peripheral equipment (including disk drives), list prices, and year of introduction. For instances in which 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* used the categories mainframe, mini/midrange, desktop personal, portable and laptop, and notebook. As of 1993, 1.8-inch drives were not being used in hand-held computers, so no data on that potential market existed.

For Figure 1.7, for each year and each class of computers, all models available for sale were ranked by price and the hard disk capacity provided with the median-priced model identified. The best-fit lines through the resultant time series were plotted as the solid lines in Figure 1.7 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 Figure 1.7 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. The upper and lower bands around the median and average figures shown in Figure 1.7 are generally parallel to the lines shown.

Because higher capacity drives were available in the market than were offered with the median-priced systems, the solid-line trajectories in Figure 1.7, as I state in the text, represent the capacities “demanded” in each market. In other words, the capacity per machine was not constrained by technological availability. Rather, it represents the selection of hard disk capacity by computer users, given the prevailing cost.

NOTES

1. A more complete history of the disk drive industry can be found in Clayton M. Christensen, "The Rigid Disk Drive Industry: A History of Commercial and Technological Turbulence," *Business History Review* (67), Winter, 1993, 531–588. This history focuses only on the manufacturers of rigid disk drives or hard drives—products on which data are stored on rigid metal platters. Companies manufacturing floppy disk drives (removable diskettes of flexible mylar coated with iron oxide on which data are stored) historically were different firms from those making hard disk drives.

2. Much of the data for this analysis came from *Disk/Trend Report*, a highly respected annual market research publication, augmented with more detailed product-specification sheets obtained from the disk drive manufacturers themselves. I am grateful to the editors and staff at Disk/Trend, Inc., for their patient and generous assistance in this project.

3. The concept of trajectories of technological progress was examined by Giovanni Dosi in "Technological Paradigms and Technological Trajectories," *Research Policy* (11), 1982, 147–162.

4. The ways in which the findings of this study differ from those of some earlier scholars of technology change while building upon those of others are discussed in greater detail in chapter 2.

5. The first technology for making heads built an electromagnet by wrapping a fine thread of copper wire around a core of iron oxide (ferrite); hence the term *ferrite head.* Incremental improvements to this approach involved learning to grind the ferrite to finer and finer dimensions, using better lapping techniques, and strengthening the ferrite by doping it with barium. *Thin-film heads* were made photolithographically, using technology similar to that used in making integrated circuits on silicon wafers to etch the electromagnet on the surface of the head. This was difficult because it involved much thicker layers of material than were common in IC manufacturing. The third

technology, adopted starting in the mid-1990s, was called *magneto-resistive heads.* These were also made with thin-film photolithography, but used the principle that changes in the magnetic flux field on the disk surface changed the electrical resistivity of the circuitry in the head. By measuring changes in resistivity rather than changes in the direction of current flow, magneto-resistive heads were much more sensitive, and hence permitted denser data recording, than prior technology. In the evolution of disk technology, the earliest disks were made by coating fine needle-shaped particles of iron oxide—literally rust—over the surface of a flat, polished aluminum platter. Hence, these disks were called *oxide* disks. Incremental improvements to this technology involved making finer and finer iron oxide particles, and dispersing them more uniformly, with fewer uncoated voids on the aluminum platter's surface. This was supplanted by a sputtering technology, also borrowed from semiconductor processing, that coated the aluminum platter with a thin film of metal a few angstroms thick. The thinness of this layer; its continuous, rather than particulate nature; and the process's flexibility in depositing magnetic materials with higher coercivity, enabled denser recording on thin-film disks than was feasible on oxide disks.

6. Richard J. Foster, *Innovation: The Attacker's Advantage* (New York: Summit Books, 1986).

7. The examples of technology change presented in Figures 1.1 and 1.2 introduce some ambiguity to the unqualified term *discontinuity*, as used by Giovanni Dosi (see "Technological Paradigms and Technological Trajectories," *Research Policy* [11] 1982), Michael L. Tushman and Philip Anderson (see "Technological Discontinuities and Organizational Environments," *Administrative Science Quarterly* [31], 1986), and others. The innovations in head and disk technology described in Figure 1.4 represent *positive* discontinuities in an established technological trajectory, while the trajectory-disrupting technologies charted in Figure 1.7 represent *negative* discontinuities. As will be shown below, established firms seemed quite capable of leading the industry over positive discontinuities, but generally lost their industry lead when faced with negative discontinuities.

8. This tendency consistently appears across a range of industries. Richard S. Rosenbloom and Clayton M. Christensen (in “Technological Discontinuities, Organizational Capabilities, and Strategic Commitments,” *Industrial and Corporate Change* [3], 1994, 655–685) suggest a much broader set of industries in which leading firms may have been toppled by technologically straightforward disruptive innovations than is covered in this book.

9. A summary of the data and procedures used to generate Figure 1.7 is included in Appendix 1.1.

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

11. This statement applies only to independent drive makers competing in the OEM market. Some of the vertically integrated computer makers, such as IBM, have survived across these generations with the benefit of a captive internal market. Even IBM, however, addressed the sequence of different emerging markets for disk drives by creating autonomous “start-up” disk drive organizations to address each one. Its San Jose organization focused on high-end (primarily mainframe) applications. A separate division in Rochester, MN, focused on mid-range computers and workstations. IBM created a different organization in Fujisawa, Japan, to produce drives for the desktop personal computer market.

12. This result is very different from that observed by Rebecca M. Henderson (see *The Failure of Established Firms in the Face of Technological Change: A Study of the Semiconductor Photolithographic Alignment Industry*, dissertation, Harvard University, 1988), who found the new-architecture aligners produced by the established manufacturers to be inferior in performance to those produced by entrant firms. One possible reason for these different results is that the successful entrants in the photolithographic aligner industry studied by Henderson brought to the new product a well-developed body of technological knowledge and experience 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 composed of managers and engineers who had defected from established drive manufacturing firms.

13. This finding is similar to the phenomenon observed by Joseph L. Bower, 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 specifically refers to manufacturing capacity, the same fundamental phenomenon —the power of the known needs of known customers in marshaling and directing the investments of a firm—affects response to disruptive technology. See Joseph L. Bower, *Managing the Resource Allocation Process* (Homewood, IL: Richard D. Irwin, 1970) 254.

14. In booking $113 million in revenues, Conner Peripherals set a record for booking more revenues in its first year of operation than any manufacturing company in United States history.

15. This finding is consistent with what Robert Burgelman has observed. He noted that one of the greatest difficulties encountered by corporate entrepreneurs has been finding the right "beta test sites" where products could be interactively developed and refined with customers. Generally, a new venture's entrée to the customer was provided by the salesperson representing the firm's established product lines. This helped the firm develop new products for established markets but not to identify new applications for new technology. See Robert A. Burgelman and Leonard Sayles, *Inside Corporate Innovation* (New York: The Free Press, 1986) 76–80.

16. I believe this insight—that attacking firms have an advantage in disruptive innovations but not in sustaining ones—clarifies, but is not in conflict with, Foster's assertions about the attacker's advantage. The historical examples Foster uses to substantiate his theory generally seem to have been disruptive innovations. See Richard J. Foster,

Innovation: The Attacker's Advantage (New York: Summit Books, 1986).

CHAPTER TWO

Value Networks and the Impetus to Innovate

From the earliest studies of the problems of innovation, scholars, consultants, and managers have tried to explain why leading firms frequently stumble when confronting technology change. Most explanations either zero in on managerial, organizational, and cultural responses to technological change or focus on the ability of established firms to deal with radically new technology; doing the latter requires a very different set of skills from those that an established firm historically has developed. Both approaches, useful in explaining why some companies stumble in the face of technological change, are summarized below. The primary purpose of this chapter, however, is to propose a third theory of why good companies can fail, based upon the concept of a *value network.* The value network concept seems to have much greater power than the other two theories in explaining what we observed in the disk drive industry.

ORGANIZATIONAL AND MANAGERIAL EXPLANATIONS OF FAILURE

One explanation for why good companies fail points to organizational impediments as the source of the problem. While many analyses of this type stop with such simple rationales as bureaucracy, complacency, or "risk-averse" culture, some remarkably insightful studies exist in this tradition. Henderson and Clark, [1] for example, conclude that companies' organizational structures typically facilitate component-level innovations, because most product development organizations consist of subgroups that correspond to a product's components. Such systems work very well as long as the product's fundamental architecture does not require change. But, say the authors, when architectural technology change is required, this type of structure impedes innovations that require people and groups to communicate and work together in new ways.

This notion has considerable face validity. In one incident recounted in Tracy Kidder's Pulitzer Prize–winning narrative, *The Soul of a New Machine*, Data General engineers developing a next-generation minicomputer intended to leapfrog the product position of Digital Equipment Corporation were allowed by a friend of one team member into his facility in the middle of the night to examine Digital's latest computer, which his company had just bought. When Tom West, Data General's project leader and a former long-time Digital employee, removed the cover of the DEC minicomputer and examined its structure, he saw "Digital's organization chart in the design of the product." [2]

Because an organization's structure and how its groups work together may have been established to facilitate the design of its dominant product, the direction of causality may ultimately reverse itself: The organization’s structure and the way its groups learn to work together can then affect the way it can and cannot design new products.

