COMPUTERWORLD
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An IBM 14-in. hard disk drive from the early 1980s next to today's highest-capacity, 3.5-in hard disk drive. The 14-in model holds 200MB; the 3.5-in. model from Western Digital holds 10TB of data -- or more than 50,000 times the amount of data. *Image credit: Western Digital.*

CW@50: Data storage goes from $1M to 2 cents per gigabyte

How we got from punch cards to flash storage, the internet and smartphones

By Lucas Mearian

Senior Reporter, Computerworld

When *Computerworld* was founded in 1967, a 1-megabyte hard drive would have set you back by $1 million.

Today, that same megabyte of capacity on a hard disk drive (HDD) costs about two cents.

Through those five decades, data storage was seen as little more than a support technology, when in actuality has always been one of five tech pillars -- like processors and software -- underpinning our modern computer systems, said Owen Melroy, vice president of Media Components at Western Digital Corp. (WD).

[See more Computerworld 50th anniversary coverage]

To understand how we got from there to here, you have to go back another 10 years before *Computerworld* was born.

It started with one decision

The year was 1956 and Reynold Johnson, who'd been sent to open a West Coast research lab for IBM four years earlier, was supervising the 50 engineers he'd hired. The task: Develop a new data recording medium to replace giant bins of punch cards.

San Jose, Calif. was chosen because it was warmer and more appealing to young engineering graduates than were IBM's Poughkeepsie, N.Y. labs.

Johnson, a former high school science teacher who invented the electronic test scoring machine that sensed No. 2 pencil lead on standardized forms, gave his San Jose-based team a wide development berth.

"He told each new hire they would have their own assignment. More important than that, they were to keep track of everything going on in the lab and be prepared to help if anyone asked for it," said David Bennet, an engineer who worked on various storage projects for IBM from 1959 through 2014.

Bennet, now a guide at the Computer History Museum, said his first assignment at IBM was to work on a direct-access mass storage device for the System/360 mainframe - the 2321 Data Cell Drive. The Cell Drive contained up to 10 removable and interchangeable data cells, each with 200 magnetic strips.

At the time, IBM mainframes used both tape drives and drum memory, which consisted of metal cylinders coated with ferromagnetic recording material. Magnetic tape had good capacity, but slow access times; drum memory had great access time, but little capacity.

IBM wanted the best of both worlds.

Johnson sent down an edict: Storage for IBM's mainframes would be on spinning platters. So his team set about building the IBM 350 Disk Storage Unit -- the world's first hard drive.

Created as high-speed storage for the IBM 305 RAMAC system, the IBM 350 weighed about a ton. It was 68 inches tall and 29 inches wide. Though it had to be transported with a forklift, it was revolutionary; it stored more data than any previous system -- up to 5 megabytes across 50,

24-in. diameter disks coated with magnetic iron oxide paint. The system had an average seek time of 600 milliseconds.

The IBM 350's disk platters spun at 1,200rpm; a pair of hockey puck-sized read/write heads affixed to a vertical shaft flew up and down the stack, stopping to read data from any of 100 tracks per platter. Within two years, the IBM 350 had doubled its storage capacity. It was a sign of things to come.

Storage and memory costs through the years

BY THE NUMBERS | *Source: John C. McCallum, IDC*

[**Price per gigabyte**]

Year	Disk Drives	DRAM	NAND flash
1965	n/a	$2.64B	–
1966	$1.05M	n/a	–
1970	$185,000	$734M	–
1975	$180,000	$180M	–
1980	$202,000	$6.48M	–
1985	$40,000	$477,500	–
1990	$4,400	$78,400	–
1995	$277	$31,633	–
2000	$7.70	$1,031	$1,255
2005	$0.79	$158	$42
2010	$0.11	$18.87	$1.76
2015	$0.05	$5.22	$0.38
2017	$0.02	$4.90	$0.32

Gaining speed, losing size

Tom Burniece, a general manager at Digital Equipment Corp. (DEC) from 1981 through 1991, got his start in the industry in 1969 when he joined Edina, Minn.-based Control Data Corp. (CDC). It was one of a dozen top tech companies making drives, working to supplant IBM.

Burniece spent the next 25 years developing hard drives, during which time he worked not only for CDC, but drive maker Maxtor. His first project was the design of the CDC 844-21 High Performance Drive (HPC), a 700lb. machine with an industrial blower that created positive air pressure between disks. (It was the size of a home furnace blower.)

