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The Rigid Disk Drive Industry: A History of Commercial and Technological Turbulence

In its early years, the disk drive industry was led by a group of large-scale, integrated firms of the sort that Alfred D. Chandler, Jr., observed in his studies of several of the world's largest industries. The purpose of this history is to explore why it was so difficult for the leading disk drive manufacturers to replicate their success when technology and the structure of markets changed. The most successful firms aggressively developed the new component technologies required to address their leading customers' needs, but this attention caused leading drive makers to ignore a sequence of emerging market segments, where innovative disk drive technologies were deployed by new entrants. As the performance of these new-architecture products improved at a rapid pace, the new firms were eventually able to conquer established markets as well. As a consequence, most of the integrated firms that established the disk drive industry were driven from it, displaced by networks of tightly focused, less integrated independent companies.

From the beginnings of the computer industry, engineers have wrestled with the challenge of storing and retrieving information. Users have wanted to store more information and access it more rapidly and to do so at decreasing cost. The effectiveness with which computer and peripheral equipment manufacturers responded to these demands has been an important factor in the

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growth of the computer industry and has enabled users to apply computing power in a broadening range of tasks.

Information storage and retrieval capabilities of computing systems comprised semiconductor (formerly magnetic-core) memory circuits and peripheral magnetic storage and retrieval devices, including tape, rigid (hard) disk, and floppy disk drives. Although the history of each of these technologies is rich, the history of the companies that developed rigid disk drives seems to have been particularly complex and tumultuous. The rigid disk drive industry grew from a research project begun in the San Jose laboratories of International Business Machines, Inc. (IBM) in 1956 to a $15 billion industry in 1990.[1] Of the 138 firms known to have entered the industry in this period, 103 subsequently failed, and six others disappeared through acquisition or absorption by competitors.

New firms entered to lead the industry in four of its six technologically defined product generations. The demise of the leading firms of each generation seems to have been triggered by the emergence of new product architectures and of new market segments in which these architectures were used.[2] This history of the rigid disk drive industry therefore is focused on the emergence of these new technologies and markets.

This article examines those firms that design and manufacture rigid magnetic disk drives for sale in the original equipment (OE) market to computer manufacturers. Because this study's emphasis is on the interactions between technological developments and market forces in the disk drive industry, primarily the open-market disk drive activities of vertically integrated computer manufacturers such as IBM and Control Data—not their internal, intra-corporate disk drive transactions—are considered here.[3]

By 1990 rigid disk drive production was a worldwide industry

[1] A description of how disk drives work, as well as definitions of technical terms used in this history, are included in the Appendix. Because few data were available about the industry prior to the publication of *Disk/Trend Report*, most of the statistical analyses employed in this article begin in 1976.

[2] In this context, "architecture" refers to the system that defines the way in which computer components interact with each other. See Rebecca M. Henderson and Kim B. Clark, "Architectural Innovation: The Reconfiguration of Existing Systems and the Failure of Established Firms," *Administrative Science Quarterly*, March 1990, 9–30.

[3] Details about the role that the captive disk drive operations of IBM and Control Data played in developing many of the key technologies used in the OE market industry are recounted in a companion paper. See Clayton M. Christensen, "Industry Maturity and the Vanishing Rationale for Industrial Research and Development," Harvard Business School Working Paper, 1993.

populated by multinational firms with headquarters in twelve countries spanning four continents. Several produced drives outside the country where their headquarters were located; for example, Rodime, a Scottish firm, produced drives in Florida; IBM and Quantum both manufactured drives in California and Japan; the manufacturing operations of most U.S. firms were centered in Singapore; and some Japanese firms manufactured drives in the United States. References in this article to the "United States," "Japanese," or "European" disk drive industries thus relate to those groups of firms whose headquarters are in those countries.[4]

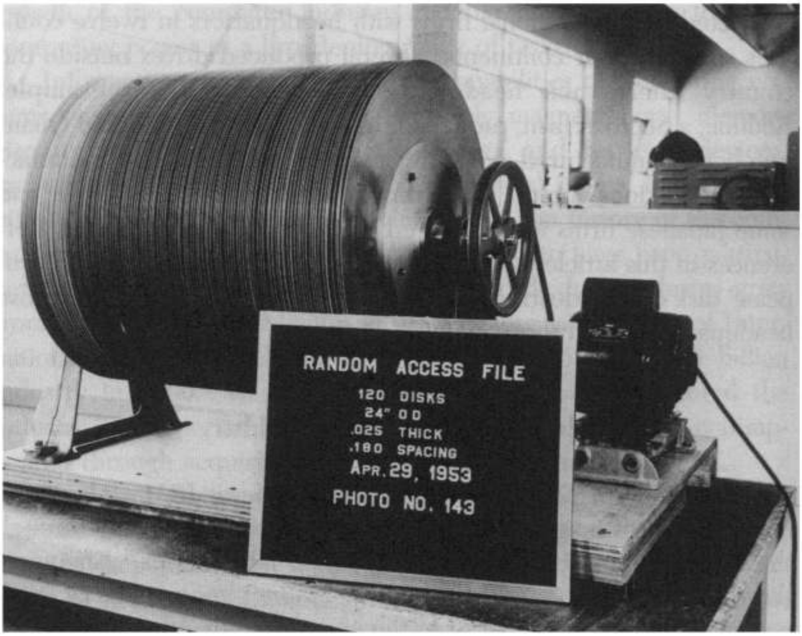
The Emergence of the Industry

Technological Definition of the Disk Drive at IBM • Almost all development of magnetic information-recording technology through the mid-1960s occurred at IBM's San Jose laboratories.[5] Engineers there guided the company through six distinct generations of magnetic recording products prior to the emergence of a dominant product design: magnetic drums; 0.5-inch reel-to-reel tape; moving-head fixed-disk drives; rigid removable disks and disk packs; flexible (floppy) removable diskettes; and, finally, sealed, non-removable "Winchester" rigid disks.

The earliest peripheral magnetic information-storage devices were magnetic drums—an architecture similar in concept to Thomas Edison's early phonograph cylinders. The drums were developed at IBM in the late 1940s and until the mid-1950s were the primary storage devices used with early computing machines. Magnetic drum technologies gave way to magnetic tape in the mid-1950s, and

[4] This is consistent with the importance of corporate headquarters activities in industries studied in Michael Porter, *The Competitive Advantage of Nations* (New York, 1991).

[5] This section's information about IBM's pioneering work was drawn from James Engh, "The IBM Diskette and Diskette Drive"; J. M. Harker, et al., "A Quarter Century of Disk File Innovation"; and L. D. Stevens, "The Evolution of Magnetic Storage"—all in the twenty-fifth anniversary issue of the *IBM Journal of Research and Development* 25 (Sept. 1981). Other useful information sources were H. V. Bordwell, "Cornerstone of a Division," *Reflections* (a periodical publication of IBM's Santa Teresa Laboratory), June 1984, 6–11; "The IBM 350 RAMAC Disk File," American Society of Mechanical Engineers, Santa Clara Valley Section, Feb. 1984; "How One Company's Zest for Technological Innovation Helped Build the Computer Industry," IBM Corporation, San Jose Calif., 1984; "Disk Storage Technology," IBM Corporation, San Jose, Calif., 1980; a long and delightful personal interview with Mr. Reynold Johnson, head of the IBM team that developed the first disk drive, 5 May 1992, in Palo Alto, Calif.; and personal interviews with twelve other early members of IBM's disk drive team.



IBM's RAMAC Disk File • Introduced in 1956, the RAMAC was the first rigid disk drive. Skeptical engineers in the San Jose laboratories called it "the baloney slicer." In 1984, the original RAMAC Disk File was designated an International Historic Landmark by the American Society of Mechanical Engineers. (Photograph reproduced courtesy of IBM.)

through 1963 tape was the dominant data storage and retrieval medium. The primary drawback of tape storage was access time: if a user needed to access data at the end of a tape, the drive had to read through the entire tape before it could access the desired file. Moreover, changing a record anywhere within the tape required re-recording the entire tape.

IBM's efforts to address its customers' thirst for increased processing speeds bore fruit in 1956, when the company shipped its first moving-head magnetic disk drive, called RAMAC—an acronym for Random Access Method for Accounting and Control. The use of rotating disks in the IBM RAMAC represented a major change in engineering thinking for the magnetic information-storage industry. In all previous generations, the need to position the read-write head precisely led engineers to fix it rigidly in place and to move the magnetic media—drums, tapes, or strips—past it. In contrast, the RAMAC drive had a movable head, positioned in the first product 0.0008 inch above the disk's surface via a hydrostatic air bearing. The

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RAMAC drive was a mechanical marvel, with one moving arm and head for each of fifty 24-inch diameter disks in the drive.

In 1962 the fourth generation of magnetic storage devices—the removable disk pack—surpassed the RAMAC's fixed-disk architecture in capacity and flexibility. By interchanging packs of rigid disks, users could store far more data than was possible in a fixed-disk system. The disk pack was the industry's dominant architectural design for more than a decade, and it was the product vehicle that most of the early participants in the original equipment market used to enter the disk drive industry. In 1971, IBM introduced the first drive using removable, flexible (floppy) diskettes to enable more efficient offline storage and loading of the proliferating number of specialized routines and programs for its mainframe computers, where frequency of use did not justify permanent residence for those programs in core memory. The original Model FS33 floppy disk drive was a read-only device, but a read-write version followed in 1973.

IBM's Model 3340—a sealed rigid 14-inch disk drive introduced in 1973 and dubbed the Winchester— was IBM's crowning architectural achievement in magnetic storage.[6] Over the next decade the Winchester design was adopted throughout the world industry. Competing firms have incrementally improved, but have not yet radically altered, the fundamental Winchester design. In the disk-pack architecture, particulate contamination and the removability of the disks prevented close head-to-disk spacing, which inherently limited improvements in recording density. The Winchester drive addressed these issues by permanently sealing the disks with heads, motors, actuators, and electronics inside a dust-proof drive housing. This enabled IBM to reduce the height at which the head flew over the disk surface to .000008 inch—a height one-thousandth of the head-to-disk distance in the RAMAC drive. The cost per megabyte of Winchester drives was 30 percent less than the cost of disk-pack drives of equivalent capacity.

The Rise of Plug-Compatible Equipment Manufacturers • Until IBM introduced its disk-pack architecture in 1962, it was the only

[6] The term "Winchester" was the name of IBM's project to develop the Model 3340. The name was chosen by the project's manager, who owned a 30–30 Winchester rifle. These numbers matched the objectives originally specified for the 3340 project, to develop a drive with 30 megabytes each of fixed and removable capacity. Other industry participants subsequently borrowed the term for their sealed-system drives, and "Winchester" joined the ranks of cellophane and nylon as a generic name for a category of products. James Porter, editor of *Disk/Trend Report*, interview with author, October 1991, Mountain View, Calif.

disk drive manufacturer in the world. But in the early 1960s several companies that had been founded to make add-on tape storage systems that were plug-compatible (the computer equivalent of interchangeability of parts) with IBM equipment copied IBM's disk-pack drive concept and began marketing plug-compatible drives directly to users of IBM computer systems—marking the beginning of an industry of independent disk drive manufacturers.

The market for IBM plug-compatible disk drives was pioneered by eleven firms, most of which diversified into disk technology from earlier positions in other magnetic recording product markets. Eight had been tape drive manufacturers: Telex Corp. (Tulsa, Okla.); Storage Technology Corp. (Boulder, Colo.); the peripherals division of Control Data Corp. (Minneapolis, Minn.); and five smaller Los Angeles–area firms: Century Data, International Storage Systems (ISS), Pertec, Wangco, and Kennedy.[7] These firms were joined by Memorex, which had been the leading supplier of magnetic tape (but not drives) since it was founded in 1961, and by two start-up companies, Iomec and Caelus.

For the plug-compatible equipment makers, IBM was not just a competitor; it was the environment. Plug-compatible manufacturers could be product imitators, but not innovators. They sold tape and disk drives directly to users of IBM computers who needed additional or replacement data storage capability, pricing their products beneath IBM's substantial price umbrella (they priced their drives between $8,000 and $12,000, compared to IBM's Model 1311 price of $26,000) and offering whatever performance advantages they could within the constraints of IBM specifications. By the late 1960s the plug-compatible disk drive business was booming; the market had reached $100 million by 1970; $250 million by 1976; and nearly $700 million in its peak year, 1985. IBM and the group of plug-compatible manufacturers each consistently accounted for 20–30 percent of worldwide disk drive shipments through the 1970s. But the proportion of total drives made by plug-compatible manufacturers declined from 27 percent in 1976 to under 7 percent by 1987

[7] Each of these LA-area firms had been acquired by the mid-1970s by a larger firm—Century by Calcomp, and then Xerox; ISS by Univac; Pertec by Adler; Wangco by Perkin Elmer; and Kennedy by Allegheny Ludlum. Under the acquirors' management, Pertec, Wangco, ISS, and Kennedy evaporated rather quickly. Century hung on with roughly flat revenues (and dramatically declining market share) until 1988, when it was finally closed by Xerox.

(see Table 1).[8] The firms that captured an increasing share of the world disk drive market during this period were independent suppliers of disk drives in the OE market. Table 1 also shows that overall industry revenues grew at an average 22 percent annual rate between 1976 and 1989. Unit shipments over the same period averaged 34 percent annual growth.

The Development of the Disk Drive Industry for the OE Market • It was the explosive growth of the minicomputer industry in the 1970s that spawned the original equipment market for disk drives. Throughout the 1960s and 1970s, the larger computer manufacturers—IBM, Digital Equipment, Control Data, Data General, Burroughs, Fujitsu, Hitachi, and Univac—made most of their own drives. It was the growth of computer manufacturers that were not as extensively integrated—firms like Wang, Prime, NCR, and Nixdorf in the 1970s, and Apple, Commodore, Compaq, Tandy, and Sun Microsystems in the 1980s—that created a major OE market for independent disk drive manufacturers. The original equipment market differed from the plug-compatible market primarily in that disk drive manufacturers sold to computer *manufacturers*, rather than to users of computers.

The robust OE market demand described in Table 1 attracted a host of entrant firms. In addition to the eleven makers of plug-compatible products previously mentioned, at least eighty-seven other firms entered the OE market fray between 1975 and 1989. For the purposes of this article, they can be grouped into five categories:

Start-Up Firms were generally venture capital–backed companies founded to design and manufacture rigid disk drives. Most focused almost exclusively on the disk drive business. Although a few start-ups had entered between 1965 and 1970 to manufacture plug-compatible drives, by 1973 this early group of firms had all been acquired by larger, diversified firms. The vast majority of start-ups entered after 1978.[9]

Related-Technology Firms were diversified concerns that entered by adapting magnetic data-recording technologies they had developed in other product-market contexts to rigid disk drive prod-

[8] The dollar figures for captive shipments shown in Table 1 and all subsequent tables in this article have been adjusted to reflect OE market, rather than retail pricing, levels. This enables a clearer comparison of market and captive activity.

[9] Histories of the venture capital and IPO market financing activities of these start-ups can be found in William Sahlman and Howard Stevenson, "Capital Market Myopia," *Journal of Business Venturing* 1 (1983): 7–30.