CAPABILITIES AND RADICAL TECHNOLOGY AS AN EXPLANATION

In assessing blame for the failure of good companies, the distinction is sometimes made between innovations requiring very different technological capabilities, that is, so-called radical change, and those that build upon well-practiced technological capabilities, often called incremental innovations. [3] The notion is that the magnitude of the technological change relative to the companies' capabilities will determine which firms triumph after a technology invades an industry. Scholars who support this view find that established firms tend to be good at improving what they have long been good at doing, and that entrant firms seem better suited for exploiting radically new technologies, often because they import the technology into one industry from another, where they had already developed and practiced it.

Clark, for example, has reasoned that companies build the technological capabilities in a product such as an automobile hierarchically and experientially. [4] An organization's historical choices about which technological problems it would solve and which it would avoid determine the sorts of skills and knowledge it accumulates. When optimal resolution of a product or process performance problem demands a very different set of knowledge than a firm has accumulated, it may very well stumble. The research of Tushman, Anderson, and their associates supports Clark's hypothesis. [5] They found that firms failed when a technological change destroyed the value of competencies previously cultivated and succeeded when new technologies enhanced them.

The factors identified by these scholars undoubtedly affect the fortunes of firms confronted with new technologies. Yet the disk drive industry displays a series of anomalies accounted for by neither set of theories. Industry leaders first introduced sustaining technologies of *every* sort, including architectural and component innovations that rendered prior competencies irrelevant and made massive investments in skills and assets obsolete. Nevertheless, these same firms stumbled over technologically straightforward but disruptive changes such as the 8-inch drive.

The history of the disk drive industry, indeed, gives a very different meaning to what constitutes a radical innovation among leading, established firms. As we saw, the nature of the technology involved (components versus architecture and incremental versus radical), the magnitude of the risk, and the time horizon over which the risks needed to be taken had little relationship to the patterns of leadership and followership observed. Rather, if their customers needed an innovation, the leading firms somehow mustered the resources and wherewithal to develop and adopt it. Conversely, if their customers did not want or need an innovation, these firms found it impossible to commercialize even technologically simple innovations.

VALUE NETWORKS AND NEW PERSPECTIVE ON THE DRIVERS OF FAILURE

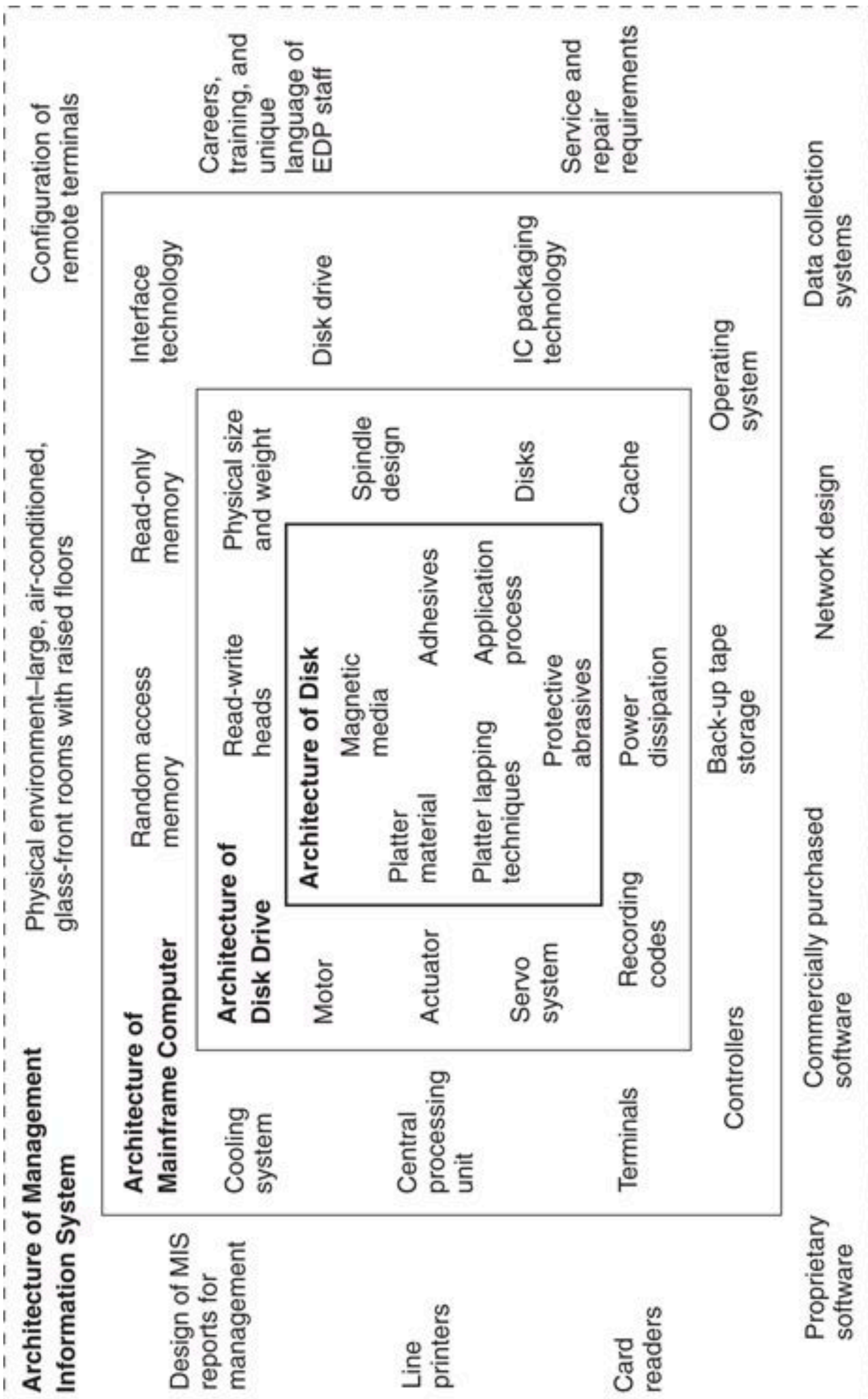
What, then, *does* account for the success and failure of entrant and established firms? The following discussion synthesizes from the history of the disk drive industry a new perspective on the relation between success or failure and changes in technology and market structure. The concept of the *value network*—the context within which a firm identifies and responds to customers' needs, solves problems, procures input, reacts to competitors, and strives for profit—is central to this synthesis. [6] Within a value network, each firm's competitive strategy, and particularly its past choices of markets, determines its perceptions of the economic value of a new technology. These perceptions, in turn, shape the rewards different firms expect to obtain through pursuit of sustaining and disruptive innovations. [7] In established firms, expected rewards, in their turn, drive the allocation of resources toward sustaining innovations and away from disruptive ones. This pattern of resource allocation accounts for established firms' consistent leadership in the former and their dismal performance in the latter.

Value Networks Mirror Product Architecture

Companies are embedded in value networks because their products generally are embedded, or nested hierarchically, as components within other products and eventually within end systems of use. [8] Consider a 1980s-vintage management information system (MIS) for a large organization, as illustrated in Figure 2.1. The architecture of the MIS ties together various components—a mainframe computer; peripherals such as line printers and tape and disk drives; software; a large, air-conditioned room with cables running under a raised floor; and so on. At the next level, the mainframe computer is itself an architected system, comprising such components as a central processing unit, multi-chip packages and circuit boards, RAM circuits, terminals, controllers, and disk drives. 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 constituting such a system of use may all be produced within a single, extensively integrated corporation such as AT&T or IBM, most are tradable, especially in more mature markets. This means that, while Figure 2.1 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 components at each level are made and sold to integrators at the next higher level in the system. Firms that design and assemble disk drives, for example, such as Quantum and Maxtor, procure read-write heads from firms specializing in the manufacture of those heads, and they buy disks from other firms and spin motors, actuator motors, and integrated circuitry from still others. At the next higher level, firms that design and assemble computers may buy their integrated circuits, terminals, disk drives, IC packaging, and power supplies from various firms that manufacture those particular products. This nested commercial system is a *value network.*

Figure 2.1 A Nested, or Telescoping, System of Product Architectures



Source: Reprinted from Research Policy 24, Clayton M. Christensen and Richard S. Rosenbloom, “Explaining the Attacker’s Advantage: Technological Paradigms, Organizational Dynamics, and the Value Network,” 233–257, 1995 with kind permission of Elsevier Science–NL, Sara Burgerhartstraat 25, 1055 KV Amsterdam, The Netherlands.

Figure 2.2 illustrates three value networks for computing applications: Reading top to bottom they are the value network for a corporate MIS system-of-use, for portable personal computing products, and for computer-automated design (CAD). Drawn only to convey the concept of how networks are bounded and may differ from each other, these depictions are not meant to represent complete structures.