The drive held up to 100MB of data.

Over the decades, Burniece and his industry colleagues spent their careers mainly on one task: Finding ways to make denser and faster hard drives. It wasn't just about shrinking circuits, but about overcoming mechanical and physical limitations -- and creating industry standards.

As they succeeded, data storage went from a washing machine-sized container of disks to a 3.5-in. platter that could store up to 10 terabytes (TB) of data (or a 2.5-in. drive with 2TB).

[Check out this video that explains how storage has morphed over the years]

Consider that 10TB could store the Library of Congress; that's the equivalent of 130 million items on about 530 miles of bookshelves, including 29 million books, 2.7 million recordings, 12 million photographs, 4.8 million maps and 58 million manuscripts.

To get there, the industry had to shrink the areal density of disk platters from a few thousand bits per square inch in RAMAC's days to 1.33 trillion bits per square inch today.

"That's an areal density down six to eight orders of magnitude," said Burniece, who since 2001 has chaired the Computer History Museum's Storage Special Interest Group.

Prices for storage followed suit. From the time that first disk drive was manufactured by IBM in 1956, the average cost of hard drives has dropped by 41% a year, identical to the Moore's Law rate for semiconductors. Put another way: Hard disk pricing went from $2 million per gigabyte of capacity to just 2 cents per gig today.

By the time Burniece got to DEC, the hard drive industry was pushing past the 1GB barrier and experts predicted drive densities would continue to double every 12 to 18 months.

Not surprisingly, hard drives quickly became a standard component in the proliferating personal and portable computing systems markets. Their very ubiquity obscured the technical challenges that had been overcome.

At the time, a drive's read/write heads sat just 10 micro inches off a spinning disk. (A micro inch is 1/1,000 of an inch.) That's hard to envision, so the industry came up with an analogy: Picture a Boeing 747 flying at 600 miles per hour six inches off the ground. That's how difficult it was to move a read/write head 10 micro inches from a platter.

IBM started the ball rolling, but other firms kept it moving

While IBM dominated the industry in the 1960s, other technology companies saw an opportunity to manufacture their own storage, which they could also sell for less. IBM, at the time, was known for charging full retail prices -- even for bulk purchases.

In 1966, Memorex developed the world's first IBM plug-compatible drive disk pack -- the Memorex 630. Not only did the Memorex 630 disk drive pack have four times the capacity of IBM's 1311 disk pack, it also cost less than half the price. IBM's 1311 sold for $27,000 with a manufacturing cost estimated to be about $1,700.

Other companies began producing compatible storage for IBM's mainframe systems as well as their own. Thus was born the Plug Compatible Manufacturer (PCM) industry.