Table 1
Size and Proportional Shares of Captive, Plug-Compatible, and Original Equipment Rigid Disk Drive Market Segments, 1976–1989
(Dollars in Millions)

Year	*IBM Captive*		*Other Captive*		*Plug-Compatible Market*		*Original Equipment Market*		*T*
	$	%	$	%	$	%	$	%	$
1976	251	27.0	172	18.5	254	27.4	251	27.0	928
1979	268	14.5	566	30.6	356	19.2	661	35.7	1,851
1981	744	23.7	665	21.2	532	17.0	1,197	38.1	3,138
1983	1,193	27.4	912	20.9	287	6.6	1,965	45.1	4,357
1985	2,139	31.2	955	13.9	690	10.1	3,068	44.8	6,852
1987	2,282	23.7	1,240	12.9	646	6.7	5,477	56.8	9,645
1989	3,219	24.5	1,640	12.5	na	na	8,256	63.0	13,115

Note: Separate figures on the sizes of the plug-compatible and original equipment markets for 1989 were not available, and the figure given for the 1989 Ol represents the size of the combined original equipment and plug-compatible market segments. Original equipment and plug-compatible market size figure: sales of vertically integrated manufacturers such as IBM, Fujitsu, and Hitachi into the plug-compatible and original equipment markets. Reported *Disk/Trenc* captive production have been adjusted to OE market pricing levels.

Source: Author's analysis of *Disk/Trend Report* data.

ucts. Examples include Storage Technology Corporation (from tape drives) and Ampex (from audio and video recorders).

Related-Market Firms such as Memorex, Diablo, Perkin Elmer, and Calcomp were diversified concerns for which disk drives were one of several product lines made for the burgeoning computer industry.[10] In contrast to the related-technology firms, for which disk drives represented a business technologically related to their previous activities, the related-market firms had expanded into disk drive production in a strategy related to markets and customers.[11]

Forward Integrators began by manufacturing critical disk drive components such as read-write heads or controllers, and then integrated forward to the design and assembly of complete disk drives.

Vertically Integrated Computer Manufacturers historically produced a large proportion of the world's disk drives (see Table 1). Some, such as IBM and Digital Equipment, generally manufactured for internal, captive consumption. Others, such as Control Data, Fujitsu, and Hitachi, always competed actively in the OE market in addition to supplying some captive needs.

Table 2 describes the entry patterns of each of these groups of firms in the United States, as well as those of independent Japanese and European firms.[12] Eighty-seven U.S.-based firms entered the OE market, compared to thirty-one Japanese and thirteen European

[10] Three firms treated as related-market firms in this study entered the industry by acquiring start-up firms. Between 1969 and 1973 Data 100, Electronic Memories, and Calcomp acquired Iomec, Caelus, and Century Data, respectively. Iomec made disk-pack products; Caelus made primarily the disk packs themselves, along with a few drives; and Century made fixed-disk drives. In 1988 Western Digital, a controller manufacturer (and therefore classed as a forward integrator when it entered in 1988), acquired the floundering disk drive operations of Tandon, which had entered on a related-technology basis.

[11] The dimensions of relatedness among the different activities of diversified firms have been extensively studied by industrial economists. Prominent among these are Leonard Wrigley, "Divisional Autonomy and Diversification" (Unpub. DBA diss., Harvard University Graduate School of Business Administration, 1970), which offers a taxonomy of diversification strategies. James M. MacDonald, "R&D and the Directions of Diversification," *Review of Economics and Statistics*, 1985, 583–90, discusses the relationship between a firm's R&D strategy and patterns of diversification. The related-market and related-technology rationale for diversification were first identified by Richard Rumelt, *Strategy, Structure and Economic Performance* (Cambridge, Mass., 1974), 17.

[12] The term "independent" here refers to firms that were not vertically integrated into computer manufacturing. In Japan all independent firms were either related-technology or related-market firms; there were no start-ups. There was one European start-up, Rodime, founded in Scotland by engineers defecting from Burroughs Corp. Rodime pioneered the 3.5-inch drive and for a time was quite successful, with revenues exceeding $100 million. It withdrew from the market in 1991. No attempt was made in this history to sort Japanese or European firms into related-market, related-technology, or forward integrator categories.

Table 2

Number of U.S.-Based Firms Entering, Exiting, and Participating in the Rigid Drive Market, by Type of Firm, 1976–1989

NUMBER OF ENTRANT FIRMS	*Pre-1977*	*1977*	*1978*	*1979*	*1980*	*1981*	*1982*	*1983*	*1984*	*1985*	*1986*	*1987*	*1988*	*1989*
Start-Ups	0	0	1	4	7	3	9	4	2	3	3	3	0	1
Related-Technology Firms	4	2	1	0	1	1	0	1	0	0	0	0	0	0
Related-Market Firms	10	1	1	1	1	1	1	1	1	1	0	1	0	0
Forward Integrators	0	0	2	0	0	1	0	2	0	0	0	0	1	0
Vert. Integrated Mfrs. in OE/PC Market[a]	3	0	1	0	1	0	1	0	1	1	1	0	0	0
Vert. Integrated Mfrs. in Captive Production (includes firms just above)	8	1	0	1	0	0	0	1	0	0	0	0	0	0
Subtotal—U.S. Entrant Firms	**22**	**4**	**6**	**6**	**9**	**6**	**10**	**9**	**3**	**4**	**3**	**4**	**1**	**1**
Independent Japanese Entrants	2	0	0	0	1	5	0	2	9	3	2	1	0	0
Vertically Integrated Japanese Entrants	5	0	0	0	0	0	0	0	1	0	0	0	0	0
Independent European Entrants	3	0	1	2	1	0	0	0	0	1	0	0	0	0
Vertically Integrated European Entrants	3	0	2	0	0	0	0	0	0	0	0	0	0	0
Total Entrants—World Industry	**35**	**4**	**9**	**8**	**11**	**11**	**10**	**11**	**13**	**8**	**5**	**5**	**1**	**1**
NUMBER OF ACTIVE FIRMS														
Start-Ups	0	0	3	7	13	15	23	23	24	24	24	21	16	16
Related-Technology Firms	4	6	7	7	9	8	8	8	8	8	5	5	3	2
Related-Market Firms	10	11	11	11	12	10	10	10	9	9	7	4	2	2
Forward Integrators	0	0	2	2	1	1	1	3	3	3	2	1	1	1
Vert. Integrated Mfrs. in OE/PC Market	3	3	4	4	4	3	4	3	3	3	4	3	3	2
Vert. Integrated Mfrs. in Captive Production (includes firms just above)	8	9	9	10	10	10	10	10	9	8	6	6	6	6
Subtotal—Active U.S. Firms	**22**	**26**	**32**	**38**	**45**	**44**	**52**	**54**	**53**	**51**	**43**	**37**	**30**	**27**

Table 2 (continued)

Active Japanese Independents	2	2	2	2	3	8	7	8	16	18	19	15	7	5
Active Japanese Vert. Integrated Mfrs.	5	5	5	5	5	5	5	5	6	6	6	6	6	6
Active European Independents	3	3	3	3	4	6	7	4	4	5	4	4	3	2
Active European Vert. Integrated Mfrs.	3	3	3	3	5	5	5	4	4	4	4	3	3	1
Total Active Firms in World Industry	**35**	**39**	**45**	**51**	**62**	**68**	**76**	**75**	**83**	**84**	**76**	**65**	**49**	**41**
WORLD MARKET SHARES OF PRIMARY GROUPS (%)	*1976*	*1977*	*1978*	*1979*	*1980*	*1981*	*1982*	*1983*	*1984*	*1985*	*1986*	*1987*	*1988*	*1989*
U.S. Start-Ups	0	0	0	0.4	1.2	5.9	7.6	23.5	26.2	27.5	31.5	37.8	39.9	56.5
U.S. Related-Technology Firms	10.2	10.6	20.5	19.2	20.8	27.6	28.6	11.8	12.3	8.1	11.3	11.2	7.0	5.2
U.S. Related-Market Firms	49.9	42.8	28.5	28.9	26.0	17.7	13.2	6.6	3.4	3.7	1.1	1.6	1.9	0.5
U.S. Forward Integrators	0	0	0	0	0	0	0	0	0	0.2	0.1	0	1.8	3.2
U.S. Vert. Int. Mfrs.' Share of OE Market	39.9	46.5	35.8	41.1	46.4	37.4	41.1	29.2	24.9	16.7	16.0	15.1	15.9	2.2
Subtotal—U.S. Firms	100	100	84.9	89.6	94.3	85.8	90.5	71.0	66.8	56.2	60.0	65.7	66.5	67.6
Independent Japanese Firms	—[b]	—	0	0	0.3	0	0	1.8	2.5	1.8	2.5	1.9	2.0	3.9
Vert. Int. Japanese Mfrs.' Share of OE Market	—	—	9.8	5.7	2.1	6.3	3.8	19.0	22.1	32.4	30.0	25.8	26.0	23.8
Independent European Firms			5.4	4.6	1.7	4.4	2.5	3.7	5.0	5.6	4.6	2.3	4.3	2.1
Vert. Int. European Mfrs.' Share of OE Market	—	—	0	0	1.5	3.5	3.2	4.5	3.7	3.9	2.9	4.3	4.3	2.1
Total—World Industry	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Size of world OE/PC Markets ($millions):	504	516	890	1,017	1,161	1,729	1,899	2,252	3,330	3,757	4,592	6,123	7,315	8,256

[a] OE/PC = original equipment/plug-compatible.

[b] Data for the size of Japanese and European participants in 1976 and 1977 could not be found. The shares given for the groups of U.S. firms in those years are, therefore, shares of U.S. firms' production only.

Source: Author's analysis of *Disk/Trend Report* data.

entrants. The total number of active U.S. firms rose from twenty-two in 1976 to fifty-four in 1983, and then declined to twenty-seven by 1989. The number of Japanese participants peaked two years after the U.S. high point. European firms were never important factors in the world industry.

The bottom section of Table 2 charts the shares of the world original equipment/plug-compatible market claimed by these groups of firms. Clearly, the rigid disk drive industry was not an industry pioneered by classic venture capital–backed Silicon Valley start-up firms. The pioneering firms were the larger, diversified concerns that entered the disk drive industry on the basis of technological relatedness, market relatedness, or by backward integration from computer manufacturing. Most of these disk drive manufacturers were further vertically integrated into the manufacture of components such as heads, disks, and motors that were employed in their drives. This pattern of integration was consistent with those that Alfred D. Chandler, Jr., observed: in the industry's formative years, the need to assure and coordinate the availability of key components gave vertically integrated firms a strong competitive advantage.[13]

Much of the entry and exit activity summarized in Table 2 occurred at the industry's periphery, among firms that never became commercially viable. But the turbulence permeated the ranks of the industry's largest firms as well. The combined world market share of the integrated firms, which was 84.8 percent in 1978, had declined to 7.9 percent by 1989. The older firms were essentially driven from the market by the start-ups.[14] These start-ups, which claimed less than 1 percent of the world market in 1979, accounted for more than half of it a decade later. In 1989, seven of the world original equipment/plug-compatible market's ten largest participants were U.S.-based start-up firms.

Table 3 offers a closer look at the ten largest disk drive manufacturers in the original equipment market in selected years between 1976 and 1989. The firms that led the industry in 1976 are shown in regular type; entrants to the industry after 1976 are listed in boldface. The entire initial population of leaders had disappeared by

[13] Alfred D. Chandler, Jr., *Strategy and Structure: Chapters in the History of the Industrial Enterprise* (Cambridge, Mass., 1962); and Chandler, *The Visible Hand: The Managerial Revolution in American Business* (Cambridge, Mass., 1977).

[14] The peripherals division of Control Data Corporation was by far the largest vertically integrated manufacturer in the OE market, and the 1989 shift in market share from the vertically integrated to the start-up categories reflects Seagate Technology's purchase of the Control Data disk drive operations in 1989.

Table 3

Market Shares of the Ten Leading U.S. Disk Drive Manufacturers, 1976–1992 (percent)

Rank	*1976*	*1978*	*1980*	*1981*	*1982*	*1983*	*1984*	*1985*	*1986*	*1987*	*1988*	*1989*	*1992*
1	CDC	CDC	CDC	CDC	CDC	CDC	CDC	CDC	**Seagate**	**Seagate**	**Seagate**	**Seagate**	**Conner**
	34	50	62	62	55	40	32	27	28	30	28	46	24
2	Diablo	Diablo	Century	Century	Century	**Seagate**	**Seagate**	**Seagate**	CDC	CDC	CDC	**Conner**	**Seagate**
	22	10	11	9	7	16	16	15	24	22	21	13	22
3	Century	Memorex	Memorex	Memorex	**Seagate**	**Priam**	**Miniscribe**	**CMI**	**Micropolis**	**Miniscribe**	**Miniscribe**	**Miniscribe**	**Quantum-2**
	12	9	8	7	5	6	6	8	9	10	12	9	15
4	Pertec	Century	Ampex	Ampex	**Shugart**	**Miniscribe**	**Quantum-1**	**Quantum-1**	**Miniscribe**	**Micropolis**	**Micropolis**	**Maxtor**	**Maxtor**
	7	7	4	4	4	5	6	7	7	8	7	8	10
5	Memorex	Ampex	Pertec	**IMI**	Ampex	**Quantum-1**	**IMI**	**Miniscribe**	**Maxtor**	**Maxtor**	**Maxtor**	**Quantum-2**	IBM
	6	5	3	3	4	4	5	6	6	6	6	6	10
6	ISS/Univac	Perk.Elmer	Wst. Dynex	**Seagate**	**Priam**	Century	**Priam**	**Priam**	**Priam**	**Microsci.**	**Conner**	**Micropolis**	**Wstrn. Digital**
	6	5	3	3	3	4	4	6	5	4	5	6	9
7	Perk.Elmer	Pertec	**Shugart**	**Shugart**	**Quantum-1**	**Tandon**	**CMI**	**Micropolis**	**Quantum-1**	IBM	IBM	**Tandon**	**Micropolis**
	4	4	3	3	3	3	4	5	5	3	3	5	7
8	Data 100	Wst. Dynex	Perk.Elmer	ISS/Univac	ISS/Univac	**CMI**	**Tandon**	**Maxtor**	IBM	**Priam**	**Priam**	IBM	
	3	4	2	1	3	3	3	5	4	3	2	3	
9	Ampex	No.Tel.	STC	STC	Memorex	Ampex	**Micropolis**	**Tandon**	**Tandon**	**Conner**	**Tandon**	**Microsci.**	
	3	2	0.5	0.4	2	3	3	5	3	3	3	1	
10	Microdata	ISS/Univac	Microdata	Burroughs	**Tandon**	**IMI**	Century	IBM	**Microsci.**	**Tandon**	**Quantum-2**	**Priam**	
	0.4	0.3	0.1	0.2	2	3	2	5	3	3	2	1	
Others	3	3	5	9	12	12	20	13	7	8	11	2	3
Totals	100	100	100	100	100	100	100	100	100	100	100	100	100
4-Firm Concentration Ratio	75.6	75.8	84.8	81.7	69.9	68.0	59.0	56.2	67.6	69.1	67.7	75.5	71.0
U.S. Share of World OE Market		84.8	94.3	85.8	90.5	71.1	66.8	56.2	60.0	65.7	66.5	67.6	

Notes: Xerox-D was the Diablo division of Xerox, which withdrew in 1979. Xerox-C was the Century Data division of Xerox, which was purchased from Calcomp in 1979. Shugart was purchased by Xerox in 1977, but is listed in this table as Shugart, rather than as Xerox. Quantum-1 refers to the original firm; Quantum-2 refers to the firm after it was recombined with Plus Development.

1989. The decline of Control Data was particularly spectacular. Its market share, built largely on 14-inch disk-pack and Winchester drives, peaked at 62 percent in 1980–81. Its share had declined to 21 percent by 1988, before it was acquired by Seagate Technology, the new industry leader.