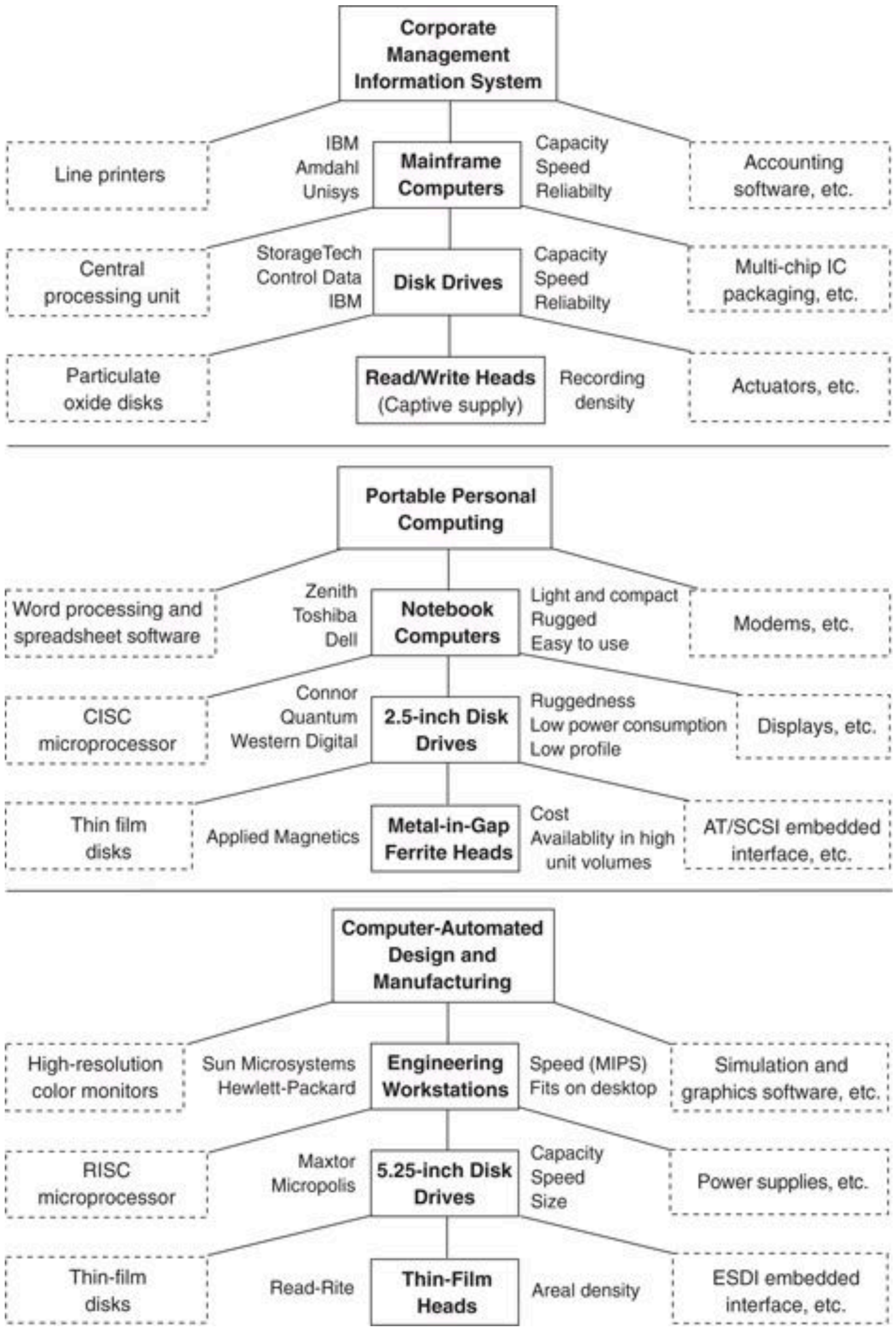
Metrics of Value

The way value is measured differs across networks. [9] In fact, the unique rank-ordering of the importance of various product performance attributes defines, in part, the boundaries of a value network. Examples in Figure 2.2, listed to the right of the center column of component boxes, show how each value network exhibits a very different rank-ordering of important product attributes, even for the same product. In the top-most value network, disk drive performance is measured in terms of capacity, speed, and reliability, whereas in the portable computing value network, the important performance attributes are ruggedness, low power consumption, and small size. Consequently, parallel value networks, each built around a different definition of what makes a product valuable, may exist within the same broadly defined industry.

Although many components in different systems-of-use may carry the same labels (for example, each network in Figure 2.2 involves read-write heads, disk drives, RAM circuits, printers, software, and so on), the nature of components used may be quite different. Generally, a set of competing firms, each with its own value chain, [10] is associated with each box in a network diagram, and the firms supplying the products and services used in each network often differ (as illustrated in Figure 2.2 by the firms listed to the left of the center column of component boxes).

As firms gain experience within a given network, they are likely to develop capabilities, organizational structures, and cultures tailored to their value network's distinctive requirements. Manufacturing volumes, the slope of ramps to volume production, product development cycle times, and organizational consensus identifying the customer and the customer's needs may differ substantially from one value network to the next.

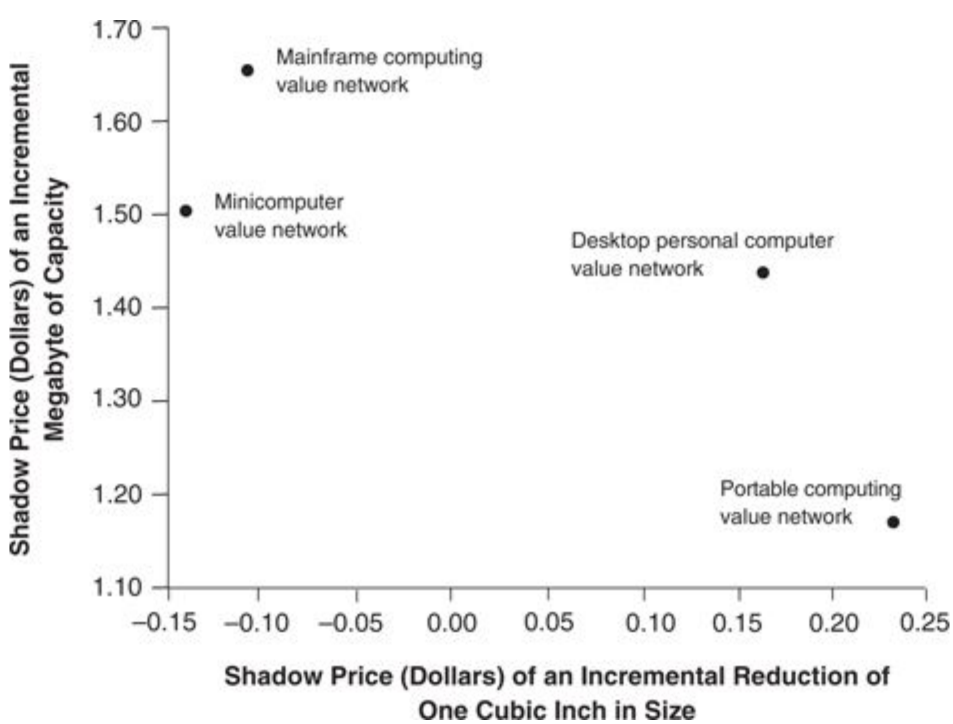
Figure 2.2 Examples of Three Value Networks



Source: Reprinted from *Research Policy* 24, Clayton M. Christensen and Richard S. Rosenbloom, “Explaining the Attacker’s Advantage: Technological Paradigms, Organizational Dynamics, and the Value Network,” 233–257, 1995 with kind permission of Elsevier Science—NL, Sara Burgerhartstraat 25, 1055 KV Amsterdam, The Netherlands.

Given the data on the prices, attributes, and performance characteristics of thousands of disk drive models sold between 1976 and 1989, we can use a technique called *hedonic regression analysis* to identify how markets valued individual attributes and how those attribute values changed over time. Essentially, hedonic regression analysis expresses the total price of a product as the sum of individual so-called shadow prices (some positive, others negative) that the market places on each of the product's characteristics. Figure 2.3 shows some results of this analysis to illustrate how different value networks can place very different values on a given performance attribute. Customers in the mainframe computer value network in 1988 were willing on average to pay $1.65 for an incremental megabyte of capacity; but moving across the minicomputer, desktop, and portable computing value networks, the shadow price of an incremental megabyte of capacity declines to $1.50, $1.45, and $1.17, respectively. Conversely, portable and desktop computing customers were willing to pay a high price in 1988 for a cubic inch of size reduction, while customers in the other networks placed no value on that attribute at all. [11]

Figure 2.3 Difference in the Valuation of Attributes Across Different Value Networks