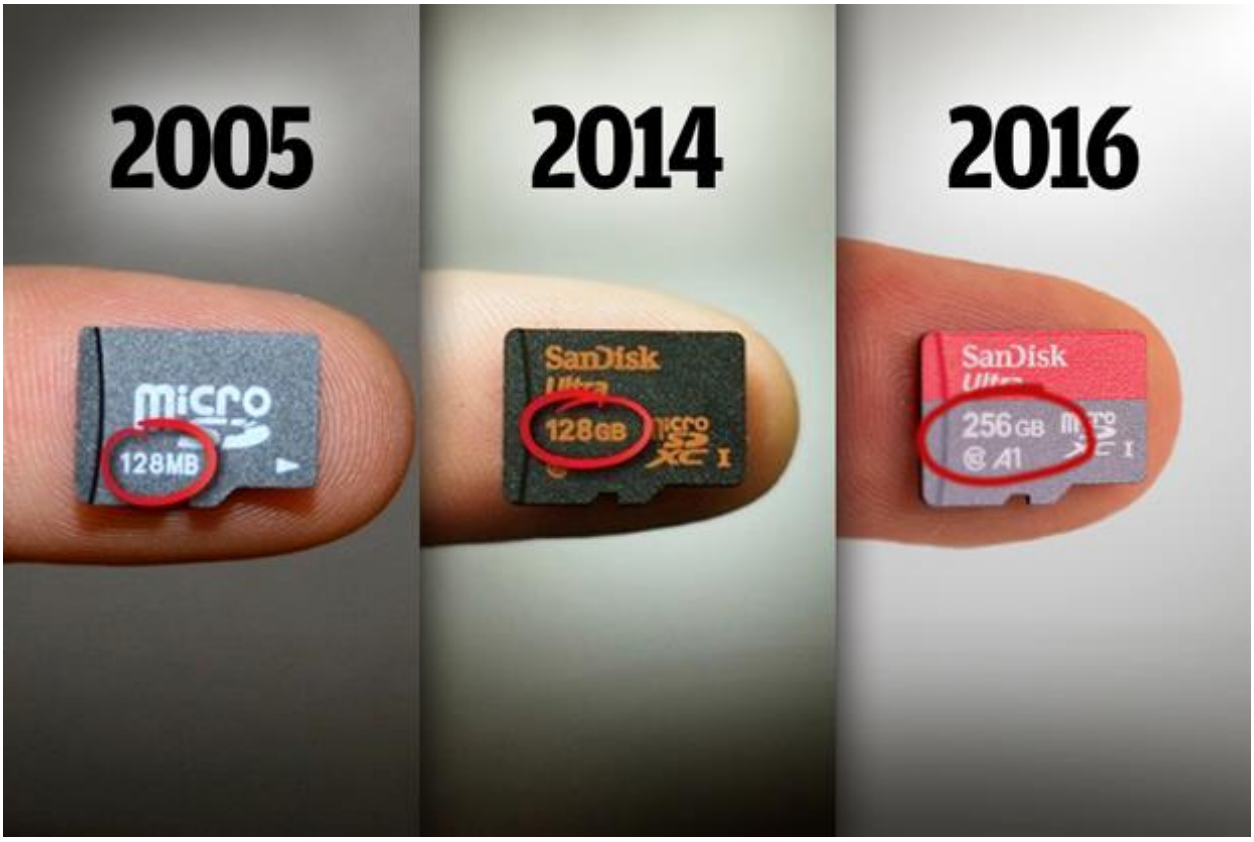
As more companies began to challenge IBM, its engineers saw greater opportunities and some began leaving. One group, known as "The Dirty Dozen," founded Information Storage Systems (ISS) in 1967; another group left to work with Alan Shugart, who'd gone to Memorex in 1969. (He would later found drive-maker Shugart Associates, which later became Seagate Technology.)

But IBM wasn't sitting still. In 1970, it announced the 3330 Direct Access Storage Facility, which could be loaded with easily portable disk packs. Each pack could store 100MB of data for IBM System/370 mainframes, though it had roughly the same data transfer rate as the RAMAC -- about 806 kilobits per second.

By 1972, the 10-disk removable pack had shrunk to 5 disks that would fit in an industry standard 10.5-in rack. The read/write head flew less than 30 micro-inches from platters then spinning at 3600 RPM.

In 1973, IBM came out with the 3340 disk drive, which became known as the father of the modern hard drive industry. Still the size of a washing machine, the 3340 held 30MB of fixed data and 30MB of removable disk pack. It was nicknamed "The Winchester," after the historic 30-30 caliber rifle.

The IBM 3340 drive had the first sealed read/write head, which kept contaminants out and allowed the distance from the spinning disk platters to drop to just 18 micro inches with an average seek time of just 25 milliseconds. The 3340 HDD could be leased for $7.81 a month and became IBM's new low-cost technology, dominating the industry.



Part 2: Data storage comes into its own

By Lucas Mearian

Senior Reporter, Computerworld

In 1973, CDC saw a chance to one-up IBM and produced the 9760 Storage Module Drive (SMC). It held 40MB of data and represented the first significant departure from IBM standards for disk storage media.

[See more Computerworld 50th anniversary coverage]

While increasing the capacity of its drives, CDC and others were also decreasing the gap between a read/write head and the magnetic platters on which data was stored, boosting read/write speeds.

By the mid-1970s, industry efforts accelerated to standardize on ways to connect hard drives to computers. Seemingly every few years, something emerged to push the storage market forward:

- In 1977, CDC's Storage Module Drive became a standard.
- In 1982, Shugart Associate's Systems Interface was adopted for the Small Computer System Interface (SCSI).