The misfortune of the initially dominant integrated disk drive manufacturers reflected in Table 3 seems to have typified the fate of the other integrated U.S.-based manufacturers that entered the market in its later years. Only three (11 percent) of the twenty-eight related-technology, related-market, forward-integrator, and vertically integrated firms that entered between 1976 and 1989 survived to the end of the period. In contrast, sixteen (40 percent) of the forty start-up entrants survived.

Without exception, the start-ups that grew to dominate the world industry were focused exclusively on manufacturing rigid disk drives—they made no other products. Furthermore, the start-ups that successfully entered later in the period were progressively less vertically integrated than those that had entered earlier. This trend is illustrated in Table 4, which lists the five companies with the largest total cumulative disk drive sales in the industry's history. The early leading manufacturers, IBM and Control Data, were completely integrated into the manufacturing of critical components and even into the research activities required to support new component development. Seagate, the dominant firm through the 1980s, was integrated quite extensively into component manufacturing, but its commitment to research in support of advanced component development was not nearly as extensive as that maintained by IBM and Control Data. Conner Peripherals was much less vertically integrated: its only commitment to component development and manufacture was its acquisition in the late 1980s of a small firm that made drive heads that glided on the surface of disks. Quantum, the most recent entrant, was the least integrated of all—it sourced all of its components in the external supplier market and had a Japanese partner, Matsushita, manufacture its drives by contract.[15] This rever-

[15] The original Quantum Corporation was founded in 1979 to make 8-inch drives. It was one of the most successful 8-inch drive makers, but it missed the 5.25-inch generation almost completely. As its revenues were evaporating in 1986–87, Quantum merged a partially owned subsidiary, Plus Development Corporation, back into the parent company; canceled all of its 8- and 5.25-inch production arrangements, and used Plus's 3.5-inch diameter "Hardcard" architecture as the basis for a new business. The executives of Plus

Table 4
Trend Toward Less Vertical Integration in the Disk Drive Industry

Extent of Vertically Integrated Activities (X denotes the firm had integrated into that activity)	*IBM*	*Control Data*	*Seagate*	*Conner Peripherals*	*Quantum*
Date Entered Industry	*1956*	*1962*	*1980*	*1986*	*1987*
Approximate 1991 Rigid Disk Drive Sales	$4,500	[a]	$2,600[a]	$1,600	$1,100
Computer Manufacturing	X	X			
Disk Drive Design	X	X	X	X	X
Disk Drive Assembly	X	X	X	X	
Head Manufacturing	X	X	X		
Disk Manufacturing	X	X	X		
Research in New Head and Disk Technologies	X	X		[b]	

[a] Includes sales of the former Control Data Corporation disk drive operation, which logged revenues of approximately $1 billion in each of the several years prior to its acquisition by Seagate.

[b] Although Conner Peripherals did not conduct the sort of research and development in which IBM engaged, it did acquire a fledgling firm that was developing an advanced "contact" head that would glide on the surface of disks coated with a lubricant.

sal of fortunes—the inability of the integrated firms that created the industry to maintain their leadership—might in some sense be considered "un-Chandlerian." The ability of the successful firms that Chandler studied to assure supplies of critical materials and to control distribution and sales through a vertically integrated infrastructure seems to have been the key to those firms' sustained competitive success. In the cases studied here, integration progressively seems to have become a disadvantage as the industry matured. A primary objective of the research reported in the remaining pages of this history is to develop a deeper understanding of why this reversal of fortunes between integrated and start-up firms occurred.

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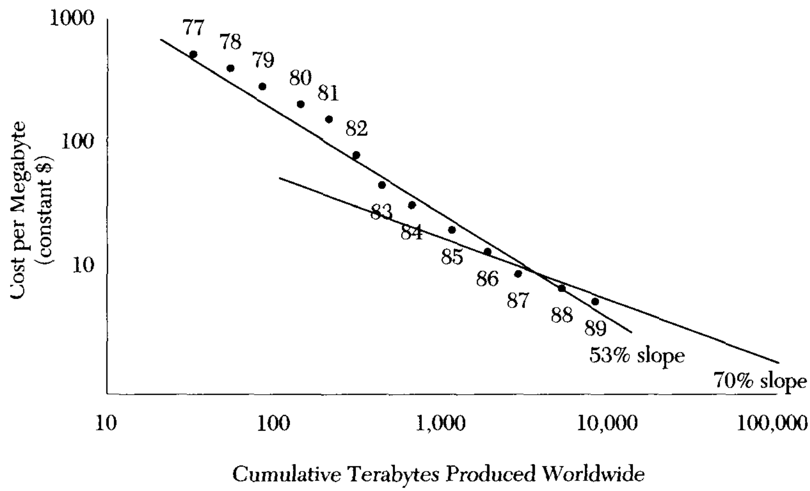
became the executives of Quantum. These executives, as well as most industry observers, consider this to have marked the closing of the "old" Quantum, and the birth of an essentially new company.

Figure 1
The Disk Drive Experience Curve:
Declining Cost Per Megabyte vs. Cumulative Capacity Produced



The Development and Diffusion of New Technology in the Disk Drive Industry

In an industry as technologically turbulent as the disk drive industry, the relative abilities of large, integrated firms and small, focused firms to respond to rapidly changing technologies and markets is a natural issue to explore. Indeed, disk drive technology changed very rapidly between 1976 and 1989. Table 5 summarizes improvements in the performance of disk drives along several important dimensions over the period. Recording density increased by a factor of 20; average data access time fell 38 percent; and the physical volume occupied by the smallest available 20 megabyte (MB) drive in 1989 was .0015 of the volume required for the same capacity in 1977.

Enormous decline in the cost per megabyte of memory was an important industry growth driver (see Fig. 1). The average price per megabyte of memory in the OE market declined from $560 in 1977, when only 33 cumulative terabytes had been shipped since the industry's inception, to $6.60 per megabyte in 1989, by which time over 6,000 cumulative terabytes had been shipped. The experience

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Table 5
Improvements in Technical Performance of Rigid Disk Drives, 1977–1989

	1977	*1979*	*1981*	*1983*	*1985*	*1987*	*1989*	*Compounded Annual Rate of Improvement (%)*
Capacity (MB)								
Average[a]	93	92	102	117	164	233	336	11
Highest Available	554	635	1,260	1,260	2,521	2,488	3,784	17
Recording Density[b]								
Average	1,857	2,832	3,995	6,782	11,646	18,925	37,552	28
Highest Available	3,732	7,705	12,192	14,784	28,329	43,476	98,040	35
Access Time[c]								
Average	49	47	66	58	57	39	31	-3.9
Fastest Available	28	26	24	24	23	18	16	-4.5
Disk Diameter (inches)								
Average	14	12.1	9.0	7.2	5.9	5.2	4.6	-8.9
Smallest Available	14	8	5.25	5.25	3.5	3.5	2.5	-13.4
Physical Volume of Smallest Available Drive of *Any* Capacity (cubic inches)	5,400	972	288	144	64	32	8	-42

[a] Average of all models available in the market during the stated year.

[b] Megabits per square inch, calculated by multiplying track density (tracks per inch) by linear density (bits per inch)

[c] Milliseconds

Source: Author's analysis of *Disk/Trend Report* data.

Figure 2
Types of Technological Innovation
Identified by Henderson and Clark

Impact on Core Technological Concepts in Componentry (rows); Impact on Architectural Concept: The Way Components Interact within the Design (columns)

	Reinforced	Changed
Changed	Modular Innovation	Radical Innovation
Reinforced	Incremental Innovation	Architectural Innovation

curve fitted through the points declined along a 53 percent slope, meaning that every time cumulative output in the industry doubled, costs per megabyte declined to 53 percent of their former level.[16]

A useful framework for characterizing changes in disk drive technologies was proposed by Rebecca Henderson and Kim Clark.[17] They posit that, in general, a product's fundamental technological approach is embodied in its components, which are designed into a system architecture. Henderson and Clark classify innovations by the degree to which they reinforce or render obsolete firms' expertise along these two dimensions—component technology and architectural design. They conclude from this logic that there are four distinct types of innovation, as shown in Figure 2.

Incremental innovation is defined as any change that builds on a firm's expertise in component technology and that occurs within its

[16] The unusually steep rate of price decline measured by the experience curve seems, in part, to be due to the substitution of Winchester-architecture for removable disk-pack architecture between 1980 and 1985—when the individual points on Figure 1 decline most rapidly. For drives of equivalent capacities, cost per MB of a Winchester drive was typically 30 percent lower than that of removable-disk architecture. It appears that the experience curves within removable-disk and Winchester architectures followed approximately a 70 percent slope, which is typical for such curves in the electronic components industry.

[17] Henderson and Clark, "Architectural Innovation," 9–30.

established product architecture. An example of incremental innovation would be the development of a faster electric spin motor driving the rotation of disks. *Modular innovation* occurs when a new core technology, embodied in a component, is "plugged" into a fundamentally unchanged system architecture—as when a thin-film head is substituted for a ferrite head in a 5.25-inch Winchester disk drive. *Architectural innovation* leaves the core technological concepts of the components intact but changes the way they are designed to work together, as in the change from removable disk packs to the sealed Winchester disk drive architecture. *Radical innovation*, exemplified by the emergence of optical (as opposed to magnetic) disk drives, involves change along both dimensions.

Examples of each type of technological change can be found in the disk drive industry between 1973 and 1989. There were modular changes in every significant disk drive component. Disks coated with thin metal films substituted for disks coated with particles of iron oxide; heads made through photolithographic processes substituted for heads made by winding copper wire around a machined ferrite core; and the codes in which data were recorded came to employ more economical, space-conserving concepts. And there were innumerable incremental improvements. In ferrite heads, for instance, the development of barium-doped ferrite greatly increased the physical strength of the material, permitting the heads to be ground to much finer, more precise dimensions without chipping or cracking. The development of lapping processes permitted manufacturers to grind the ferrite cores even more finely. And depositing a strip of metal in the gap separating the leading and trailing surfaces of the head increased the strength of the magnetic field generated by the ever-shrinking ferrite head.

Between 1973 and 1989, five waves of major architectural change swept through the disk drive industry. The first, in which 14-inch Winchester disk drives substituted for removable disk-pack drives, has already been described. Each of the subsequent architectural generations was associated with a reduction in size within the Winchester paradigm—from 14 to 8 inches in 1978; from 8 to 5.25 inches in 1980; to 3.5 inches in 1985; and to 2.5 inches in 1989. Although each of these downsizings involved shrinking the size of the components used, they also each involved significant redesign of the way components interacted within the architecture.[18]

[18] In industry parlance, the different sizes of Winchester disk drives are called the 14-inch form factor, the 8-inch form factor, etc. An example of the architectural unique-

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Many scholars of technological change have observed that new technologies are often introduced into industries by firms entering an industry, rather than by the established firms.[19] In this examination of the extent to which this was true of the disk drive industry, established firms are defined as those that had previously manufactured drives employing earlier technology. Entrant firms are those whose initial product on entry into the industry employed the new technology being analyzed.

In the disk drive industry, the firms that led in the development and use of new *component* technologies were generally established firms. Entrant firms—whether start-ups or larger integrated concerns—rarely used new component technology in their initial, entry products. No such generalization can be made about points where *architectural* technological change entered the industry, however. Of the five transitions in architectural technology between 1973 and 1989, established firms led in introducing two, and entrant firms were the leaders in three. The following case histories of two innovations in component technology and two innovations in architectural technology will provide the reader with a sense of what technological innovations in components and architecture were like, how they originated and became diffused through the industry, and how they differed from each other in these respects. These examples were chosen because their histories are representative of a broader set of new technologies.

Leading Innovators in New Read-Write Head and Recording-Code Technologies • IBM began exploring the use of thin-film photolithography to etch an electromagnet onto the surface of a read-write head in 1965, in response to a preliminary technological

ness of these form factors is that in the 8-inch drive, a 110-volt AC motor was typically positioned in the corner of the system, and it drove the disks by pulleys and a belt. In reducing the size to 5.25 inches, the motor was changed to a 12-volt, DC, flat "pancake" design and positioned beneath the spindle. Such a rearrangement in the way components relate to each other, where the fundamental technological concepts of magnetic recording on rotating disks powered by electric motors are preserved, is the essence of Henderson and Clark's definition of "architectural" innovation. The architectures listed here were those that came to be broadly adopted in large segments of the market. Many other architectures were introduced, and the manufacturers of some of these products became commercially successful in niche segments of the market.

[19] See, for example, Joseph A. Schumpeter, *The Theory of Economic Development* (Cambridge, Mass., 1934); A. Cooper and D. Schendel, "Strategic Responses to Technological Threats," *Business Horizons* 19 (Feb. 1976); Edwin Mansfield, et al., *The Production and Application of New Industrial Technology* (New York, 1977); and Richard Foster, *Innovation: The Attacker's Advantage* (New York, 1986).

forecast that the current method for making heads—winding copper threads around a core of ferrite material—would eventually become constrained by manufacturers' inability to grind the ferrite to finer dimensions. The thin-film approach required a completely different set of engineering competencies, a completely different set of manufacturing equipment, and a very different manufacturing process flow than was required to manufacture ferrite heads competitively. Thin film was, in terms coined by Michael Tushman and Philip Anderson, a *competence- destroying* technological innovation.[20]

By the time IBM had established proof of the thin-film concept in the early 1970s, other leading integrated disk drive makers such as Control Data and Burroughs had also launched thin-film head development projects. Burroughs announced a model equipped with a thin-film head in 1976 but was never able to manufacture it. In 1979, however, IBM successfully introduced its Model 3340 with thin-film heads—fourteen years, and $300 million dollars, after it had initiated development. Thin film was a difficult, competence-destroying technology—and yet the firms that led in its development and use were the established practitioners of ferrite-head technology. From 1981 to 1986, when over sixty firms entered the rigid disk drive industry, only five of them (all commercial failures) attempted to do so using thin-film heads as a source of performance advantage in their initial products (see Table 6). All other entrant firms—even aggressive, performance-oriented firms such as Maxtor and Conner Peripherals—found it preferable to use ferrite heads in their entry products before tackling thin-film technology in subsequent generations.

One explanation for why the leaders in component innovation were the industry's large, established firms is Chandlerian: these innovations generally were complex, time-consuming, and expensive, and only leading incumbent firms commanded the resources required to undertake and coordinate such development. However, established firms' leadership in developing and deploying new component technologies extended literally to every component-level innovation—even relatively simple, inexpensive ones—for which a history can be reconstructed. An example of such an inexpensive innovation was the substitution of Run Length Limited (RLL) recording codes for Modified Frequency Modulation (MFM) codes

[20] Michael Tushman and Philip Anderson, "Technological Discontinuities and Organizational Environments," *Administrative Science Quarterly* 31 (1986): 439–65.

Table 6
Numbers of Established and Entrant Firms Introducing Models Equipped with Thin-Film Heads and RLL Recording Codes, 1976–1988

Year	*Thin Film Heads*		*RLL Codes*	
	No. of Established Firms	*No. of Entrant Firms*	*No. of Established Firms*	*No. of Entrant Firms*
1976	1			
1977				
1978				
1979	1			
1980	1			
1981	3	1		
1982	5	0		
1983	6	1		
1984	8	2	4	1
1985	12	1	11	2
1986	15	0	20	3
1987	17	1	25	6
1988	22	4	26	8

Source: Author's analysis of *Disk/Trend Report* data.

between 1982 and 1988.[21] Development of RLL codes, which enabled a 30 percent improvement in recording density, was a software development project that consumed several hundred thousand to a few million dollars per firm. In spite of this relatively low barrier to development, the established, rather than the entrant, firms still led in this important innovation. Table 6 shows that thirteen firms introduced new models employing RLL technology in 1985. Eleven were established firms, meaning that they had previously offered models based on MFM technology; two were entrants, meaning that their initial products employed RLL codes. Although RLL technology represented a relatively cheap way to increase recording density (and therefore should have been an attractive

[21] These codes are essentially "markers" recorded by the head on the disk to denote the start of a new piece of data. The markers used in early disk drives consumed a significant portion of the available recording area on the disk. As a consequence, engineers worked to find more efficient marker systems that preserved data integrity but consumed less storage area. The development of RLL codes is one such innovation.

technology to entrant firms), entrants lagged behind established firms in its introduction.