Cost Structures and Value Networks

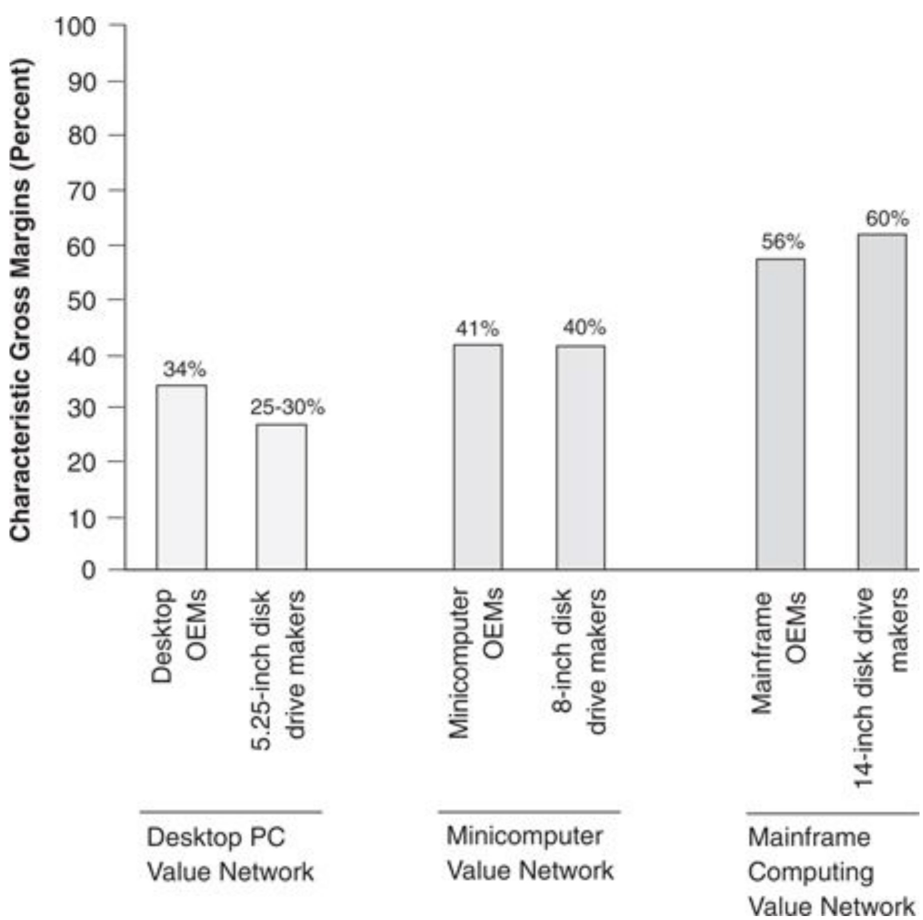
The definition of a value network goes beyond the attributes of the physical product. For example, competing within the mainframe computer network shown in Figure 2.2 entails a particular cost structure. Research, engineering, and development costs are substantial. Manufacturing overheads are high relative to direct costs because of low unit volumes and customized product configurations. Selling directly to end users involves significant sales force costs, and the field service network to support the complicated machines represents a substantial ongoing expense. All these costs must be incurred in order to provide the types of products and services customers in this value network require. For these reasons, makers of mainframe computers, and makers of the 14-inch disk drives sold to them, historically needed gross profit margins of between 50 percent and 60 percent to cover the overhead cost structure inherent to the value network in which they competed.

Competing in the portable computer value network, however, entails a very different cost structure. These computer makers incur little expense researching component technologies, preferring to build their machines with proven component technologies procured from vendors. Manufacturing involves assembling millions of standard products in low-labor-cost regions. Most sales are made through national retail chains or by mail order. As a result, companies in this value network can be profitable with gross margins of 15 percent to 20 percent. Hence, just as a value network is characterized by a specific rank-ordering of product attributes valued by customers, it is also characterized by a specific cost structure required to provide the valued products and services.

Each value network's unique cost structure is illustrated in Figure 2.4. Gross margins typically obtained by manufacturers of 14-inch disk drives, about 60 percent, are similar to those required by mainframe computer makers: 56 percent. Likewise, the margins 8-inch drive makers earned were similar to those earned by minicomputer companies (about 40 percent), and the margins typical of the desktop value network, 25 percent, also typified both the computer makers and their disk drive suppliers.

The cost structures characteristic of each value network can have a powerful effect on the sorts of innovations firms deem profitable. Essentially, innovations that are valued within a firm's value network, or in a network where characteristic gross margins are higher, will be perceived as profitable. Those technologies whose attributes make them valuable only in networks with *lower* gross margins, on the other hand, will not be viewed as profitable, and are unlikely to attract resources or managerial interest. (We will explore the impact of each value network's characteristic cost structures upon the established firms' mobility and fortunes more fully in chapter 4.)

Figure 2.4 Characteristic Cost Structures of Different Value Networks



Source: Data are from company annual reports and personal interviews with executives from several representative companies in each network.

In sum, the attractiveness of a technological opportunity and the degree of difficulty a producer will encounter in exploiting it are determined by, among other factors, the firm's position in the relevant value network. As we shall see, the manifest strength of established firms in sustaining innovation and their weakness in disruptive 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.

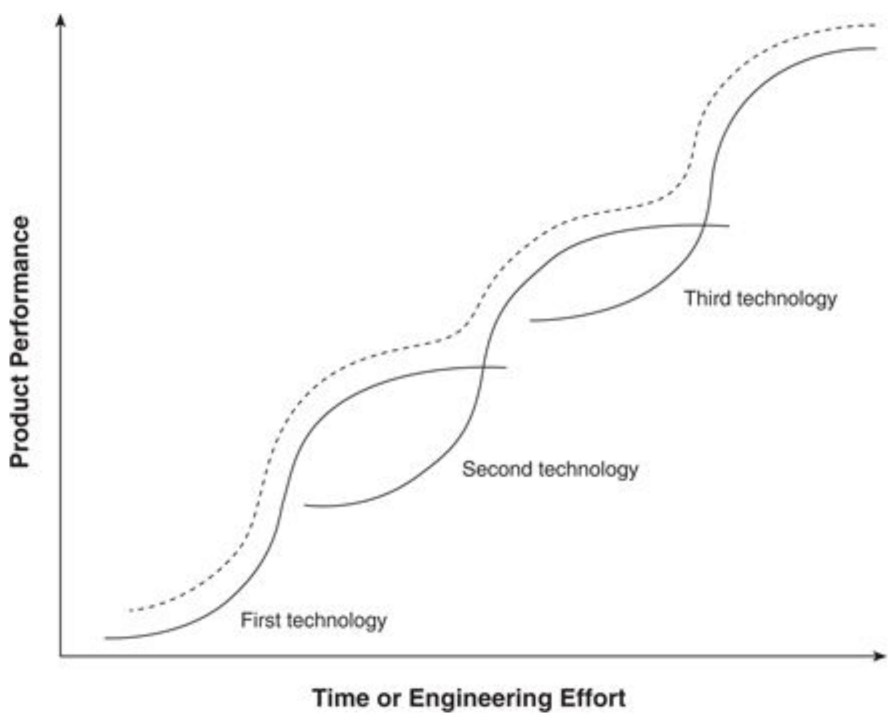
TECHNOLOGY S-CURVES AND VALUE NETWORKS

The technology S-curve forms the centerpiece of thinking about technology strategy. It suggests that the magnitude of a product's performance improvement in a given time period or due to a given amount of engineering effort is likely to differ as technologies mature. The theory posits that in the early stages of a technology, the rate of progress in performance will be relatively slow. As the technology becomes better understood, controlled, and diffused, the rate of technological improvement will accelerate. [12] But in its mature stages, the technology will asymptotically approach a natural or physical limit such that ever greater periods of time or inputs of engineering effort will be required to achieve improvements. Figure 2.5 illustrates the resulting pattern.

Many scholars have asserted that the essence of strategic technology management is to identify when the point of inflection on the present technology's S-curve has been passed, and to identify and develop whatever successor technology rising from below will eventually supplant the present approach. Hence, as depicted by the dotted curve in Figure 2.5, the challenge is to successfully switch technologies at the point where S-curves of old and new intersect. The inability to anticipate new technologies threatening from below and to switch to them in a timely way has often been cited as the cause of failure of established firms and as the source of advantage for entrant or attacking firms. [13]

How do the concepts of S-curves and of value networks relate to each other? [14] The typical framework of intersecting S-curves illustrated in Figure 2.5 is a conceptualization of *sustaining* technological changes within a single value network, where the vertical axis charts a single measure of product performance (or a rank-ordering of attributes). Note its similarity to Figure 1.4, which measured the sustaining impact of new recording head technologies on the recording density of disk drives. Incremental improvements within each technology drove improvements along each of the individual curves, while movement to new head technologies involved a more radical leap. Recall that there was not a *single* example in the history of technological innovation in the disk drive industry of an entrant firm leading the industry or securing a viable market position with a sustaining innovation. In every instance, the firms that anticipated the eventual flattening of the current technology and that led in identifying, developing, and implementing the new technology that sustained the overall pace of progress were the leading practitioners of the prior technology. These firms often incurred enormous financial risks, committing to new technologies a decade or more in advance and wiping out substantial bases of assets and skills. Yet despite these challenges, managers of the industry's established firms navigated the dotted line course shown in Figure 2.5 with remarkable, consistent agility.

Figure 2.5 The Conventional Technology S-Curve

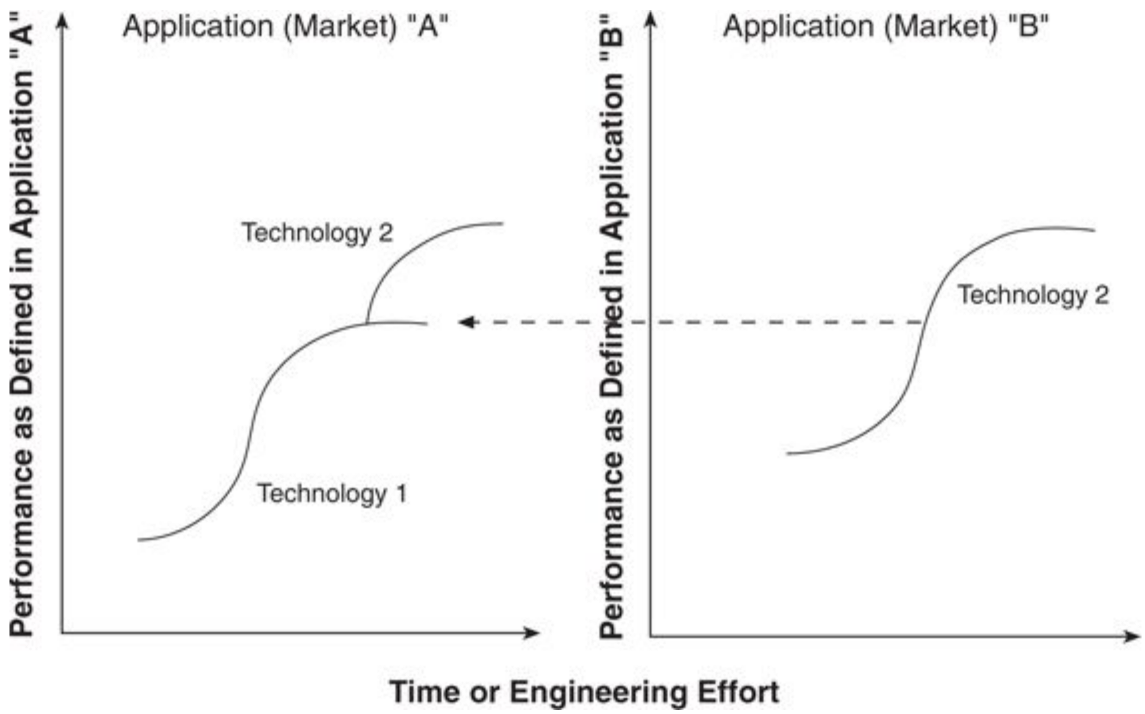


Source: Clayton M. Christensen, "Exploring the Limits of the Technology S-Curve. Part I: Component Technologies," *Production and Operations Management* 1, no. 4 (Fall 1992): 340. Reprinted by permission.