- In 1984, Sun Microsystems released its Network File System, a distributed file system protocol that allowed servers to share storage space with computers on the same network.
- In 1985, CDC, Compaq Computer, and Western Digital collaborated to develop the Integrated Data Electronics specification -- a 40-pin connector for attaching Host Bus Adapters to disk drives.
- In 1998, the Fibre Channel specification was developed to give SCSI and other industry drive specifications a higher-performance, switched serial interface. Fibre Channel offered 100MBps block-level access to all types of storage – disk arrays, optical jukeboxes and tape libraries. Fibre Channel, in turn, enabled the development of storage area networks, a dedicated storage high-speed infrastructure separate from a corporation's local area networks.

On the right is a 5.25-in. HDD (model ST-412) introduced by Shugart Technology (now Seagate) in 1981; it held up to 10MB of data and cost about $1,500 at the time. On the left is a Seagate 3.5-in. drive with 10TB capacity -- or about one million times the capacity of the ST-412. Seagate's 10TB HDD can be purchased on Amazon for about $370. *Image credit: Seagate*

As interface standards evolved, IBM continued to lead in hardware development. In 1979, it created the first 8-in. disk drive, nicknamed Piccolo, which stored 64MB on six platters, for the IBM 62 PC. IBM also sold it as the 3310-attachable direct access storage device (DASD).

More importantly, IBM introduced the first drive to use thin-film heads, which allowed areal density to increase. In 1981, IBM used thin-film technology to ship a drive with four times the capacity of its predecessor.

While IBM's DASD continued to shrink in size and grow in capacity into the 1980s, the huge disk drives "were kind of the company's undoing" when it came to storage, said David Bennet, an engineer who worked on various storage projects for IBM from 1959 through 2014. Other companies, notably Seagate, had started working on smaller formats as IBM continued to build its 14-in. platters. "By the time IBM got into the smaller form-factor drives, there were competitors way ahead of them."

Storage rivals rise

The work of other vendors marked the beginning of an explosive era in hard drive development, beginning with the birth of the PC industry in the late 1970s and early 1980s. Among those companies pushing the industry forward: Microsoft and Apple Computer, which created the market for ubiquitous desktop computers; those in turn created the economies of scale for the hard drives that proliferated within them.

"About the time IBM launched its PC is when Al Shugart developed 5-in. hard disk drive," said John Rydning, IDC's research vice president for hard disk drives (HDDs). "It was the 5-in drive that made the PC possible."

[Check out this video that explains how storage has morphed over the years]

Seagate's 5.25-in hard disk drive -- the ST506 -- could hold up to 5MB and became the de facto standard for the PC industry.

"A lot of advanced technology happened on HDDs from that point forward," Rydning said. "Seagate launched the hard disk drive industry because you had the increased volume driven by the PC market... and that fueled the other corporations as well." After Seagate's 5.25-inch drive came competitors from other vendors: The 3.5-inch drive, then a 2.5 inch model and finally a 1-incher.

In 1990, IBM introduced the first disk drive with thin-film magnetoresistive (MR) heads, which alternated layers of thin magnetic and non-magnetic conductive materials, enabling the first multigigabyte drives.

While IBM had used MR heads in tape drives in the mid-1980s, the company's San Jose research lab adapted the technology for a hard disk code-named "Sawmill." It shipped as the IBM 9345 DASD system.

By 1994, other manufacturers followed suit as Fujitsu, Hitachi, and Hewlett Packard developed their own MR heads. By 1999, the technology was ubiquitous.

Drive capacity continued to grow, but areal density was running up against a wall at around 100Gbp square inch. It wasn't until 2005 that a technology breakthrough would smash past that limitation and launch a new era.

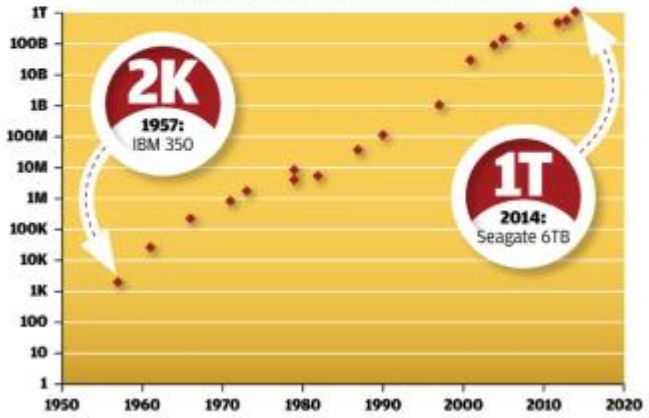
HDD Areal Density

BY THE NUMBERS | *Source: David Laws, 'The Storage Engine', Computer History Museum*