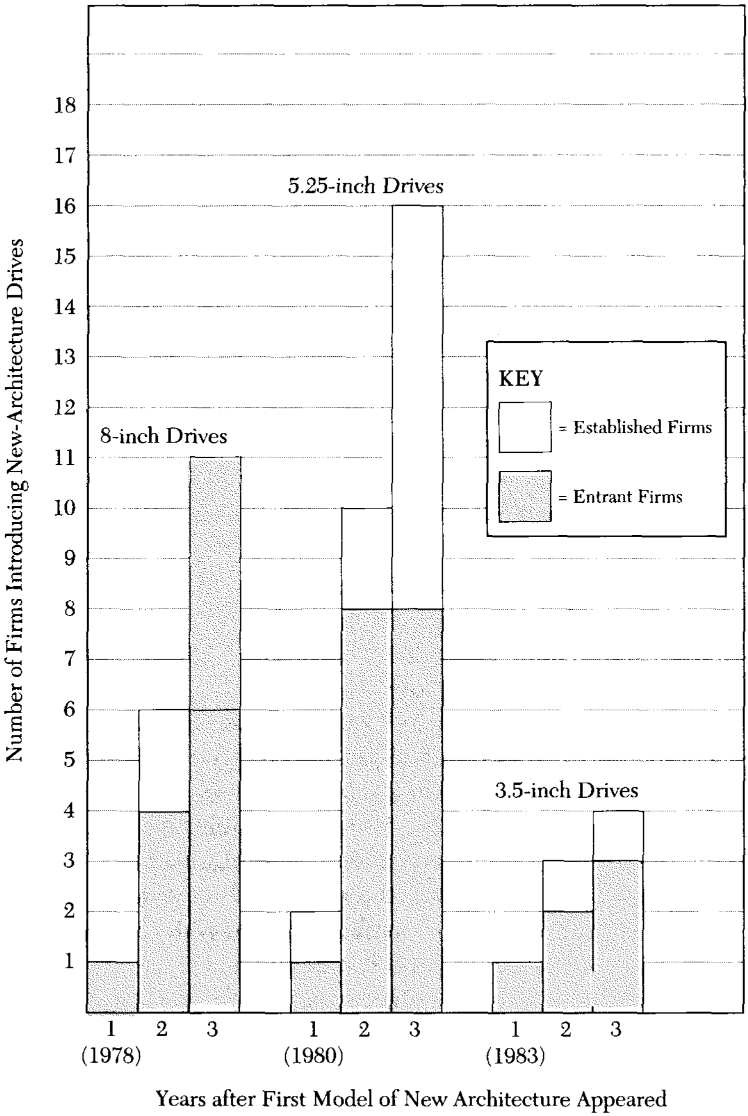
The history of other relatively simple but important component-level innovations—such as embedded servo systems, zone-specific recording densities, and higher RPM motors—reveals a similar pattern: established firms led in the adoption of new component technology. Entrant firms were the component technology followers. This was true both when the new component technologies had to be developed in-house, as with thin-film heads and RLL codes, and when components, such as spin motors, could be procured from outside vendors. Generalizations that radically new technologies tend to be brought into industries by entrant firms; that established firms will excel primarily at the types of innovation that build on established technological competencies; or that established firms lead in component-level innovation because of their relatively greater ability to countenance greater complexity, risk, and expense seem to be inaccurate and insufficient to explain these patterns of innovation in the disk drive industry.[22]

Leaders in Architectural Innovation • In contrast to the pattern just noted, where established firms led in the development and introduction of new component technology, the pioneers of the 8-, 5.25-, and 3.5-inch generations of architectural technologies were entrant rather than established firms. For example, in 1978 an entrant to the rigid drive industry (Shugart Associates) offered the industry's first 8-inch drive. By the end of 1979, six firms were offering 8-inch drives; two-thirds of them were entrants. Two years after the first 5.25-inch drive appeared, eight of the ten firms offering 5.25-inch drives were entrants. Entrants likewise dominated the early population of firms offering 3.5-inch drives (see Fig. 3). In general, between half and two-thirds of the established manufacturers of the prior architectural generation never introduced a model in the subsequent architecture, and those that did move into the new technology introduced their new-architecture models an average of two years behind the leading entrant innovators.

The reasons why established firms lagged entrants in introducing these new architectural technologies seem unrelated to intrinsic technological difficulty—new architectural designs typically cost less

[22] Cooper and Schendel, "Strategic Responses to Technological Threats," and Foster, *Innovation: The Attacker's Advantage*, are two highly influential studies that take the general viewpoint that radical innovation tends to come from new firms.

Figure 3
Patterns of Entrants' Leadership
in the 8-, 5.25-, and 3.5-Inch Architectural Generations



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than $2 million to develop, and most employed widely available, proven components. If one adjusts for differences in the types of components employed, the new architectural designs of those established firms that did belatedly introduce them performed just as efficiently as the products of entrant firms introduced in the same year.[23]

The puzzle in these patterns of leadership is intensified by the asymmetry between the risk and expense of innovations in component and architectural technologies and the rewards reaped by the innovators. On the one hand, although new architectural designs were inexpensive and technologically straightforward, their impact was industry-shaking. Each of the leading entrant firms shown in the 1989 and 1992 columns of Table 3 entered the industry with an innovative product architecture employing generally available, proven componentry. On the other hand, despite the risk, time, and expense expended in developing new component technologies, the historical evidence suggests that component-level innovations were essentially defensive in character; they helped innovators remain competitive in their markets but, despite the costs and risks incurred, did not create a sufficient competitive advantage to change the market shares or profitability of innovating firms substantially.

In contrast to the sluggish movement that the established firms demonstrated in the three architectural innovations just described, they aggressively led the industry in its other two architectural transitions—the substitution of the 14-inch Winchester drive for its 14-inch disk-pack predecessor between 1973 and 1977 and the emergence of the 2.5-inch drive, which began in 1989. After its invention by IBM in 1973, the 14-inch Winchester drive was quickly adopted by the other firms that had been leading suppliers of disk-pack drives, such as Control Data, ISS, Burroughs, and EMM. Seven of the eight firms that had introduced 14-inch Winchester-architecture drives by 1977 were established producers of the prior architectural generation.

The first firm to introduce the 2.5-inch drive in 1989 was an entrant, Prairietek—a spin-off of Miniscribe, the second-largest maker of 5.25-inch drives. However, within a year the two largest makers of 3.5-inch drives, Conner Peripherals and Quantum, had

[23] See Clayton M. Christensen, "The Innovator's Challenge: Understanding the Influence of Market Environment on Processes of Technology Development in the Rigid Disk Drive Industry" (Unpub. DBA thesis, Harvard University Graduate School of Business Administration, 1992), chap. 7.

weighed in with their own 2.5-inch models, and by 1991 they had captured over 95 percent of the 2.5-inch market. Prairietek was bankrupt by 1992.

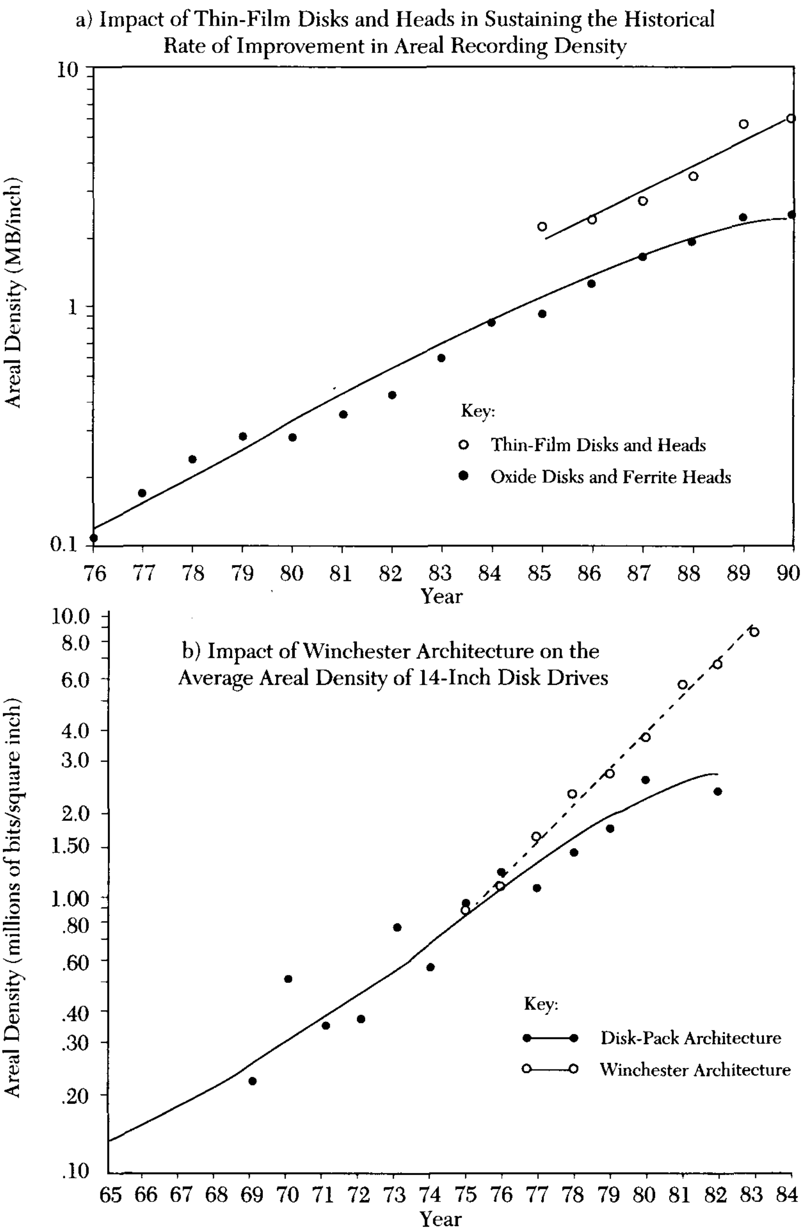
Sustaining vs. Disruptive Technological Change

The pattern of technological leadership in these two drive architectures was remarkably similar to the one described earlier for thin-film heads: established firms aggressively led the industry, and there were fatal consequences for the entrants that attempted to lead. Why were these so similar to the leadership patterns in component technology? And what was it about the 8-, 5.25-, and 3.5-inch architectures that facilitated the entrant firms' leadership? The hypothesis raised by this research is that the innovations in component technology and in the 14-inch and 2.5-inch Winchester architectures all had a similar impact on the customers of the leading established firms. Each of these technologies *sustained* the trajectory of product performance improvement that these firms' customers demanded and had come to expect. In contrast, the 8-, 5.25-, and 3.5-inch architectures *disrupted* the trajectory of performance improvement in established markets and hence had initial appeal only in new, emerging market segments.

These differences in the way the technologies affected established firms' customers are displayed in Figures 4 and 5. Figure 4a charts the trend in recording density achieved in drives using conventional ferrite-head/oxide-disk technology compared to that achieved in drives employing advanced thin-film heads and disks. Figure 4b contrasts trends in density achieved with disk-pack drives with that of the 14-inch Winchester architecture. In both charts, the solid dots and the curves fitted through them chart the trajectory of improvement achieved in the earlier technology. Each seems to have followed the sort of S-curve pattern that Richard Foster shows to be typical of technology life cycles.[24] Thin-film component technology and Winchester architectural technology each enabled the firms innovating with those technologies to sustain the rate of performance improvement that historically had become established. In this

[24] See Foster, *Innovation: The Attacker's Advantage*; and Clayton Christensen, "Exploring the Limits of the Technology S-Curve, Part 1: Component Technologies"; and "Exploring the Limits of the Technology S-Curve, Part 2: Architectural Technologies," *Production and Operations Management* 1 (Fall 1992): 334–66.

Figure 4
Two Examples of Trajectory-Sustaining Innovations:
Thin-Film Heads and the 14-Inch Winchester Architecture



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respect, these two charts are archetypical of all other innovations in componentry and of the 2.5-inch Winchester architecture.

In contrast, Figure 5 highlights the disruptive nature of the 8-, 5.25-, and 3.5-inch architectures by mapping the average capacity of all drives designed with each architecture compared to the capacity of drives in other architectures. In this graph, the dotted lines chart the average capacity of all drives within each architecture introduced in each year beginning in 1976. The top dotted line shows that the capacity of the average 14-inch disk-pack drive was about 250 MB in 1976. As the capacity trajectory of the disk-pack architecture began to level off, the Winchester architecture emerged to sustain the historical trajectory of 22 percent annual growth. In 1978, the first 8-inch Winchester drives were introduced. Physically much smaller, the average 8-inch drive packed only 20 MB of capacity—compared to an average of 350 MB for the 14-inch drives introduced that year. The 8-inch technology, in other words, did not sustain the established capacity trajectory of 14-inch drives—it created a new trajectory.[25] Once the 20 MB starting point was established, however, the makers of 20 MB drives subsequently were able to boost the capacity of their drives along a very steep 50 percent annual improvement trajectory.

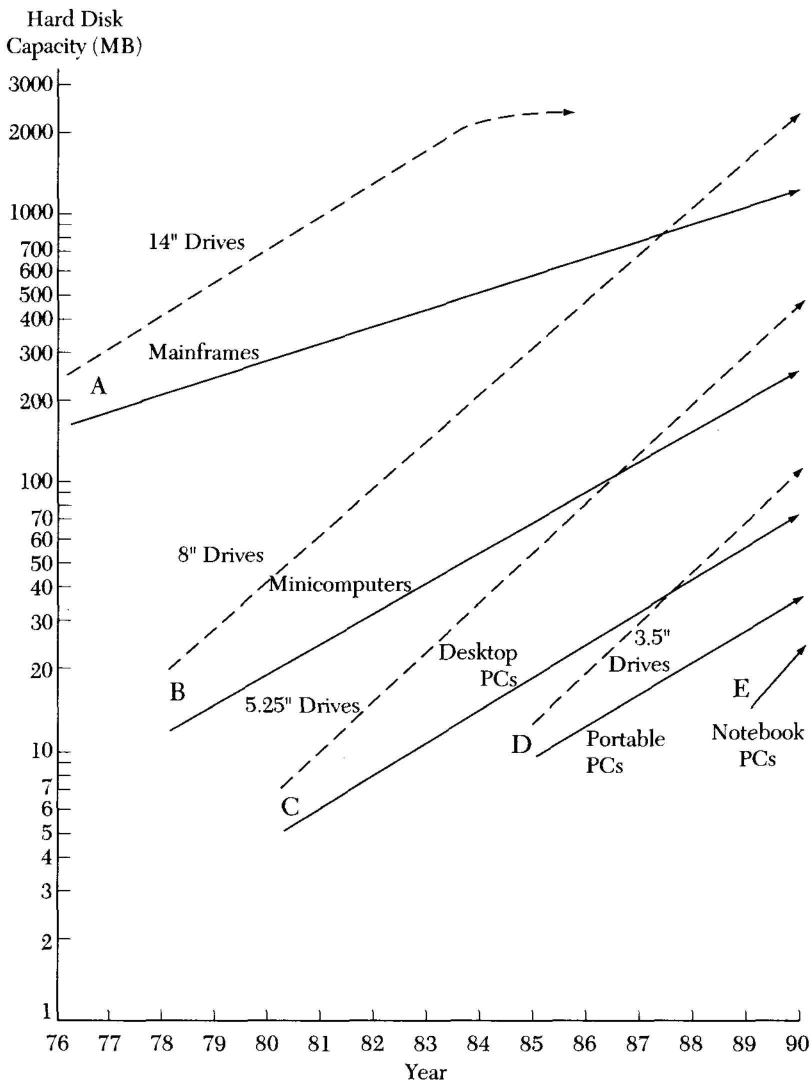
Figure 5 shows that, when the 5.25-inch architecture emerged in 1980, it had a similar disruptive impact on the established trajectories of capacity improvement. The new 5.25-inch products offered only 5-10 MB of capacity that year, compared to 50 MB in the average 8-inch drive and 700 MB in the average 14-inch Winchester product. Again, once they had begun production, the 5.25-inch drive makers were able to push the capacities of their products along a trajectory roughly parallel to that of the 8-inch products. The 3.5-inch architecture, introduced in 1985, had a similar disruptive impact vis-à-vis the earlier products, and 3.5-inch drives also improved along a trajectory parallel to that of earlier architectures.[26]

Although each packed less total capacity than predecessor prod-

[25] The concept of technological trajectories was first introduced in Giovanni Dosi, "Technological Paradigms and Technological Trajectories," *Research Policy* 11 (1982): 147–62.