A disruptive innovation, however, cannot be plotted in a figure such as 2.5, because the vertical axis for a disruptive innovation, by definition, must measure *different* attributes of performance than those relevant in established value networks. Because a disruptive technology gets its commercial start in emerging value networks before invading established networks, an S-curve framework such as that in Figure 2.6 is needed to describe it. Disruptive technologies emerge and progress on their own, uniquely defined trajectories, in a home value network. If and when they progress to the point that they can satisfy the level and nature of performance demanded in another value network, the disruptive technology can then invade it, knocking out the established technology and its established practitioners, with stunning speed.

Figures 2.5 and 2.6 illustrate clearly the innovator's dilemma that precipitates the failure of leading firms. In disk drives (and in the other industries covered later in this book), prescriptions such as increased investments in R&D; longer investment and planning horizons; technology scanning, forecasting, and mapping; as well as research consortia and joint ventures are all relevant to the challenges posed by the *sustaining* innovations whose ideal pattern is depicted in Figure 2.5. Indeed, the evidence suggests that many of the best established firms have applied these remedies and that they can work when managed well in treating sustaining technologies. But none of these solutions addresses the situation in Figure 2.6, because it represents a threat of a fundamentally different nature.

Figure 2.6 Disruptive Technology S-Curve



Source: Clayton M. Christensen, "Exploring the Limits of the Technology S-Curve. Part I: Component Technologies," *Production and Operations Management* 1, no. 4 (Fall 1992): 361. Reprinted by permission.

MANAGERIAL DECISION MAKING AND DISRUPTIVE TECHNOLOGICAL CHANGE

Competition within the value networks in which companies are embedded defines in many ways how the firms can earn their money. The network defines the customers' problems to be addressed by the firm's products and services and how much can be paid for solving them. Competition and customer demands in the value network in many ways shape the firms' cost structure, the firm size required to remain competitive, and the necessary rate of growth. Thus, managerial decisions that make sense for companies outside a value network may make no sense at all for those within it, and vice versa.

We saw, in chapter 1, a stunningly consistent pattern of successful implementation of sustaining innovations by established firms and their failure to deal with disruptive ones. The pattern was consistent because the managerial decisions that led to those outcomes made sense. Good managers do what makes sense, and what makes sense is primarily shaped by their value network.

This decision-making pattern, outlined in the six steps below, emerged from my interviews with more than eighty managers who played key roles in the disk drive industry's leading firms, both incumbents and entrants, at times when disruptive technologies had emerged. In these interviews I tried to reconstruct, as accurately and from as many points of view as possible, the forces that influenced these firms' decision-making processes regarding the development and commercialization of technologies either relevant or irrelevant to the value networks in which the firms were at the time embedded. My findings consistently showed that established firms confronted with disruptive technology change did not have trouble developing the requisite *technology:* Prototypes of the new drives had often been developed before management was asked to make a decision. Rather, disruptive projects stalled when it came to allocating scarce resources among competing product and technology development proposals (allocating resources between the two value networks shown at right and left in Figure 2.6, for example). Sustaining projects addressing the needs of the firms' most powerful customers (the new waves of technology within the value network depicted in Figure 2.5) *almost always* preempted resources from disruptive technologies with small markets and poorly defined customer needs.

This characteristic pattern of decisions is summarized in the following pages. Because the experience was so archetypical, the struggle of Seagate Technology, the industry's dominant maker of 5.25-inch drives, to successfully commercialize the disruptive 3.5-inch drive is recounted in detail to illustrate each of the steps in the pattern. [15]

[illegible]~

[illegible]

- [illegible]
- [illegible]
- [illegible]

[illegible][illegible] https://www.chenjin5.com

- [illegible]
- [illegible]
- [illegible]

Step 1: Disruptive Technologies Were First Developed within Established Firms

Although entrants led in *commercializing* disruptive technologies, their development was often the work of engineers at established firms, using bootlegged resources. Rarely initiated by senior management, these architecturally innovative designs almost always employed off-the-shelf components. Thus, engineers at Seagate Technology, the leading 5.25-inch drive maker, were, in 1985, the second in the industry to develop working prototypes of 3.5-inch models. They made some eighty prototype models before the issue of formal project approval was raised with senior management. The same thing happened earlier at Control Data and Memorex, the dominant 14-inch drive makers, where engineers had designed working 8-inch drives internally, nearly two years before the product appeared in the market.

Step 2: Marketing Personnel Then Sought Reactions from Their Lead Customers

The engineers then showed their prototypes to marketing personnel, asking whether a market for the smaller, less expensive (and lower performance) drives existed. The marketing organization, using its habitual procedure for testing the market appeal of new drives, showed the prototypes to lead customers of the existing product line, asking them for an evaluation. [16] Thus, Seagate marketers tested the new 3.5-inch drives with IBM's PC Division and other makers of XT-and AT-class desktop personal computers—even though the drives had significantly less capacity than the mainstream desktop market demanded.

Not surprisingly, therefore, IBM showed no interest in Seagate's disruptive 3.5-inch drives. IBM's engineers and marketers were looking for 40 and 60 MB drives, and they already had a slot for 5.25-inch drives designed into their computer; they needed new drives that would take them further along their established performance trajectory. Finding little customer interest, Seagate's marketers drew up pessimistic sales forecasts. In addition, because the products were simpler, with lower performance, forecast profit margins were lower than those for higher performance products, and Seagate's financial analysts, therefore, joined their marketing colleagues in opposing the disruptive program. Working from such input, senior managers shelved the 3.5-inch drive—just as it was becoming firmly established in the laptop market.

This was a complex decision, made in a context of competing proposals to expend the same resources to develop new products that marketers felt were critical to remaining competitive with current customers and achieving aggressive growth and profit targets. "We needed a new model," recalled a former Seagate manager, "which could become the next ST412 [a very successful product generating $300 million sales annually in the desktop market that was near the end of its life cycle]. Our forecasts for the 3.5-inch drive were under $50 million because the laptop market was just emerging, and the 3.5-inch product just didn't fit the bill."

Seagate managers made an explicit decision not to pursue the disruptive technology. In other cases, managers did approve resources for pursuing a disruptive product—but, in the day-to-day decisions about how time and money would actually be allocated, engineers and marketers, acting in the best interests of the company, consciously and unconsciously starved the disruptive project of resources necessary for a timely launch.

When engineers at Control Data, the leading 14-inch drive maker, were officially chartered to develop CDC's initial 8-inch drives, its customers were looking for an average of 300 MB per computer, whereas CDC's earliest 8-inch drives offered less than 60 MB. The 8-inch project was given low priority, and engineers assigned to its development kept getting pulled off to work on problems with 14-inch drives being designed for more important customers. Similar problems plagued the belated launches of Quantum's and Micropolis's 5.25-inch products.

Step 3: Established Firms Step Up the Pace of Sustaining Technological Development

In response to the needs of current customers, the marketing managers threw impetus behind alternative sustaining projects, such as incorporating better heads or developing new recording codes. These gave customers what they wanted and could be targeted at large markets to generate the necessary sales and profits for maintaining growth. Although often involving greater development expense, such sustaining investments appeared *far* less risky than investments in the disruptive technology: The customers existed, and their needs were known.

Seagate's decision to shelve the 3.5-inch drive in 1985 to 1986, for example, seems starkly rational. Its view downmarket (in terms of the disk drive trajectory map) was toward a small total market forecast for 1987 for 3.5-inch drives. Gross margins in that market were uncertain, but manufacturing executives predicted that costs per megabyte for 3.5-inch drives would be much higher than for 5.25-inch drives. Seagate's view upmarket was quite different. Volumes in 5.25-inch drives with capacities of 60 to 100 MB were forecast to be $500 million by 1987. Companies serving the 60 to 100 MB market were earning gross margins of between 35 and 40 percent, whereas Seagate's margins in its high-volume 20 MB drives were between 25 and 30 percent. It simply did not make sense for Seagate to put its resources behind the 3.5-inch drive when competing proposals to move upmarket by developing its ST251 line of drives were also being actively evaluated.

After Seagate executives shelved the 3.5-inch project, the firm began introducing new 5.25-inch models at a dramatically accelerated rate. In 1985, 1986, and 1987, the numbers of new models annually introduced as a percentage of the total number of its models on the market in the prior year were 57, 78, and 115 percent, respectively. And during the same period, Seagate incorporated complex and sophisticated new component technologies such as thin-film disks, voice-coil actuators, [17] RLL codes, and embedded SCSI interfaces.