YEAR*	AREAL DENSITY (BITS/SQ IN)	PRODUCT	TECHNOLOGY INNOVATION
1957	2,000	IBM 350	Hydrostatic bearing magnetic induction R/W head
1961	26,000	IBM 1301	"Flying head" hydrodynamic bearing
1966	220,000	IBM 2314	Ceramic flying heads and ceramic ferrite cores
1971	780,000	IBM 3330	Track-following servo & rectangular ceramic slider
1973	1,690,000	IBM 3340	Low-load, landing Read/Write heads
1979	3,800,000	IBM 62PC	Sector servo control & rotary voice coil actuator
1979	7,800,000	IBM 3370	Thin-film read/write heads (8 turns of wiring)
1982	5,220,000	Syquest Q-100	Carbon-coated metal film media disks
1987	35,900,000	IBM 3380K	Thin-film read/write heads (31 turns of wiring)
1990	107,000,000	IBM Sawmill/9345	AMR (Anisotropic Magnetoresistive) Read Head
1997	1,000,000,000	IBM Deskstar 16GP	GMR (Giant Magnetoresistive) Read Head
2001	27,000,000,000	IBM Travelstar	Antiferromagnetically-coupled (AFC) media
2004	84,000,000,000	Segate Momentus II	TMR (Tunneling Magnetoresistive) Read Head
2005	133,000,000,000	Toshiba MK4007GAL	Perpendicular Magnetic recording (PMR)
2007	325,000,000,000	HGST Deskstar 7K1000	None stated (First commercial 1 TB drive)
2012	446,000,000,000	HGST Deskstar 7K4000	LDPC (Low Density Parity Check)
2013	544,000,000,000	WD 6TB Ultrastar He6	Helium filled
2014	1,000,000,000,000	Seagate 6TB	SMR (Shingled Magnetic Recording)

* *This is the year of commercial introduction, not necessarily the year of lowest cost per bit for that technology*

AREAL DENSITY [bits per square inch]



It was called perpendicular magnetic recording (PMR), and it took bits of data that had laid horizontally (or longitudinally) on the disk platter and stood them upright -- shoulder to shoulder -- so they could be packed closer together.

The development of PMR by Toshiba and Seagate increased magnetic media's capacity as much as 10-fold, which meant microdrives that held 3,000 songs now had room for about 30,000 songs.

When the industry again faced capacity limits in 2013, Seagate overlapped data tracks like roof shingles, increasing capacity by 25%; then in 2014, HGST introduced helium-filled drives, boosting capacity by another 50%.

"There were just so many brilliant people working on data storage that have taken so many innovations and commercialized them so quickly," Rydning said.

Faster than Moore's Law

Since the 1980s, hard drive makers have also competed against a different kind of storage rival: NAND flash memory, where cost and density reductions have been no less spectacular. In the early 1980s, Toshiba developed the first programmable non-volatile memory -- NOR flash (so named because the device could erase a large amount of memory).

By 1987, Toshiba had unveiled the first NAND flash memory, which stored data directly to silicon, rather than on spinning platters. Four years later, Toshiba debuted its first 4Mb NAND-type Electrically Erasable and Programmable Read-only Memory.

At about the same time, three-year-old SunDisk shipped the world's first NAND flash-based Solid State Drive (SSD). The 20MB SSD came in a 2.5-inch form factor and was aimed as a replacement for the hard drive in an IBM ThinkPad computer. The retail price was $1,000, or $50 per MB. (SunDisk was later renamed SanDisk.)

Just as PMR technology had created drives with greater density, flash memory was about to get its first big density boost when, in 1997, manufacturers began storing two bits of data instead of one per transistor -- ushering in multi-level cell (MLC) products. And, in 2008, they began packing three bits per cell, which further increased chip storage capacity and reduced cost.

The rise of smartphones and other mobile devices that use NAND flash for onboard storage also lowered prices through economies of scale.

The effect was dramatic.