[26] The parallelism in the trajectories of capacity improvement across the 8-, 5.25-, and 3.5-inch architectures seems to have occurred because assemblers of each of these architectural generations had reasonable access to the same improvements in basic component technologies. Because component technology improvements were the engine of performance improvement within a given architectural paradigm, one might expect the trajectories to be parallel.

Figure 5
Definition of New Technological Trajectories by the 8-, 5.25-, and 3.5-Inch Architectural Generations, Compared with the Trajectories of Capacity Demanded in the Mainframe, Mini, Desktop PC, and Portable PC Markets



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ucts, these disruptive architectures did not necessarily represent a sequence of successively inferior technological approaches—they simply offered a very different package of attributes than were offered in the prior architectural generation. The 5.25-inch drive, for example, was inferior to 8-inch products in capacity and speed. But it was smaller and less expensive; it could fit physically and economically in a desk-top computer. Similarly, the capacity and speed of the 3.5-inch drive were inferior to those of 5.25-inch products when it was first introduced. But it had other redeeming attributes—it was small and rugged enough to be used in the early portable and laptop computers. Hence, although each of these new architectures could be deemed inferior according to the standards used to assess the performance of predecessor technologies, the new drives had appealing properties for other purposes. Trajectory-disrupting architectures therefore tended to be used initially in new, emerging market segments rather than in the large, mainstream markets served by the leading disk drive manufacturers. In contrast, the trajectory-sustaining technologies were first used within the mainstream markets.

The forgoing examination of the history of leadership in technological innovation in the disk drive industry has disclosed that established firms consistently led the industry in developing and adopting new technologies—whether in componentry or in architecture—that reinforced or sustained the trajectory of performance improvement that their customers expected. When new technologies disrupted established trajectories and redefined the metrics by which performance was measured, entrant firms were the leading innovators.

Market Demand vs. Technology Supply as Drivers of Change in Industry Leadership

We have just seen that drives with disruptive new architectural technologies were generally deployed in new market segments, where computing products needed the new package of attributes that these drives offered. A fit between a particular product architecture and the product characteristics demanded in a specific market segment might have resulted in a series of "niche" markets, each with its own relatively unique definition of product performance. In the disk drive industry, however, such a market structure never emerged—because the rate of increase in performance that disk drive manufacturers were able to provide within each new product architecture was substantially greater than the rate of performance improvement demanded by customers.

These differences in the rates of performance improvement are contrasted in Figure 5. The dotted lines emanating from points A, B, C, and D measure trends in the average capacity that disk drive manufacturers were able to provide within each successive disk drive architecture. These steep trends in performance improvement within each architecture were driven by the sorts of trajectory-sustaining improvements in componentry described earlier. The disruptions in these trajectories—the movements from point A to points B, C, and D—were the result of changes in architectural technology. In light of the preceding discussion on technology leadership, we can now assert that the firms that led the industry along each dotted-line technology trajectory were established firms, and that the leaders in jumping to new points of departure (B, C, and D) were entrants.

The solid lines in Figure 5 map the demand trajectories for hard disk capacity within the major successive market segments of the computer industry: mainframes, minicomputers, desktop personal computers (PCs), portable and laptop PCs, and notebook PCs.[27] These lines show, for example, that in 1976 the median-priced mainframe computer was equipped with 160 MB of hard disk capacity. The hard disk storage capacity supplied with the median-priced mainframe increased about 17 percent a year through the period studied, so that by 1990 the typical mainframe was equipped with 1,300 MB of hard disk capacity. Points B, C, D, and E mark the years in which 8-, 5.25-, 3.5-, and 2.5-inch drives were first used in the minicomputer, desktop personal computer, portable, and notebook computer market segments, respectively. The hard disk capacity demanded per computer (charted by the solid lines starting at each point) increased at annual rates of approximately 30 percent in each of these segments.

[27] These trajectories of capacity demanded were calculated by plotting the hard disk capacity shipped with the median-priced computer system in each market category for each year, and then fitting a best-fit regression line through those points. The trajectories of capacities that the technology was able to supply within each architecture were calculated by determining the average capacity of all models introduced in each year in each architectural form factor, and then using regression analysis to calculate the equation of the best-fit line through them. Details of these procedures can be found in Christensen, "The Innovator's Challenge," which also describes the trajectories in capacity demanded in the engineering workstation market segment.

The mismatch between what the markets demanded and what the technology could provide enabled technologies that initially were not performance-competitive in established markets eventually to intersect with the demand in those markets. For example, by 1986 the average 8-inch drive packed the capacity required in the median-priced mainframe computer. The average 5.25-inch drive, which initially could satisfy only the performance demanded in desktop personal computers, by 1986 packed the capacity demanded by the typical minicomputer user. By 1989 the 5.25-inch architecture was invading the lower end of the mainframe market.

To understand better what happened at the points where these new technologies emerged and where technology and market trajectories intersected, I interviewed over sixty executives who played key roles in the marketing, engineering, and manufacturing functions of the industry's leading firms at these points of intersection. Data from these interviews were used to recreate as clearly as possible the processes that led to the firms' decisions to invest, or to delay investing, in key component and architectural technologies. Although each firm's experience differed in detail, there was remarkable similarity across the firms in the forces that influenced their technology investment decisions and in the outcomes that each experienced at the emergence of the 8-, 5.25-, and 3.5-inch architectures. These findings are generalized in the following sequence of events.

First, engineers in established firms conceived of new architectural concepts enabling the disruptive-architecture drives; they fabricated prototype samples and tested the market appeal of the products, in the form of drawings or prototypes, with mid-level marketing counterparts in their firms. The marketing personnel in turn showed the prototypes or drawings to key customers, who showed little interest in the products, because the new drives packed less capacity and typically had slower access times than the larger-architecture drives the customers currently sourced for design into their existing computer systems. In response to customers' feedback, the established disk drive manufacturers scaled back the resources committed to the new-architecture projects or canceled the efforts altogether. They then intensified their efforts to fill the need their customers had clearly articulated—in the case of mainframe computer manufacturers, greater capacity and faster access times *within* the 14-inch architecture. To accomplish this, the established drive makers intensified their focus on improving and employing advanced component technologies.

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In response to the loss or scaling back of their program, members of the engineering team that developed the smaller architecture often defected in frustration, launching one or more start-ups to manufacture drives based on the new technology. The start-up companies also were unable to interest large computer makers in the new-architecture drives. They therefore had to find new market applications for their drives. There was substantial uncertainty in this search for customers—what the markets might be and how large they might become were unknown. The applications that materialized during these search processes were the minicomputer, the desktop personal computer (and later the engineering workstation), and the portable computer industries. Although these markets are easily understood today as natural applications for hard disk drives, this was not at all clear when the new markets were first emerging.

When the start-ups had established a beach-head business in these new applications, they found that, by incorporating advances in new component technologies, they could increase the capacity of their drives at a faster rate than was required to satisfy customers in their home markets. They therefore fixed their strategic sights on the established computer markets immediately above them. When the capacity of the new-architecture drives had increased to the levels required in these higher market segments, computer manufacturers in those markets began switching to the "new" (now established) technology. At this point they generally found that the drives not only provided the capacity they needed, but that their smaller size and relative architectural simplicity also made them less costly and more reliable.

When the smaller drives began to gain share in these higher markets, the drive makers that had established themselves by supplying the larger architectures took the new technology "off the shelf" and introduced their own versions as a defensive response to a competitive attack from below. As a result, these models generally cannibalized established disk drive manufacturers' sales of larger-architecture products. Yet, because they launched their new architecture models so late, the established drive makers rarely were able to build significant incremental business in the market segment that had recently emerged. Although a few established drive makers were able to defend their prior market positions by launching the new architecture, most found that the entrant firms had developed insurmountable volume-based manufacturing cost advantages through their positions in the new market segment, and the older firms ceded the established markets to the invaders.

To illustrate more deeply the process through which the established firms tended to deal with disruptive architectural transitions, the story of one industry leader, Seagate Technology, is documented in detail in the next section.[28]

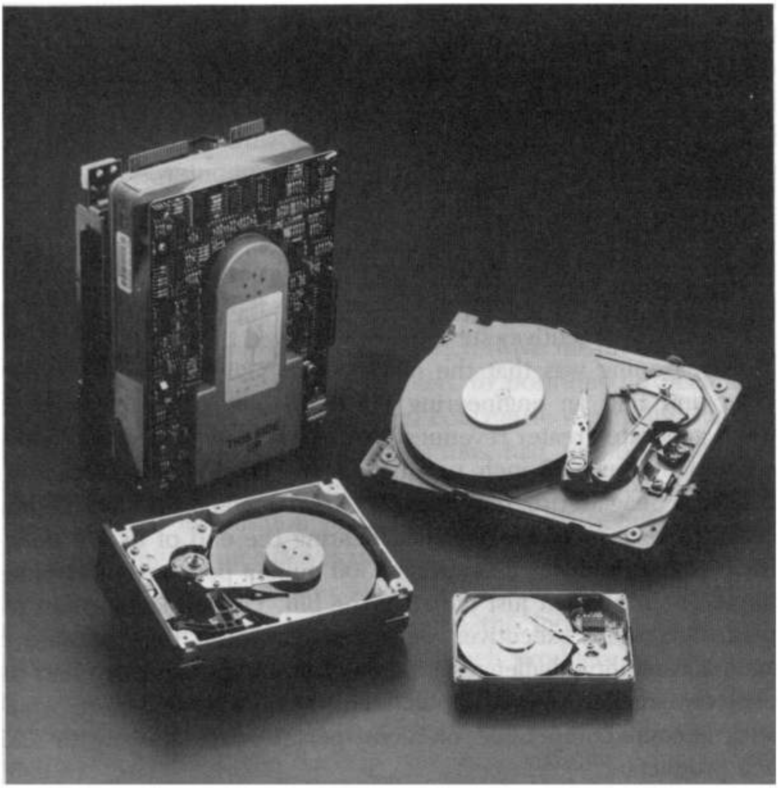
Seagate and the Transition from 5.25- to 3.5-Inch Drives

The 3.5-inch drive was first developed in 1984 by Rodime, a Burroughs spin-off. Sales of this architecture were not significant, however, until Conner Peripherals, a Seagate-Miniscribe spin-off, started operations in 1986. Conner's small, lightweight drive architecture was much more rugged than its 5.25-inch ancestors; it handled functions electronically that had previously been managed with mechanical parts and used microcode to replace functions that previously had been addressed electronically. Over 90 percent of Conner's record first-year revenues of $113 million came from Compaq Computer, which had funded most of Conner's start-up with a $16 million investment.

The 3.5-inch Conner drives were used primarily in a new application—portable and laptop machines, in addition to a few "small footprint" desktop models—where customers were willing to accept lower capacities and higher costs per megabyte in order to get the smaller size and weight, greater ruggedness, and lower power consumption that 3.5-inch drives offered. Like most firms that entered the disk drive market on the basis of a new product architecture, Conner attracted little notice from the established drive makers, because it sold products on the basis of performance attributes that established firms did not appreciate to customers that the established firms did not know. Conner's relationship with Compaq, which was itself a company new to the computer business and whose own volume trajectory was meteoric, enabled Conner to build a substantial volume base without attracting serious competitive attention.

The leading 5.25-inch drivemaker, Seagate Technology, clearly foresaw the 3.5-inch architecture's advent. By early 1985, less than one year after the first 3.5-inch drive was introduced by Rodime and

[28] A similarly detailed account of each architectural transition is contained in Christensen, "The Innovator's Challenge."



Modern Disk Drives • Shown, clockwise from upper left, are a 20 megabyte full-height 5.25-inch drive used in an early IBM AT personal computer; a 20 MB 5.25-inch drive that was half that height, to allow space for an additional floppy drive in the AT; a 2.5-inch drive (40 MB) used in notebook computers; and a 3.5-inch drive used in early portable and laptop computers. (Photograph, of disk drives in the author's possession, by Ed Malitsky, Boston, Mass.)

two years before Conner Peripherals started shipping its product, Seagate engineers had developed working 3.5-inch prototype drives. Their development had actually been instigated at the request of Seagate's largest customer, IBM, whose product planners were considering replacing the 5.25-inch drives in the PC-AT desktop computer with the smaller 3.5-inch drive. When IBM evaluated the Seagate 3.5-inch prototypes and understood that their capacities were limited to 10 and 20 MB models, however, the product planners decided to go with next-generation 5.25-inch drives instead. They sensed that the AT's customers wanted 40 and 60 MB of disk storage in the next AT models to be released rather than the less

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tangible benefits of a physically smaller drive housed within the large AT box on their desktops.

Having been abandoned at the altar by IBM, Seagate marketers subsequently worked to sell the 3.5-inch product to other customers. But the customers to whom the 3.5-inch drives were shown were also manufacturers of full-sized desktop computer systems. Like IBM, they were looking for capacities of 40 and 60 megabytes for their next generation machines and showed little interest in the smaller drive.[29] In response to these lukewarm reviews from customers, Seagate's program manager lowered his 3.5-inch sales estimates, and the firm's executives subsequently shelved the 3.5-inch program. Their reasoning was that the markets for 5.25-inch products were larger and that an engineering effort on new 5.25-inch products would generate greater revenues for the company than would efforts targeted at new 3.5-inch products. "We needed a new model," recalled a Seagate program manager, "which could become the next ST412 [a very successful product nearing the end of its life cycle], which at the time was generating $300 million per year in revenues. The 3.5-inch product just didn't fit the bill. The market was just too small."[30] Seagate executives were also convinced that, because of manufacturability challenges inherent in the 3.5-inch drive and the relatively smaller size of its market, the new architecture would never become competitive, on a cost-per-megabyte basis, with 5.25-inch products.

From 1984 to 1989, when the 3.5-inch architecture was becoming firmly established in portable and laptop applications, Seagate had in no way lost its ability to innovate. It was highly responsive to its own customers. The capacity of its drives increased at about 30 percent a year—a perfect match with the market demand charted in Figure 5 and a testament to the firm's focus on the desktop computing market. Seagate also introduced new models of 5.25-inch drives at an accelerated rate. During this period Seagate announced new products that employed most of the available new component

[29] This finding is consistent with the observations of Burgelman, who noted that one of the greatest difficulties encountered by corporate entrepreneurs was finding the right "beta test sites," where products could be interactively developed and refined with customers. Generally, the entré 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 did not help it identify new applications for its new technology. See Robert Burgelman and Leonard Sayles, *Inside Corporate Innovation* (New York, 1986), 76–80.