Clearly, the motivation in doing this was to win the competitive wars against other established firms, which were making similar improvements, rather than to prepare for an attack by entrants from below. [18]

Step 4: New Companies Were Formed, and Markets for the Disruptive Technologies Were Found by Trial and Error

New companies, usually including frustrated engineers from established firms, were formed to exploit the disruptive product architecture. The founders of the leading 3.5-inch drive maker, Conner Peripherals, were disaffected employees from Seagate and Miniscribe, the two largest 5.25-inch manufacturers. The founders of 8-inch drive maker Micropolis came from Pertec, a 14-inch drive manufacturer, and the founders of Shugart and Quantum defected from Memorex. [19]

The start-ups, however, were as unsuccessful as their former employers in attracting established computer makers to the disruptive architecture. Consequently, they had to find *new* customers. The applications that emerged in this very uncertain, probing process were the minicomputer, the desktop personal computer, and the laptop computer. In retrospect, these were obvious markets for hard drives, but at the time, their ultimate size and significance were highly uncertain. Micropolis was founded before the emergence of the desk-side minicomputer and word processor markets in which its products came to be used. Seagate began when personal computers were simple toys for hobbyists, two years before IBM introduced its PC. And Conner Peripherals got its start before Compaq knew the potential size of the portable computer market. The founders of these firms sold their products without a clear marketing strategy— essentially selling to whoever would buy. Out of what was largely a trial-and-error approach to the market, the ultimately dominant applications for their products emerged.

Step 5: The Entrants Moved Upmarket

Once the start-ups had discovered an operating base in new markets, they realized that, by adopting sustaining improvements in new component technologies, [20] they could increase the capacity of their drives at a faster rate than their new market required. They blazed trajectories of 50 percent annual improvement, fixing their sights on the large, established computer markets immediately above them on the performance scale.

The established firms' views downmarket and the entrant firms' views upmarket were asymmetrical. In contrast to the unattractive margins and market size that established firms saw when eyeing the new, emerging markets for simpler drives, the entrants saw the potential volumes and margins in the upscale, high-performance markets above them as highly attractive. Customers in these established markets eventually embraced the new architectures they had rejected earlier, because once their needs for capacity and speed were met, the new drives' smaller size and architectural simplicity made them cheaper, faster, and more reliable than the older architectures. Thus, Seagate, which started in the desktop personal computer market, subsequently invaded and came to dominate the minicomputer, engineering workstation, and mainframe computer markets for disk drives. Seagate, in turn, was driven from the desktop personal computer market for disk drives by Conner and Quantum, the pioneering manufacturers of 3.5-inch drives.

Step 6: Established Firms Belatedly Jumped on the Bandwagon to Defend Their Customer Base

When the smaller models began to invade established market segments, the drive makers that had initially controlled those markets took their prototypes off the shelf (where they had been put in Step 3) and introduced them in order to defend their customer base in their own market. By this time, of course, the new architecture had shed its disruptive character and become fully performance-competitive with the larger drives in the established markets. Although some established manufacturers were able to defend their market positions through belated introduction of the new architecture, many found that the entrant firms had developed insurmountable advantages in manufacturing cost and design experience, and they eventually withdrew from the market. The firms attacking from value networks below brought with them cost structures set to achieve profitability at lower gross margins. The attackers therefore were able to price their products profitably, while the defending, established firms experienced a severe price war.

For established manufacturers that did succeed in introducing the new architectures, survival was the only reward. None ever won a significant share of the new market; the new drives simply cannibalized sales of older products to existing customers. Thus, as of 1991, almost none of Seagate's 3.5-inch drives had been sold to portable/laptop manufacturers: Its 3.5-inch customers still were desktop computer manufacturers, and many of its 3.5-inch drives continued to be shipped with frames permitting them to be mounted in XT-and AT-class computers designed to accommodate 5.25-inch drives.

Control Data, the 14-inch leader, never captured even a 1 percent share of the minicomputer market. It introduced its 8-inch drives nearly three years after the pioneering start-ups did, and nearly all of its drives were sold to its existing mainframe customers. Miniscribe, Quantum, and Micropolis all had the same cannibalistic experience when they belatedly introduced disruptive technology drives. They failed to capture a significant share of the new market, and at best succeeded in defending a portion of their prior business.

The popular slogan “stay close to your customers” appears not always to be robust advice. [21] One instead might expect customers to lead their suppliers toward sustaining innovations and to provide no leadership—or even to explicitly *mis*lead—in instances of disruptive technology change. [22]

FLASH MEMORY AND THE VALUE NETWORK

The predictive power of the value network framework is currently being tested with the emergence of *flash memory:* a solid-state semiconductor memory technology that stores data on silicon memory chips. Flash differs from conventional dynamic random access memory (DRAM) technology in that the chip retains the data even when the power is off. Flash memory is a disruptive technology. Flash chips consume less than 5 percent of the power that a disk drive of equivalent capacity would consume, and because they have no moving parts, they are far more rugged than disk memory. Flash chips have disadvantages, of course. Depending on the amount of memory, the cost per megabyte of flash can be between five and fifty times greater than disk memory. And flash chips are not as robust for writing: They can only be overwritten a few hundred thousand times before wearing out, rather than a few million times for disk drives.

The initial applications for flash memory were in value networks quite distant from computing; they were in devices such as cellular phones, heart monitoring devices, modems, and industrial robots in which individually packaged flash chips were embedded. Disk drives were too big, too fragile, and used too much power to be used in these markets. By 1994, these applications for individually packaged flash chips —“socket flash” in industry parlance—accounted for $1.3 billion in industry revenues, having grown from nothing in 1987.

In the early 1990s, the flash makers produced a new product format, called a flash card: credit card–sized devices on which multiple flash chips, linked and governed by controller circuitry, were mounted. The chips on flash cards were controlled by the same control circuitry, SCSI (Small Computer Standard Interface, an acronym first used by Apple), as was used in disk drives, meaning that in concept, a flash card could be used like a disk drive for mass storage. The flash card market grew from $45 million in 1993 to $80 million in 1994, and forecasters were eyeing a $230 million flash card market by 1996.

Will flash cards invade the disk drive makers' core markets and supplant magnetic memory? If they do, what will happen to the disk drive makers? Will they stay atop their markets, catching this new technological wave? Or will they be driven out?

The Capabilities Viewpoint

Clark's concept of technological hierarchies (see note 4) focuses on the skills and technological understanding that a company accumulates as the result of the product and process technology problems it has addressed in the past. In evaluating the threat to the disk drive makers of flash memory, someone using Clark's framework, or the related findings of Tushman and Anderson (see note 5), would focus on the extent to which disk drive makers have historically developed expertise in integrated circuit design and in the design and control of devices composed of multiple integrated circuits. These frameworks would lead us to expect that drive makers will stumble badly in their attempts to develop flash products if they have limited expertise in these domains and will succeed if their experience and expertise are deep.

On its surface, flash memory involves radically different *electronics* technology than the core competence of disk drive makers (magnetics and mechanics). But such firms as Quantum, Seagate, and Western Digital have developed deep expertise in custom integrated circuit design through embedding increasingly intelligent control circuitry and cache memory in their drives. Consistent with the practice in much of the ASIC (application-specific integrated circuit) industry, their controller chips are fabricated by independent, third-party fabricators that own excess clean room semiconductor processing capacity.

Each of today's leading disk drive manufacturers got its start by designing drives, procuring components from independent suppliers, assembling them either in its own factories or by contract, and then selling them. The flash card business is very similar. Flash card makers design the card and procure the component flash chips; they design and have fabricated an interface circuit, such as SCSI, to govern the drive's interaction with the computing device; they assemble them either in-house or by contract; and they then market them.

In other words, flash memory actually *builds upon* important competencies that many drive makers have developed. The capabilities viewpoint, therefore, would lead us to expect that disk drive makers may *not* stumble badly in bringing flash storage technology to the market. More specifically, the viewpoint predicts that those firms with the deepest experience in IC design—Quantum, Seagate, and Western Digital—will bring flash products to market quite readily. Others, which historically outsourced much of their electronic circuit design, may face more of a struggle.

This has, indeed, been the case to date. Seagate entered the flash market in 1993 via its purchase of a 25 percent equity stake in Sundisk Corporation. Seagate and SunDisk together designed the chips and cards; the chips were fabricated by Matsushita, and the cards were assembled by a Korean manufacturer, Anam. Seagate itself marketed the cards. Quantum entered with a different partner, Silicon Storage Technology, which designed the chips that were then fabricated and assembled by contract.

The Organizational Structure Framework

Flash technology is what Henderson and Clark would call *radical* technology. Its product architecture and fundamental technological concept are novel compared to disk drives. The organizational structure viewpoint would predict that, unless they created organizationally independent groups to design flash products, established firms would stumble badly. Seagate and Quantum did, indeed, rely on independent groups and did develop competitive products.