In 2010, a gigabyte of NAND flash capacity retailed for $1. Today, a gigabyte of flash memory costs about 26 cents.

Other technologies have swept the storage industry in recent decades.

In 1999, SanDisk, Matsushita, and Toshiba used the MultiMediaCard (MMC) specification to create the Secure Digital (SD) MemoryCard. The first SD card held 2GB and provided digital rights management based on the Secure Digital Music Initiative (SDMI) standard.

Today, companies such as WD/SanDisk sell 512GB microSD cards, which have 256 times the capacity of the original card and that can store 128,000 MP3s encoded at 128Kbps.

Indeed, NAND flash had surpassed Moore's Law in terms of the time it took to grow in density and capacity.

On the left are 50 3.5-in. floppy disks from the 1990s -- each with 1.44MB of capacity. On the right is an SD flash card with 512GB of capacity from 2016. It would take roughly 358,400 3.5-in floppy disks to equal the storage on the SD card. *Image credit: IDG.*

Take, for example, SSDs. In 2012, SSDs maxed out at about 250MBps throughput and a top capacity of 512GB. SanDisk and others now offer SSDs with more than 1,700MBps data transfer rates and with 4TB of capacity. Last year, Samsung began shipping a 15TB SSD.

Innovation continues

Manufacturers over time have also been able to shrink the geometric size of the circuitry that makes up NAND flash technology -- from 90 nanometers (nm) a few years ago to 34nm and finally to 10nm. But as circuitry shrank, problems arose. Electrons leaked from cell to cell, creating data errors. Manufacturers, in turn, designed sophisticated error correction code to obviate the problem.

Ultimately, however, NAND flash makers faced a wall: They had little room to shrink the density of the circuitry further.

So, just as PMR marked a new era for hard drives in the mid-2000s, vertical NAND (also called 3D NAND) has recently allowed memory makers to break through the capacity limitations of planar (single layer) NAND flash.

Samsung, Intel, Micron and others began working on stacking NAND flash dies one atop the other.

The 3D NAND technology used a technique called Through Silicon Via (TSV) created micron-sized holes through the chip silicon vertically instead of just horizontally to allow data transfers. The result was a NAND flash device that used 45% less power and had twice the performance and endurance of planar NAND. What was once a single layer of transistors became a microscopic skyscraper of flash cells up to 64 layers high.

"Silicon surface area over time has become most expensive real estate around; it would be $3.5 billion an acre," said Siva Sivaram, executive vice president of memory technology at Western Digital (WD), which owns SSD maker SanDisk. "So when it costs you billions of dollars per acre to make, you don't buy California ranch-style homes. You go Manhattan-style.

"We introduced our first 3D flash products in 2005, with four layers. Now we're at 64 layers. I can tell you that there is no physical limitation on how high we can go," Sivaram said. "On all three axis, we don't have any immediate limitations approaching us, which is a powerful place to be."

MultiMediaCards (MMC) released in 1997 by SanDisk and Siemens AG and Secure Digital Cards (SD) released in the mid-1999s by SanDisk, Panasonic (Matsushita Electric) and Toshiba. All offered vast amounts of storage capacity for digital cameras and other mobile devices. A 16MB MMC on the far left from 2007 compares to a 512GB SD card from 2016. *Image credit: IDG.*

This year, Intel and Micron announced plans to begin shipping the latest innovation in non-volatile memory -- 3D Xpoint, a new class of memory they say will fill a niche between NAND flash and DRAM. It is purported to have 1,000 times the performance of typical flash drives.

Micron will market its 3D XPoint memory under the name QuantX, and Intel under the name Optane.

From IBM to today

Over the past five decades, what began as a single hard drive manufacturer -- IBM -- grew into an industry that at one point had 262 hard-drive companies. Today, after years of consolidations and mergers, there are three hard-drive makers.

As the technology advances and morphs, prices continue to fall. From 2000 through 2016, the price of hard drive storage has declined 28% per year, while prices of NAND flash memory have declined 48% per year, according to IDC's Rydning.

In the next decade, the industry may see breakthroughs involving life sciences and the use of DNA to archive limitless amounts of data.

The foundation that storage has created for the tech industry is "just mind boggling," Rydning says. It has laid the ground work for the cloud, the apps we run on smartphones, Facebook, and digital music, he adds. "All that was made possible by advancements in disk drive technology."