[30] Carter O'Brien, former Seagate executive vice-president of marketing, interview with author, 4 May 1992, Scotts Valley, Calif.

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technologies—including thin-film disks, voice coil actuators, RLL codes, and embedded, SCSI interfaces.[31]

By 1987–88, 3.5-inch drives began to pack the capacity required in the desktop market (shown in Figure 5 where the dotted 3.5-inch capacity technology trajectory begins to intersect with the demand-for-capacity trajectory in desktop computing). At this point, desktop computer makers discovered that, in addition to providing the capacity they needed, the smaller architecture offered other advantages on the desktop. For example, the small drives allowed them to shrink the footprint and profile of their products and to eliminate a noisy cooling fan. And less mass in the 3.5-inch drive meant less vibration and less inertia, enabling drive makers to position the head more accurately over more densely spaced concentric recording tracks on the disk. These engineering implications had not been apparent when the 3.5-inch architecture was first presented to manufacturers.

To defend its position in the desktop market, Seagate finally began shipping 3.5-inch drives in early 1988—three years after it had designed the drives and after nearly $750 million in 3.5-inch products had been shipped cumulatively in the industry. As of 1991, however, almost none of Seagate's 3.5-inch products had been sold to manufacturers of portable, laptop, or notebook computers. Its primary customers for 3.5-inch drives were its previous customers for 5.25-inch drives, the desktop computer manufacturers; indeed, many of Seagate's 3.5-inch drives continued to be shipped with frames permitting them to be mounted in XT- and AT-class computers designed to accommodate the larger drives.

Seagate's response to the development of the 3.5-inch drive architecture 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. What led the incumbent manufacturers to resist or ignore the new technology?

The barrier to the development of competitive new-architecture products does not appear to have been engineering-based. In each case, established manufacturers that did introduce the new architecture, though late, weighed in with products whose performance was

[31] Voice coil motors could position the head much more accurately over tracks on the disk than could stepper motors, since they operated in a continuous mode and could be used with closed-loop servo systems. Voice coil motors were not new to the market when Seagate adopted them in 1984, but they represented a major shift in Seagate's design philosophy.

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actually superior to that of the entrants, and they subsequently improved their new architecture products at a faster rate than the entrants did.[32]

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, when innovative technologies are initially deployed in new-market applications, the introduction of new technology may not be inherently cannibalistic. When established firms wait until a new technology has become commercially mature in its new applications, however, and launch their own version of the technology only in response to an attack on their home markets, the fear of cannibalization can become a self-fulfilling prophecy.[33]

The primary problem of the established drive manufacturers was that they were held captive by their customers, who seemed, as the Seagate history demonstrates, to have been as oblivious as the drive makers to the potential benefits and possibilities of the new architectures. In the industry's two trajectory-sustaining architectural transitions—from disk-pack drives to 14-inch Winchester drives and from 3.5- to 2.5-inch drives—the industry leader in the prior architectural generation was able to maintain its leadership in the subsequent generation as well. In both cases, their customers led them across the architectural transition. For example, the same companies

[32] This issue is covered in detail in chapter 7 of Christensen, "The Innovator's Challenge." The primary issue investigated there deals with this question: If groups of entrant and established firms were dealt exactly the same set of components, would one group of firms consistently design higher-performance drives than the other group for a given level of component technology? In other words, might it be possible that established firms' engineers were somehow locked into an obsolete way of thinking about system design, so that their products were not as efficient in extracting performance out of a given set of components as entrant firms' engineers might have been? The results showed that, though there were consistent differences among firms in the architectural efficiency of their drives, there was no statistically significant difference between established and entrant firms' architectural efficiencies.

[33] By 1988, because the 3.5-inch drive had begun to encroach on Seagate's desktop 5.25-inch product sales, Seagate's revenues began to stagnate. Its executives responded by acquiring the disk drive operations of Control Data in 1989. Seagate then combined its volume manufacturing expertise with Control Data's advanced component technologies (such as thin-film head manufacturing) to forge a strong market position in the rapidly growing engineering workstation market. Most industry observers credit the acquisition as having saved the company, and I would agree. By 1993, Seagate had essentially been driven into a weak number three position in its original market—personal computing—by the two firms that pioneered the 3.5-inch drive, Conner Peripherals and Quantum Corporation. Seagate's corporate strength in the early 1990s derives almost exclusively from its Control Data acquisition.

that had leading market shares in portable and laptop computers—Toshiba, Sharp, and Zenith—also became the leading manufacturers of notebook computers. The same performance attributes that were valued in laptop machines, such as ruggedness, low power consumption, and capacity per unit of weight and volume, were critical in notebook computers as well. Since the 2.5-inch drive addressed these needs more effectively than did the 3.5-inch architecture, Conner Peripherals was able to follow its customers smoothly across this architectural transition. Doing so required no change in strategy.

A Deeper View of the Success and Failure of Large, Diversified Firms

The first section of this article showed that large-scale, diversified concerns were the early dominant manufacturers in the original equipment market. Having established the alignment in the disk drive industry between disruptive innovations in architectural technologies and the emergence of new market segments on the one hand, and the appeal of sustaining technological innovations to established market segments on the other, it is now possible to examine at a deeper level the overwhelming defeat by the start-ups of the large, integrated firms that once dominated the U.S. disk drive industry. The decline of these firms does not seem to have been caused by technological conservatism, short time horizons, or an unwillingness to invest in new technologies, as their leadership in a range of relatively risky, difficult, competence-destroying component innovations shows. Nor does their failure seem to have resulted from ignorance of customers' needs or by a sluggish response to them. It was their very attentiveness to their customers' needs, in fact, that drove their leadership in component and trajectory-sustaining architectural technologies. Rather, it seems that these firms failed because they listened too attentively to their established customers and ignored new product architectures whose initial appeal was in remote markets. Eventually, because of the mismatch in the trajectories of technological improvement and market demand, the established firms fell victim to attacks by start-ups and the new architectural technologies the entrants employed.

Table 2 showed that in 1976 there were seventeen active firms in the OE market: four related-technology, ten related-market, and three vertically integrated. Only one firm from each of these groups of original participants was still producing disk drives in 1989. And of the ten related-market firms that entered the industry after 1976, not one survived.

Although it is tempting to ascribe the 100 percent failure rate of related-market entrant firms to the inappropriateness of such a corporate form in a technologically turbulent market—or to ascribe the success of the start-ups to capabilities or corporate forms better suited to this environment—it appears instead that the firms' failure and success rates are influenced most strongly by the technology and market strategies they pursued, rather than by their size or corporate structure. Although the entrants to the disk drive industry pursued a wide variety of technology and market strategies, some distinct, central tendencies can be discerned.

There were seventy-seven independent (non–computer manufacturer) entrants to the U.S. rigid disk drive industry between 1971 and 1989.[34] For analytical purposes, "successful firms" in this population were arbitrarily defined as those that achieved more than $50 million in revenues in constant 1987 dollars in any single year between 1977 and 1989—even if they subsequently withdrew from the market. Failed firms were defined as those that were active at any time during the 1977–89 period; that did not achieve sales greater than $50 million in any single year; and that ceased operations in or before 1989. Firms still operating in 1989 that had not yet achieved $50 million in annual revenues were classified as "no verdict."

To examine the impact that these firms' market entry strategies had on their success, each firm's initial product-market approach was characterized according to whether it used new or proven component technology in its first products and whether these products were targeted at emerging or established markets. "New technology" was defined as an innovation in component or architectural technology that had been on the market for three years or fewer, or that fewer than 20 percent of firms in the market had adopted. Hence, thin-film heads, though introduced in 1976, were not considered a proven component technology until 1986, when over 20 percent of

[34] Vertically integrated disk drive manufacturers were not considered in the analysis that follows, on the assumption that the architectural technologies they employed in disk drives were largely determined by their strategies in downstream computer businesses. For example, IBM's decision of when to launch 5.25-inch and 3.5-inch architectures was determined by when the firm's personal computer business needed such drives, rather than being independent, strategic decisions made by the management of IBM's disk drive operation.

the firms in the market finally were offering products using them.[35] Firms were considered to have targeted a new, emerging market if their initial models employed a trajectory-disrupting architectural technology (8-, 5.25-, or 3.5-inch drives) that had been in the market for fewer than two years. They were considered to have targeted an established market if their initial products employed a trajectory-sustaining architecture (14- or 2.5-inch Winchester drives), or if their first product was an 8-, 5.25-, or 3.5-inch product that arrived in the market three or more years after that architecture was first introduced.

Figure 6 employs a 2 x 2 matrix to describe the entry technology strategies that characterized the various types of firms. Its horizontal axis denotes whether the firm targeted a new or an established market, and the vertical axis shows whether the entrant's first product incorporated new or proven component technology. The headings in each quadrant denote whether a firm was successful (S), failed (F), or is still operating but has not yet succeeded or failed (N) according to the definition of success noted earlier. T denotes the total number of firms that followed that quadrant's strategy. The numbers under each heading show the number of firms in that category, listed by type of entrant.

The "Totals" statistics show that, overall, entering established markets with proven components was the most common entry technology strategy, followed by thirty-six (48 percent) of the entrants. Only 11 percent of the firms following this strategy succeeded, however. In contrast, twenty-three (30 percent) of the entrants used proven component technologies with architectures targeted at new market applications. Sixty-five percent of these firms succeeded. The

[35] The 8-, 5.25-, 3.5-, and 2.5-inch Winchester architectures on which this study focuses were the architectural innovations that penetrated major portions of the market. There were, however, many more innovative architectures introduced by firms that never became commercially successful, or that, though successful, remained confined in a relatively small market niche. An example of the former was a head-per-track 14-inch drive that Alpha Data attempted to sell for over a decade. The 3.9-inch removable-cartridge drive introduced by Syquest in 1982 was a commercially successful architecture that has remained in a relatively small niche market for back-up desk-top devices. Maxtor's effort to pack more capacity into the standard full-height 5.25-inch form factor by building the motor into the spindle, so that additional disks could be stacked on the spindle, was another architectural innovation of the non–form-factor sort. These innovations, though they did not capture large market shares, were nonetheless considered as new architectures in the analysis reported here, because each addressed new, emerging market segments.

Figure 6

Entry Technology Strategies Employed by Related-Market, Related-Technology, Start-Up, and Forward Integrator Firms, 1973–1989

Component Technology: New

	S	*F*	*N*	*T*	*% Success*
Related-Market	0	3	0	3	0
Related-Technology	0	0	0	0	–
Start-Up	1	4	0	5	20
Forward Integrator	0	1	0	1	0
Totals	1	8	0	9	11

	S	*F*	*N*	*T*	*% Success*	*Over-All Success Rate in New Components (%)*
Related-Market	0	0	0	0	–	0/3 = 0
Related-Technology	0	1	0	1	0	0/1 = 0
Start-Up	3	4	0	7	43	4/12 = 33
Forward Integrator	0	0	0	0	–	0/1 = 0
Totals	3	5	0	8	38	4/17 = 23

Component Technology: Proven

	S	*F*	*N*	*T*	*% Success*
Related-Market	2	15	0	17	12
Related-Technology	0	3	0	3	0
Start-Up	2	8	3	13	15
Forward Integrator	0	3	0	3	0
Totals	4	29	3	36	11

	S	*F*	*N*	*T*	*% Success*	*Over-All Success Rate in Proven Components (%)*
Related-Market	2	2	0	4	50	4/21 = 19
Related-Technology	5	1	0	6	83	5/9 = 56
Start-Up	8	5	0	13	62	10/26 = 38
Forward Integrator	0	0	0	0	–	0/3 = 0
Totals	15	8	0	23	65	19/59 = 32

Established — Architectural Technology — New

Over-All Success Rate in Established Architectures:

	S	*F*	*N*	*T*	*% Success*
Related-Market	2	18	0	20	10
Related-Technology	0	3	0	3	0
Start-Up	3	12	3	18	21
Forward Integrator	0	4	0	4	0
Totals	5	37	3	45	11

Over-All Success Rate in New Architectures:

	S	*F*	*N*	*T*	*% Success*
Related-Market	2	2	0	4	50
Related-Technology	5	2	0	7	71
Start-Up	11	9	1	21	50
Forward Integrator	0	0	0	0	–
Totals	18	13	1	32	56

Source: Author's analysis of *Disk/Trend Report* data.

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success rate of firms on the right half of the matrix, at 56 percent, was five times greater than the rate of those that entered established markets.

Sixty of the seventy-seven entrants were reluctant to seek performance advantage through new component technology in their initial products—possibly reflecting the difficulty often involved in developing and using such innovations. Whether firms used proven or innovative component technology was not, however, a factor markedly related to differences in the success rate.

Figure 6 also shows that, although different types of firms tended to employ different strategies on entry, their success rates are related much more to entry strategy than to type of firm. Seventeen of the twenty-four related-market firms entered the industry with proven-component technology/established-market strategies. This is understandable. Since their basis of diversification was not technological expertise in magnetic recording, one would not expect them to seek competitive advantage by developing new component technology. They entered the disk drive industry because they believed that their marketing capabilities, derived from selling other computer peripheral products, could be the basis of success in the disk drive business as well. Related-market firms had a very low success rate, but firms of *every* sort that pursued the established-market/proven-components entry strategy had a dismal success rate, ranging from zero among related-technology firms to 15 percent for start-ups (see the lower-left quadrant of Figure 6). The proximate cause of the poor showing of related-market firms in this industry may not be that market-related diversification as a corporate strategy is inappropriate for a technologically turbulent industry, but that the *entry strategy* that a related-market corporate structure seems to have led them to pursue offered a low probability of success.

The entry-technology strategy toward which the related-technology firms tended was substantially different; it was generally based on proven components targeted at new markets. An astonishing 83 percent of related-technology entrants that employed this strategy succeeded, whereas none that targeted established markets with proven components succeeded. The start-ups showed more diversity in strategies, but their success rates follow the same tendencies as the other groups of firms. As with related-market and related-technology firms, the highest success rate for the start-ups, 62 percent, occurred among those firms that followed a proven-components/innovative-market strategy. Whether the firms used proven or new component technology does not seem to have been as strong a discriminator of success, although entering with new component technologies seems to have been more difficult for all types of firms. The forward integrators all entered established markets, and none succeeded.

The Dis-Integration of Firms in the Disk Drive Industry

The preceding sections have shown how customers consistently commanded the strategic attention of the established disk drive manufacturers. Their tendency to focus so sharply on current customers, in the face of growing demand for disk drive technology outside the established firms' traditional customer base, seems to have set in motion powerful dis-integrative forces that spun valuable people and technology out of the established integrated companies and into the marketplace—a very "un-Chandlerian" outcome for what was a very Chandlerian beginning in this industry.