The Technology S-Curve Framework

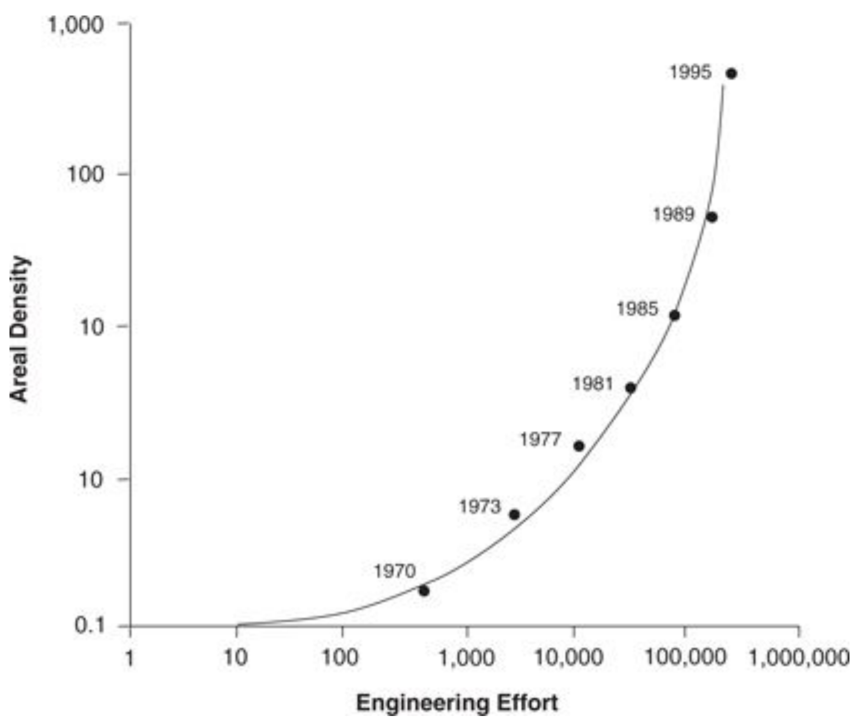
The technology S-curve is often used to predict whether an emerging technology is likely to supplant an established one. The operative trigger is the slope of the curve of the established technology. If the curve has passed its point of inflection, so that its second derivative is negative (the technology is improving at a decreasing rate), then a new technology may emerge to supplant the established one. Figure 2.7 shows that the S-curve for magnetic disk recording still has not hit its point of inflection: Not only is the areal density improving, as of 1995, it was improving at an *increasing* rate.

The S-curve framework would lead us to predict, therefore, that whether or not established disk drive companies possess the capability to design flash cards, flash memory will not pose a threat to them until the magnetic memory S-curve has passed its point of inflection and the rate of improvement in density begins to decline.

Insights from the Value Network Framework

The value network framework asserts that none of the foregoing frameworks is a sufficient predictor of success. Specifically, even where established firms did not possess the requisite technological skills to develop a new technology, they would marshal the resources to develop or acquire them if their customers demanded it. Furthermore, the value network suggests that technology S-curves are useful predictors only with sustaining technologies. Disruptive technologies generally improve at a parallel pace with established ones—their trajectories do not intersect. The S-curve framework, therefore, asks the *wrong question* when it is used to assess disruptive technology. What matters instead is whether the disruptive technology is improving from below along a trajectory that will ultimately intersect with what the *market* needs.

Figure 2.7 Improvements in Areal Density of New Disk Drives (Densities in Millions of Bits per Square Inch)

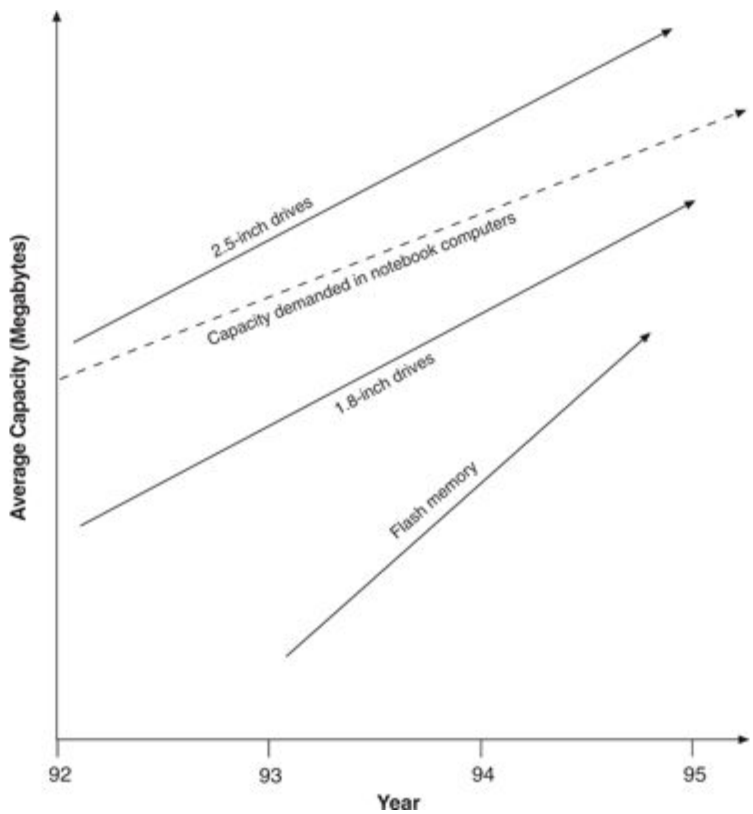


Source: Data are from various issues of *Disk/Trend Report.*

The value network framework would assert that even though firms such as Seagate and Quantum are able *technologically* to develop competitive flash memory products, whether they invest the resources and managerial energy to build strong market positions in the technology will depend on whether flash memory can be initially valued and deployed within the value networks in which the firms make their money.

As of 1996, flash memory can only be used in value networks different from those of the typical disk drive maker. This is illustrated in Figure 2.8, which plots the average megabytes of capacity of flash cards introduced each year between 1992 and 1995, compared with the capacities of 2.5-and 1.8-inch drives and with the capacity demanded in the notebook computer market. Even though they are rugged and consume little power, flash cards simply don't yet pack the capacity to become the main mass storage devices in notebook computers. And the price of the flash capacity required to meet what the low end of the portable computing market demands (about 350 MB in 1995) is too high: The cost of that much flash capacity would be fifty times higher than comparable disk storage. [23]

Figure 2.8 Comparison of Disk Drive Memory Capacity to Flash Card



Source: Data are from various issues of *Disk/Trend Report.*

The low power consumption and ruggedness of flash certainly have no value and command no price premium on the desktop. There is, in other words, no way to use flash today in the markets where firms such as Quantum and Seagate make their money.

Hence, because flash cards are being used in markets completely different from those Quantum and Seagate typically engage—palmtop computers, electronic clipboards, cash registers, electronic cameras, and so on—the value network framework would predict that firms similar to Quantum and Seagate are *not* likely to build market-leading positions in flash memory. This is not because the technology is too difficult or their organizational structures impede effective development, but because their resources will become absorbed in fighting for and defending larger chunks of business in the mainstream disk drive value networks in which they currently make their money.

Indeed, the marketing director for a leading flash card producer observed, "We're finding that as hard disk drive manufacturers move up to the gigabyte range, they are unable to be cost competitive at the lower capacities. As a result, disk drive makers are pulling out of markets in the 10 to 40 megabyte range and creating a vacuum into which flash can move." [24]

The drive makers' efforts to build flash card businesses have in fact floundered. By 1995, neither Quantum nor Seagate had built market shares of even 1 percent of the flash card market. Both companies subsequently concluded that the opportunity in flash cards was not yet substantial enough, and withdrew their products from the market the same year. Seagate retained its minority stake in SunDisk (renamed SanDisk), however, a strategy which, as we shall see, is an effective way to address disruptive technology.

[illegible]~

[illegible]

- [illegible]
- [illegible]
- [illegible]

[illegible][illegible] https://www.chenjin5.com

- [illegible]
- [illegible]
- [illegible]

IMPLICATIONS OF THE VALUE NETWORK FRAMEWORK FOR INNOVATION

Value networks strongly define and delimit what companies within them can and cannot do. This chapter closes with five propositions about the nature of technological change and the problems successful incumbent firms encounter, which the value network perspective highlights.

1. The context, or value network, in which a firm competes has a profound influence on its ability to marshal and focus the necessary resources and capabilities to overcome the technological and organizational hurdles that impede innovation. The boundaries of a value network are determined by a unique definition of product performance—a rank-ordering of the importance of various performance attributes differing markedly from that employed in other systems-of-use in a broadly defined industry. Value networks are also defined by particular cost structures inherent in addressing customers' needs within the network.

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

3. Established firms' decisions to ignore technologies that do not address their customers' needs become fatal when two distinct trajectories interact. The first defines the performance demanded over time within a given value network, and the second traces the performance that technologists are able to provide within a given technological paradigm. The trajectory of performance improvement that technology is able to provide may have a distinctly different slope from the trajectory of performance improvement demanded in the system-of-use by downstream customers within any given value network. When the slopes of these two trajectories are similar, we expect the technology to remain relatively contained within its initial value network. But when the slopes differ, new technologies that are initially 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 diminished the relevance of differences in the rank-ordering of performance attributes across different value networks. For example, the disk drive attributes of size and weight were far more important in the desktop computing value network than they were in the mainframe and minicomputer value networks. When technological progress in 5.25-inch drives enabled manufacturers to satisfy the attribute prioritization in the mainframe and minicomputer networks, which prized total capacity and high speed, *as well as* that in the desktop network, the boundaries between the value networks ceased to be barriers to entry for 5.25-inch drive makers.

4. Entrant firms have an attacker's advantage over established firms in those innovations—generally new product architectures involving little new technology per se—that disrupt or redefine the level, rate, and direction of progress in an established technological trajectory. This is so because such technologies generate no value within the established network. The only way established firms can lead in commercializing such technologies is to enter the value network in which they create value. As Richard Tedlow noted in his history of retailing in America (in which supermarkets and discount retailing play the role of disruptive technologies), "the most formidable barrier the established firms faced is that they did not want to do this." [25]

5. In these instances, although this “attacker’s advantage” is *associated* with a disruptive technology change, the essence of the attacker’s advantage is in the ease with which entrants, relative to incumbents, can identify and make strategic commitments to attack and develop emerging market applications, or value networks. At its core, therefore, the issue may be the relative flexibility of successful established firms versus entrant firms to change *strategies and cost structures*, not technologies.

These propositions provide new dimensions for analyzing technological innovation. In addition to the required capabilities inherent in new technologies and in the innovating organization, firms faced with disruptive technologies must examine the implications of innovation for their relevant value networks. The key considerations are whether the performance attributes implicit in the innovation will be valued within the networks already served by the innovator; whether other networks must be addressed or new ones created in order to realize value for the innovation; and whether market and technological trajectories may eventually intersect, carrying technologies that do not address customers’ needs today to squarely address their needs in the future.

These considerations apply not simply to firms grappling with the most modern technologies, such as the fast-paced, complex advanced electronic, mechanical, and magnetics technologies covered in this chapter. Chapter 3 examines them in the context of a very different industry: earthmoving equipment.

NOTES

1. See Rebecca M. Henderson and Kim B. Clark, "Architectural Innovation: The Reconfiguration of Existing Systems and the Failure of Established Firms" *Administrative Science Quarterly* (35), 1990, 9–30.

2. Tracy Kidder, *The Soul of a New Machine* (New York: Avon Books, Inc., 1981).

3. A few scholars have sought to measure the proportion of technological progress attributable to radical versus incremental advances. In an empirical study of a series of novel processes in petroleum refining, for example, John Enos found that half the economic benefits of new technology came from process improvements introduced after a new technology was commercially established. See J. L. Enos, "Invention and Innovation in the Petroleum Refining Industry," in *The Rate and Direction of Inventive Activity: Economic and Social Factors*, National Bureau of Economic Research Report (Princeton, NJ: Princeton University Press, 1962), 299–321. My study of the disk drive industry has shown the same result. Half the advance in areal density (megabits per square inch of disk surface) can be attributed to new component technologies and half to incremental improvements in existing components and refinements in system design. See Clayton M. Christensen, "Exploring the Limits of the Technology S-Curve," *Production and Operations Management* (1), 1992, 334–366.

4. See Kim B. Clark, "The Interaction of Design Hierarchies and Market Concepts in Technological Evolution," *Research Policy* (14), 1985, 235–251. Clark suggests, for example, that the early selections by automotive engineers of gasoline over steam or electrically powered engines defined the technical agenda for subsequent generations of engineers, who consequently did not pursue refinements in electric or steam propulsion. Clark has thus shown that the design skills and technological knowledge resident in companies today result from the cumulative choices engineers have made of what to tackle versus what

to leave alone. Clark posits that technological improvements requiring that companies build upon or extend an existing cumulative body of knowledge favor an industry's established firms. Conversely, when changes require a completely different body of knowledge, established firms will be at a disadvantage compared to firms that had already accumulated a different hierarchically structured body of knowledge, most likely in another industry.

5. See, for example, Michael L. Tushman and Philip Anderson, "Technological Discontinuities and Organizational Environments," *Administrative Science Quarterly* (31), 1986, 439–465; and Philip Anderson and Michael Tushman, "Technological Discontinuities and Dominant Designs," *Administrative Science Quarterly* (35), 1990, 604–633.

6. The concept of *value network* builds on Giovanni Dosi's concept of *technological paradigms.* See Giovanni Dosi, "Technological Paradigms and Technological Trajectories, *Research Policy* (11), 1982, 147–162. 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" (152). New paradigms represent discontinuities in trajectories of progress as 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.

7. Value network, as presented here, draws heavily on ideas I developed jointly with Professor Richard S. Rosenbloom and which are summarized in two journal articles: Clayton M. Christensen and Richard S. Rosenbloom, "Explaining the Attacker's Advantage: The Technological Paradigms, Organizational Dynamics, and the Value Network," *Research Policy* (24), 1995, 233–257; and Richard S. Rosenbloom and Clayton M. Christensen, "Technological Discontinuities, Organizational Capabilities, and Strategic Commitments," *Industrial and Corporate Change* (3), 1994, 655–685. I

am heavily indebted to Professor Rosenbloom for his contributions to the development of these perspectives.

8. See D. L. Marples, “The Decisions of Engineering Design,” *IEEE Transactions on Engineering Management* EM8, 1961, 55–71; and C. Alexander, *Notes on the Synthesis of Form* (Cambridge, MA: Harvard University Press, 1964).

9. On this point, too, correspondence between the concept of the value network and Dosi’s concept of technological paradigms is strong. (See note 6.) The scope and boundaries of a value network are defined by the dominant technological paradigm and the corresponding technological trajectory employed at the higher levels of the network. As Dosi suggests, *value* can be defined as a function of the dominant technological paradigm in the ultimate system of use in the value network.

10. Michael Porter, *Competitive Advantage* (New York: The Free Press, 1985).

11. A more complete report of this analysis can be found in chapter 7 of Clayton M. Christensen, *The Innovator’s Challenge: Understanding the Influence of Market Environment on Processes of Technology Development in the Rigid Disk Drive Industry*, thesis, Harvard University Graduate School of Business Administration, 1992.

12. D. Sahal, *Patterns of Technological Innovation* (London: Addison Wesley, 1981).

13. The most widely read proponent of this view is Richard Foster; see, for example, his *Innovation: The Attacker’s Advantage* (New York: Summit Books, 1986).

14. The insights summarized here are articulated more completely in C. M. Christensen, “Exploring the Limits of the Technology S-Curve,” *Production and Operations Management* (1), 1992, 334–366.

15. A fuller account of similar decisions made in other firms can be found in Clayton M. Christensen, *The Innovator’s Challenge: Understanding the Influence of Market Environment on Processes of*

Technology Development in the Rigid Disk Drive Industry, thesis, Harvard University Graduate School of Business Administration, 1992.

16. This procedure is consistent with Robert Burgelman's observation that one of the greatest difficulties encountered by corporate entrepreneurs is in finding the right "beta test sites," where products can be interactively developed and refined with customers. Generally, the entrée to the customer was provided by the salesperson who sold the firm's established product lines. This helped the firm develop new products for established markets, but not identify new applications for its new technology. See Robert Burgelman and Leonard Sayles, *Inside Corporate Innovation* (New York: The Free Press, 1986) 76–80. Professor Rebecca Henderson pointed out to me that this tendency always to take new technologies to mainstream customers reflects a rather narrow *marketing* competence—that although many scholars tend to frame the issue as one of technological competence, such inability to find new markets for new technologies may be a firm's most serious handicap in innovation.

17. Voice coil motors were more expensive than the stepper motors that Seagate had previously used. While not new to the market, they were new to Seagate.

18. This is consistent with the findings reported by Arnold Cooper and Dan Schendel in "Strategic Responses to Technological Threats," *Business Horizons* (19), February, 1976, 61–69.

19. Ultimately, nearly all North American disk drive manufacturers can trace their founders' genealogy to IBM's San Jose division, which developed and manufactured its magnetic recording products. See Clayton M. Christensen, "The Rigid Disk Drive Industry: A History of Commercial and Technological Turbulence," *Business History Review* (67), Winter, 1993, 531–588.

20. In general, these component technologies were developed within the largest of the established firms that dominated the established markets above these entrants. This is because new components generally (but not always) have a sustaining impact on technology

trajectories. These high-end, established firms typically were engaged in the hottest pursuit of sustaining innovations.

21. The research of Eric von Hippel, frequently cited as evidence of the value of listening to customers, indicates that customers originate a large majority of new product ideas (see Eric von Hippel, *The Sources of Innovation* [New York: Oxford University Press, 1988]). One fruitful avenue for future research would be to revisit von Hippel's data in light of the framework presented here. The value network framework would predict that the innovations toward which the customers in von Hippel's study led their suppliers would have been sustaining innovations. We would expect disruptive innovations to have come from other sources.

22. Henderson saw similar potential danger for being misled by customers in her study of photolithographic aligner equipment manufacturers. See Rebecca M. Henderson, "Keeping Too Close to Your Customers," Massachusetts Institute of Technology Sloan School of Management working paper, 1993.

23. Many industry observers have noted that there seems to be a floor on the cost of making a disk drive, somewhere around $120 per device, below which even the best manufacturers cannot plunge. This is the basic cost of designing, producing, and assembling the requisite components. Drive makers keep reducing costs per megabyte by continuously increasing the number of megabytes available in that basic $120 box. The effect of this floor on the competition between disk drives and flash cards may be profound. It means that in low-capacity applications, as the price of flash memory falls, flash will become cost-competitive with disk memory. The frontier above which magnetic disk drives have lower costs per megabyte than flash will keep moving upmarket, in a manner perfectly analogous to the upmarket movement of larger disk drive architectures. Experts predicted, in fact, that by 1997, a 40 MB flash card would be priced comparably to a 40 MB disk drive.

24. Lewis H. Young, "Samsung Banks on Tiny Flash Cell," *Electronic Business Buyer* (21), July, 1995, 28.

25. Richard Tedlow, *New and Improved: A History of Mass Marketing in America* (Boston: Harvard Business School Press, 1994).