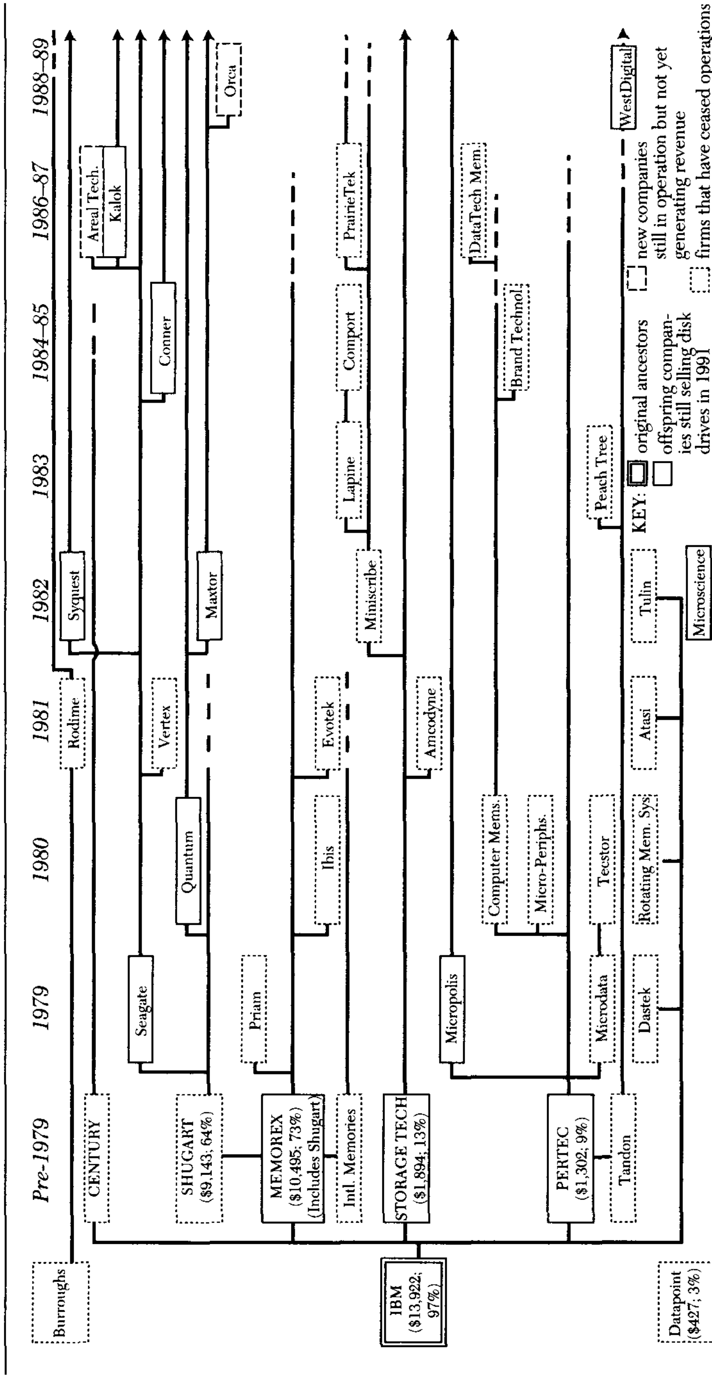
The spinning out of people and technology from the established companies occurred at the levels of both architectural and component technologies. The outcome of the processes through which new architectural technologies were spun out of the established firms, described earlier, are reflected in the corporate genealogies of the leading disk drive manufacturers shown in Figure 7. Although the chart does not show all of the start-ups that entered the industry, it captures all but four of the start-ups that actually generated revenue, and the firms shown accounted for 99.4 percent of the total cumulative revenues generated by the start-up group.[36] All but one of the start-ups can trace their genealogies to IBM, and all were sired by three plug-compatible market manufacturers that were IBM offspring—Pertec Computer, Storage Technology, and Memorex. Of the three IBM offspring with progeny, the descendants of Memorex, via Shugart Associates, were overwhelmingly the most productive, accounting for over $9.14 billion, or 64 percent, of the cumulative revenues of the start-ups.[37] (Cumulative revenues for their descen-

[36] The founders of those four start-ups had no prior direct experience in the disk drive industry.

[37] Shugart itself was founded in 1973 to manufacture 8-inch floppy drives and, by all accounts, was the primary driver behind the creation of the OE market for the floppy disk drive industry. When its sales had reached $17 million in 1977, it was acquired by Xerox for $40 million. Xerox guided Shugart into rigid drives in 1977, and although the foray generated about $400 million in cumulative revenues, it was never profitable. Xerox closed Shugart down in 1985.

Figure 7

Employment Genealogies of Founders of Leading Start-Up Disk Drive Manufacturers



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dants, in $ millions, and the percentage of the total for which they accounted are listed in the IBM, Datapoint, Memorex, STC, Pertec, and Shugart boxes.) Moreover, six of the seven Shugart spin-offs that generated revenue were still in operation in 1991 and included the U.S. industry's four largest firms—Seagate, Conner, Quantum, and Maxtor.[38] This compares with one of eight Pertec spin-offs still in operation (Micropolis) and none of the descendants of Storage Technology.

One might term the pattern of spin-outs shown in Figure 7 one of *horizontal dis-integration*, where independent firms split off from predecessor firms to focus on different market segments. There seems to have been a pattern of *vertical dis-integration* in the industry as well. Whereas the industry's original dominant firms were thoroughly integrated into component manufacturing and the research required to support advanced component development, those firms' focus on a single set of (primarily internal) customers induced the spin-out of a host of independent companies that supplied components to the progressively less integrated set of disk drive manufacturers arrayed in Figure 7. Although the story of the creation of a network of independent component manufacturers is complicated enough to merit its own history, a brief summary of how and why independent component manufacturing firms spun out of the industry's initially dominant integrated firms will be helpful here.[39]

Firms that entered the industry with a new architectural technology targeted at an emerging market generally shifted their technological sights toward improved component technology, because improved componentry was the engine of performance improvement within each established product architecture. This shift in technology strategy from architectural orientation to component orientation entailed a significant change in the economics of product development for IBM and the other early industry leaders, because no network of component supply firms existed. Development of new product architectures generally had been an engineering task, not an issue of research and development. But the development of new component technology required substantial investment in research

[38] The $9.143 billion in cumulative revenues shown in Figure 7 for Shugart's progenitors does not include the approximately $1 billion in revenues booked by Seagate in 1989 from its acquisition of Control Data's disk drive operations.

[39] An initial version of this history can be found in Christensen, "Industry Maturity and the Vanishing Rationale for Industrial Research and Development."

and development, because component technology development is where basic scientific research, engineering, system design, product design, and process development all come together. In terms of the time, expense, and expertise required, component technology development was an enterprise fundamentally different from the design of new product architectures that employed available componentry. This difference between the pace and scale of component development and those of product design eventually made it impossible for the integrated firms to perform internally the coordinating roles that Chandler observed in other industries in funneling new component technologies into new product designs.

The following account of IBM's development of the thin-film head illustrates four phases that are typical of the course of events that occurred in the development and diffusion of many components within most of the industry's early leading integrated firms, including Control Data, Xerox (which supported its Diablo, Shugart, and Century disk drive divisions through its Palo Alto Research Center), Burroughs, Digital Equipment, and Seagate Technology.

The Disparate Cycles of Component and Systems Development: IBM and the Thin-Film Head • As the industry's pioneer and dominant firm during this period, IBM led the shift in technology strategy from architecture development to component development. Improved component technology defended IBM's large, growing, and very profitable mainframe business by providing its customers with steady performance improvement within the 14-inch Winchester architecture. Backward integration reduced the uncertainty that required components might not be available to meet customer and competitive requirements in the next product generation.

In the earliest stages of thin-film head development, IBM worked alone to expand its understanding of basic scientific issues such as the physics of magnetic recording and the properties of new materials. This phase began in 1965 in IBM's advanced research facilities at Yorktown Heights, New York, and San Jose, California. The second phase (beginning roughly in 1971 and ending in 1976–78) was stimulated by proof of the concept at IBM and by the spread of that information through published scientific papers and the trade press to other firms. Statements by respected IBM scientists that thin-film technology was important and feasible led a broader group of vertically integrated manufacturers—Burroughs, Control Data, Digital Equipment, Fujitsu, Hewlett Packard, Hitachi, and NEC—to initiate their own development efforts. IBM's pathbreaking research resolved a lot of uncertainty for these other firms: once they knew that something could be done, they could focus with greater commitment on learning how to do it. The end of this second phase was marked by the building of early working prototype thin-film heads.

In the third phase, the component design was refined, a manufacturing process was established, and the component was designed into a new disk drive model. In 1976 Burroughs was the first in the industry to announce a drive with a thin-film head, but it was never able to manufacture the head reliably and withdrew the drive from the market. IBM introduced its model 3370, equipped with thin-film heads, in 1979. Positioned at the highest-performance end of IBM's line, the 3370 was a very successful product, even though the heads were extremely difficult and expensive to manufacture.

To this point, the component technology leadership of the large, vertically integrated firms—particularly IBM—was unambiguous. In moving to the fourth phase, however, the story becomes troubled. Although IBM usually initiated each component development process in behalf of the industry and was often the first to introduce the new component in a high-end product model, IBM and the other vertically integrated manufacturers subsequently were very slow to employ the componentry they had developed in other new models in their product lines. The vertically integrated firms' commercial introduction of the new components in a limited number of high-end models typically stimulated the fourth phase in the emergence of new component technology, in which demand for the new componentry became intense among certain independent, non-integrated disk drive manufacturers. These independent firms, such as Maxtor and Micropolis, generally pursued technology strategies that pushed, through innovative (some would say risky) system design, what was called in the industry "the bleeding edge" of performance—a much more aggressive engineering posture than the vertically integrated manufacturers typically were inclined to adopt.

IBM viewed its proprietary access to advanced componentry as its primary competitive advantage and was reluctant to sell its components in the external marketplace, because it viewed the bleeding-edge manufacturers that most needed thin-film heads as indirect competitors.[40] Sensing the opportunity to match component supply

[40] Although none of the IBM engineers or executives interviewed for this history cited antitrust pressure as a force that kept IBM from selling its components in the OE market,

and demand more closely, several venture capitalists recruited key IBM and Xerox engineers into new start-up firms to produce and sell the new-technology components to bleeding-edge disk drive makers in the original equipment market. This was possible because the vertically integrated firms typically enjoyed little patent protection for the components: much of the key technology consisted of process know-how. The industry's leading thin-film disk manufacturer, Komag, and the leading thin-film head manufacturer, Read-Rite, both started in this manner. In 1992, within eight years of their founding, these firms together logged over $1 billion in revenues.

When the components became available from these start-up firms, even on an irregular, unpredictable, low-yield basis, disk drive manufacturers tended to utilize the new technology throughout their product lines at a pace that was roughly commensurate with their distance from the bleeding edge. And in general, the integrated manufacturers such as IBM tended to design conservatively, some distance from the bleeding edge. As a result, although the vertically integrated firms were the first to develop and introduce the new components, they were the slowest to incorporate them across the breadth of their product lines (see Figs. 8a and 8b). This was most strikingly the case with IBM. Although it spent over $300 million developing the thin-film head, it was the last firm in the industry to use the technology broadly in its entire product line. And although IBM spent over $100 million developing thin-film disks, it did not use them in any commercial product until 1988.

The unfortunate combination of the integrated firms' leadership in component development and their followership in component use seems to have been the result of an inexorable decoupling of component development from systems design as the industry matured. This was a problem that IBM worked hard to remedy but that in many ways derives from the fundamentally different natures and time scales of the two processes. Initially, because it was such a dominant presence in the computer markets, IBM was able to control the pace at which it introduced new models into the market—roughly every four years in the 1970s. IBM was therefore reasonably capable of coordinating the emergence of new long-lead-time components with the design of the product systems in which they ini-

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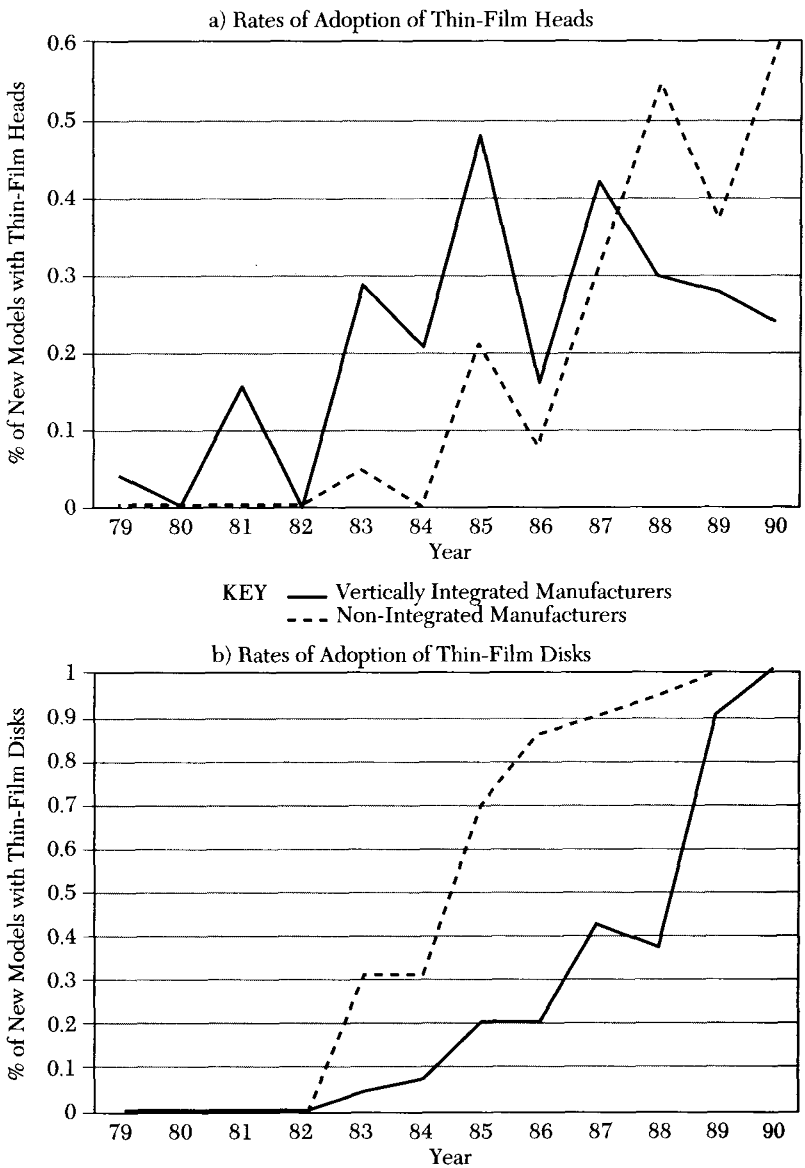
many outside observers believe that IBM was reluctant to sell key components in the open market for fear of fueling the U.S. Department of Justice's antitrust suit against the company, pending at this time.

Figure 8

Differences in the Rates at Which Vertically Integrated Computer Makers and the Largest Independent OE Market Manufacturers Adopted Thin-Film Heads and Thin-Film Disks across Their Product Lines



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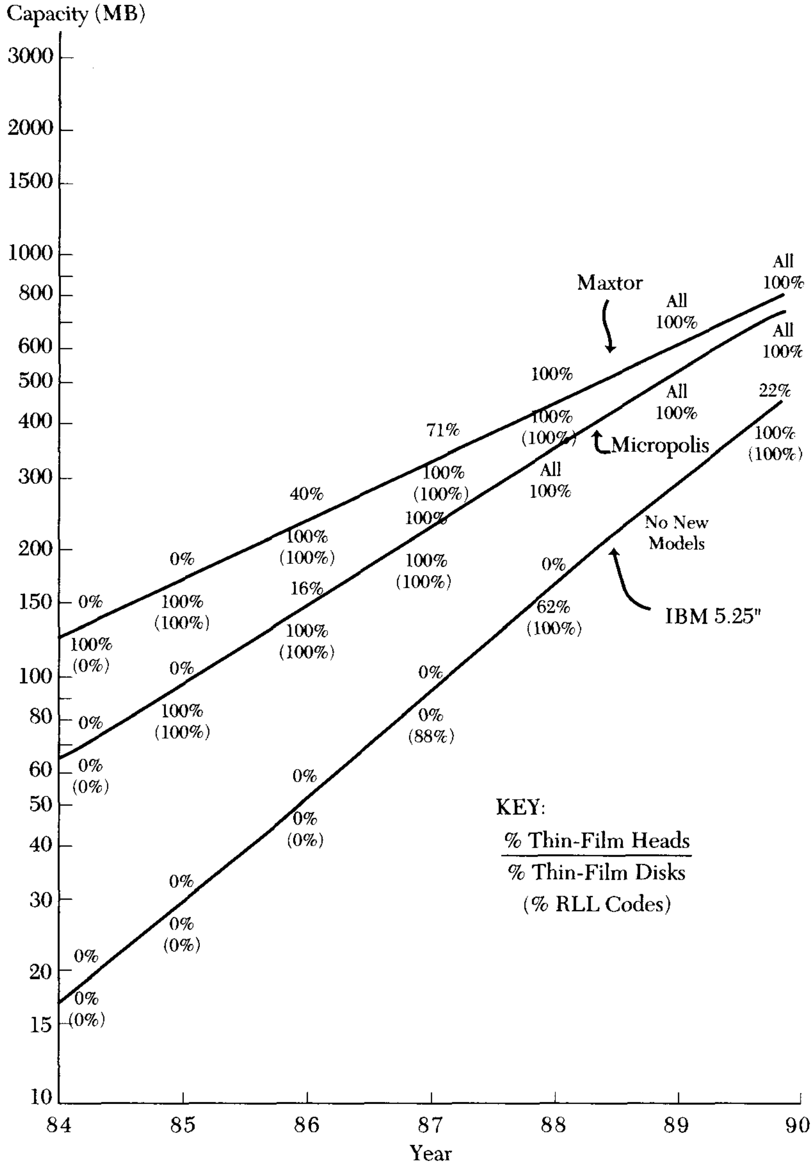
tially would be used. As the computer industry matured, however, competitive market forces increasingly became the drivers of the product development cycle. As IBM lost its ability to control that cycle, coordination between component development and system design became inherently more difficult.

When the component development cycle was decoupled from the product development cycle by the competitive market, it simply became impossible for anyone to predict accurately, a decade in advance, whether the company's product position in the market would demand that a specific new component technology be used in its products. The market shifted, the conventional technology progressed, and—possibly the most unpredictable of all—the company's product-market strategy changed. When fully committed development of thin-film head and disk technology was initiated in the early 1970s, almost no one could have imagined that, a decade later, 80 percent of IBM's drives would be used in relatively non- demanding desktop personal computer applications.

In response to the decoupling forces, IBM's managerial practice evolved toward a sort of "free market" system. When new component technologies were developed, they were made available to (but not forced on) product design engineers. The designers of new disk drive systems were free to choose whatever component technologies IBM had in its arsenal to meet the performance objectives of their product. Under this arrangement, IBM's market position—the demands of its customers—determined the pace at which the company employed advanced component technologies in its new models. Figure 9 charts over time the product positions (average megabytes of all models in the 5.25-inch architecture) of Micropolis, Maxtor, and IBM. It shows that in 1984 Maxtor's average 5.25-inch model held 125 megabytes, Micropolis's held 64, and IBM's held 16.5. There is nothing normative about this observation—these firms were simply serving different markets. Maxtor was selling to the memory-starved engineering workstation market, whereas IBM was making 5.25-inch drives for its XT and AT personal computers.

Figure 9 also shows the percentage of each firm's 5.25-inch models in a given year that employed thin-film heads, thin-film disks, and RLL codes. Each of these technologies was developed at IBM but, in 1984, none of them was used in the IBM or Micropolis product lines, whereas Maxtor used thin-film disks in all of its models, with ferrite heads and MFM codes. In 1985, Micropolis adopted thin-film disks on 100 percent of its new models, and Max-

Figure 9
Capacity Points at which Maxtor, Micropolis, and IBM Incorporated Advanced Component Technologies in Their 5.25-Inch Disk Drives



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tor and Micropolis converted completely to RLL codes. But IBM still did not use these technologies—it continued to support its market position with established technologies, which were much less costly and risky to use. In 1986, Maxtor and Micropolis both began using thin-film heads, while IBM was still able to satisfy its requirements with conventional technology. Finally, when its average 5.25-inch drive approached the 80–100 MB range in 1987, IBM began using RLL codes in 88 percent of its new models (Micropolis had adopted RLL codes when its products had penetrated this same range two years earlier). When its 5.25-inch drives reached even more demanding territory in 1988, IBM adopted thin-film disks on 62 percent of its new models. Although this step was taken four years after Maxtor had adopted thin-film disks, it occurred when IBM's drives reached the same capacity territory that Maxtor and Micropolis had occupied when they first used thin-film disks. Finally, though IBM had first used thin-film heads in a few high-end 14-inch drives as early as 1979, thin-film heads were not used in its 5.25-inch models until 1990.

By drawing horizontal lines across Figure 9, one can create product performance zones that seem to have mandated the use of particular component technologies. IBM's computer business had devolved to a performance position far from the market's leading edge by the mid-1980s, and it had not yet entered the zones requiring use of the component technologies it had developed. On this basis, it would be difficult to argue that IBM's failure to utilize more broadly the component technologies it had paid so dearly to develop was the result of conservative or inept technical management. Simply put, the firms that needed the new component technologies used them; the firms that did not, did not.

Because IBM turned out not to need all of the component technology it had developed when it became available and yet had a policy of not selling components outside the company, the independent component suppliers that spun out of IBM generally grew to become larger producers of the components than did IBM itself. As a result, the firms that incurred the development costs of the new component technology were not those that generated the revenues (see Table 7 for the case of thin-film heads). IBM, which spent one-third of the industry's R&D dollars for this technology, has produced altogether only 8 percent of the industry's cumulative output of thin-film heads. The independent start-ups, after incurring only 15 percent of development costs, have captured most of the market. A

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Table 7
Amount and Share of Development Costs Incurred vs. Amount and Share of Total Production of Thin-Film Heads
(includes captive use and OE market sales—dollars in millions)

Firm or Group	*Total R&D Costs*	*R&D per Firm*	*Percent of Industry R&D Costs*	*Percent of Industry Units Produced, 1990*
IBM	$300	$300	32	8
Other Vertically Integrated[a]	$500	$86	53	38
Independent Start-Ups	$150	$15	15	54

[a] Burroughs, Control Data, Digital Equipment, Fujitsu, Hitachi, NEC

Sources: Estimates given by former employees; *Disk/Trend Report;* Peripheral Research Corporation.

similar table could be constructed for thin-film disk technology as well. Although the disparity between costs incurred and units produced may represent an unfortunate subsidization of the competition from the point of view of the IBM shareholders, it is clear that the disk drive industry—and a great many entrepreneurs and venture capitalists within it—have benefited greatly from IBM's extraordinary technological largesse.

Conclusion

Coordinating the very different enterprises of component development and product system design in an increasingly segmented market became a nearly impossible challenge for the integrated firms as the disk drive industry matured through the 1980s. And in the face of strong, diverse market demand, managers in vertically integrated firms found it difficult to protect or retain valuable component and architectural technologies that their customers did not want. As a result, by the 1990s nearly all of the industry's firms had decoupled their vertically integrated operations to some degree, enabling groups at each stage of the value chain to sell their output in the original equipment market. Control Data, Fujitsu, Hitachi, and NEC had followed a policy of selling completed disk drives in the OE market from the late 1970s. By 1990, IBM, Digital Equipment, and Hewlett Packard all had followed suit, selling disk drives aggressively

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in the OE market to their computer system competitors, rather than continuing to cede that business to defecting engineers. And some firms, such as Digital Equipment and Seagate, became leading suppliers of thin-film disks and heads, not just to their own downstream disk drive operations, but to direct disk drive competitors as well. Hence, an industry whose foundation and growth were built through the activities of large-scale, integrated organizations became in its more mature years an industry where market mechanisms forced the decoupling and specialized focus of enterprises that once were extensively integrated. This process created an industry structure where market mechanisms and interfirm transactions, rather than managerial coordination within large-scale firms, became the means for coordinating the development and manufacture of disk drives.

Appendix

How Disk Drives Work and a Glossary of Technical Terms

Disk drives write and read information in the same sort of binary code that computers use. Most disk drives comprise a read-write head, 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; disks, which are aluminum or glass platters coated with magnetic material; at least two electric motors—a spin motor that drives the rotation of the disk, 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. 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 positive- and negative-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's and 0's—to "write" information onto disks. Drives read information from disks in essentially the opposite process—changes in the flux fields of the magnetic domains on the disk surface, from positive to negative and back again, induce changes in the microcurrent flowing through the head.

More information about how individual components of typical disk drives work is provided in the following glossary of terms.

Actuator. The mechanism that positions the head over the proper track on the drive. The class of actuators that is now most commonly used, because of its superior positioning ability, is called a *"voice coil" motor*. This operates on a

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principle similar to that used in telephones—an arm is moved in and out via electromagnetic forces. Voice coil motors have been made in linear and rotary designs, but the rotary design (which works like the arm on a phonograph) has become the dominant design because it requires less space. A much less expensive actuator mechanism is a *stepper motor*, in which a shaft rotates in discrete steps to new positions in response to changes in the surrounding magnetic field. Stepper motors were used primarily on low-capacity drives targeted to price-sensitive markets. *Torque motors* and *DC motors* were also used on a limited number of models in the low-to-moderate performance range.

Areal Density. The amount of information that can be stored in a square inch of disk surface, measured in megabits per square inch (mbpsi). This is determined by multiplying the number of bits of information storable along a linear inch of track (*bit density*) by the number of tracks per inch of disk radius (*track density*).

Disk. The round, rigid platter on which data is magnetically recorded. It is composed of a substrate, typically made of aluminum polished perfectly flat, coated with particles of magnetic metal oxide or thin metal films. These magnetic coatings are, in turn, coated with lubricating and protecting materials to prevent dislodging of information-bearing material out of the disk in the event that the head crashes into the disk surface.

Drive. The computer industry's term for the equipment that contains and rotates magnetic media—reels of tape, flexible (floppy) disks, or rigid disks—and that controls the flow of electronic information to and from those media.

Embedded Servo System. Mechanical shocks, differential thermal expansion, and a host of other factors can affect the accuracy with which an actuator can position a head over a particular track on a disk. Low-performance drives using stepper motor actuators got around this problem by spacing the tracks far enough apart that such subtle changes and misadjustments rarely caused the head to be mispositioned. High-performance drives, however, require a closed-loop feedback system to the actuator, so that the head can continuously be repositioned precisely over the proper track on the disk. This enables much greater track density. One way of keeping precise head-disk alignment was to dedicate one complete surface of one disk on the spindle to tracking information only. The head reading information off that track and feeding it back to the actuator motor provided such a closed-loop, continuous-adjustment mechanism. In an *embedded servo system*, track identification markers are written (embedded) on each individual track of each recording surface. This frees up for user information the entire surface that otherwise would have been reserved for tracking information only.

Ferrite. A magnetic compound composed of iron and oxygen. In disk drives, the primary use of ferrite has been as the core material around which fine copper wires were coiled to form an electromagnet in the head.

Head. A device that contains a tiny electromagnet, positioned on an arm extending over the rotating disk. When the direction of current through the head changes, its polarity switches. Because opposite magnetic poles attract, changes

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in the polarity of the head causes an opposite change in the polarity of the magnetic material on the disk as it spins immediately beneath the head. The head writes information in binary code in this fashion. Heads read data in the opposite manner—changes in the magnetic flux field over the disk's surface as it spins beneath the head induce changes in the direction of current in the head, reversing the information flow. In rigid disk drives, heads are aerodynamically designed to fly a few millionths of an inch above the surface of the disk; they generally rest on its surface when the drive is at rest, take off as the disk begins spinning, and land when the disk stops again. Heads in floppy disk drives generally do not fly but glide on the disk's surface.

Interface. This term refers to the electronic circuitry through which the drive and computer communicate. A thorough description of the differences among interfaces is beyond the scope of this article. Originally, interfaces were custom-written by each drivemaker for each customer. Although some standard interfaces such as SMD emerged as 8-inch drives were used with minicomputers, the trend toward standardization was accelerated by Seagate Technology's ST412 interface, which required that the rate at which the drive took data off the disk was equal to the rate at which the drive could transfer data to the computer. Although low-cost and efficient, this system effectively put a ceiling on the bit density of the drive. Subsequent interfaces such as *SCSI* (used primarily with Apple computers), *AT* (used with IBM-compatible computers), and *ESDI* (used primarily with engineering workstations) decoupled these activities. With these interfaces, the drive could take data off the disk as rapidly as its designers wanted, cache it, and then transfer it to the computer as rapidly as the computer could accept it. This enabled much greater bit densities than had been possible under the ST412 interface. Other interfaces used on only a limited number of models were *IPI-1*, *IPI-2*, and *ANSI*.

MFM. An acronym for *modified frequency modulation*, an early coding technique used in writing data on disks, wherein a magnetic marker was placed on the disk to denote the beginning and ending of each individual piece of information.

MIG Heads. An acronym for *metal-in-gap*, a version of ferrite head wherein a strip of metal was deposited in the gap between the leading and trailing portions of the head. This strengthened the magnetic flux fields that could be created and sensed by the head, enabling data to be written and read on smaller domains on the disk surface.

Oxide. The term used in the industry for particles made from a compound of oxygen and a magnetic metal, such as iron, cobalt, and chromium. Oxide particles were used to coat mylar substrates to create magnetic tape and floppy disks and to coat aluminum disks in rigid or "hard" disk drives. The oxide particles are the media in which, through changes in the particles' magnetic polarity, data are stored magnetically. The particles generally have an elongated, needle-like shape.

Photolithography. The manufacturing process through which a desired pattern of one material is applied onto another substrate material. Typically, the substrate is first coated (by plating or *sputtering*) with the material from which the final pattern is to be made. This is in turn coated with a light-sensitive monomeric material, called a *photoresist*. A mask of the desired pattern is then held over the photoresist, and the unmasked material is exposed to light, causing the exposed material to cure. The unexposed photoresist is then washed away. Through a subsequent series of etching and washing steps, only the desired material, in the desired pattern, is left on the substrate. Integrated circuits are built on silicon wafers and thin-film heads are built through photolithographic processes.

PRML. An acronym for *partial response, maximum likelihood*, a coding technique that has followed RLL and MFM recording codes.

Recording Density. See *areal density*.

RLL. An acronym for *run-length limited* recording codes, which enable data to be written more densely that was possible with MFM codes. Two versions of RLL codes have been used: 2,7 and 1,7.

Spin Motor. The electric motor that drives the rotation of the spindle on which the disks are mounted. In 14- and 8-inch drives, the spin motor was situated in the corner of the drive and drove the stack of disks via a pulley. In the 5.25-inch and subsequent drive architectures, a flat, "pancake" motor was developed and positioned beneath the spindle, whose rotation it drove directly.

Spindle. The shaft on which one or more disks was mounted.

Stepper Motors. See *Actuators*.

Thin Film. A continuous, very thin film (often only a few angstroms thick) of a material (often a metal) on another substrate material. This is generally applied through a process called *sputtering*, in which a substrate is placed at the bottom of a vacuum chamber. A target of the film material is then bombarded with electrons, which dislodge ions of the target material. These ions float like a vapor in the vacuum chamber and then gradually settle in a thin, continuous film on the surface of the substrate. This deposition technique is one of the early production steps in the manufacture of integrated circuits and thin-film heads. It is also the technique used to coat disks with very thin films of magnetic material.

Torque Motors. See *Actuators*.