

# History of Digital Storage

Dean Klein

*Vice President of System Memory Development*

Micron Technology, Inc.

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## Purpose

Throughout modern history many and various digital storage systems have been researched, developed, manufactured, and eventually surpassed in an effort to address ever-increasing demands for density, operating speed, low latency, endurance, and economy.<sup>1</sup> This cycle of innovation has led us to a new generation of NAND Flash memory-based solid state drives (SSDs) that represent the next evolutionary step in both enterprise and consumer storage applications.

This paper surveys the memory storage landscape of the past 50 years—starting at the beginning of digital storage and paying homage to IBM’s groundbreaking RAMAC disk storage unit and StorageTek’s DRAM-based SSD; then enumerating the benefits of modern NAND Flash memory and advanced SSDs; and finally looking forward to the near-future possibilities of nonvolatile storage.

## Introduction: The Need to Store Data

Since men first scribbled on cave walls, humanity has recognized the intrinsic value of information and has employed a variety of ways and means to safely store it. The ability to reference numbers for calculation or to review information for planning, learning, and action is fundamental since “all computations, either mental, mechanical, or electronic require a storage system of some kind, whether the numbers be written on paper, remembered in our brain, counted on the mechanical devices of a gear, punched as holes in paper, or translated into electronic circuitry.”<sup>2</sup>

In day-to-day life, this fundamental need to store data generates innumerable documents, spreadsheets, files, e-mails, and trillions of other work-related bytes all stored on disks around the globe. Add to this commercial data the billions of photographs, songs, videos, and

<i>IBM introduces the 350 Disk Storage Unit HDD</i>	September 1956
<i>IBM introduces the 3340 Direct Access Storage Facility</i>	March 1973
<i>StorageTek develops the first modern SSD</i>	1978
<i>Seagate introduces 5.25" HDD</i>	June 1980
<i>Davong Systems introduces 5MB HDD</i>	March 1982
<i>Curtis Markets first SSD for PC</i>	1985
<i>Western Digital shows IDE SSD prototype</i>	1989
<i>IBM introduces the giant-magnetoresistive head</i>	November 1997
<i>Hitachi introduces first perpendicular-oriented HDD</i>	April 2006



other personal information or files saved every day, and it is little wonder that the storage industry has seen an unprecedented boon of late. This boon will ultimately transform storage along an evolutionary path toward better performance, greater density, and higher reliability. It will make storage a system rather than a subsystem.”<sup>3</sup> To best understand where an industry is headed, often we must look to where it has been.

## The 726 and UNISERVO Tape Drives: The Beginning of Digital Storage

Engineers first used magnetic tape to record audio signals prior to World War II<sup>4</sup>, but it would take nearly two decades of refinement and development before magnetic tape drives were capable enough for data storage and commercialization.

In 1951, the newly formed UNIVAC company produced the first magnetic tape drive for computer data storage. The UNISERVO used a one-half-inch-wide metal tape made from phosphor bronze coated in nickel plating. This metal tape was a reliable recording media. And the UNISERVO could record “128 characters [or bits] per inch on eight tracks at a linear speed of 100 in/s,” for a total data rate of 12,800 bits per second. Six of the UNISERVO’s eight tracks were devoted to data, another track was used for parity, and the eighth track was a timing track or clock.<sup>5</sup>

Most of the development work for the UNISERVO actually started in the 1940s, at what was then the Eckert-Mauchly division of the Remington Rand Corporation (which became UNIVAC in 1950).<sup>6</sup> The process of recording data on tape was extremely difficult. Engineers of that era had to develop complicated systems not only to

record data, but to manage the spinning reels, heads, capstans, and other mechanical and pneumatic systems associated with early tape drives. The relatively heavy metal tape made this task more difficult, particularly during drive acceleration.

In 1952 IBM introduced its first tape drive, the 726 Magnetic Tape Reader/Recorder.<sup>7</sup> Unlike the UNISERVO and its rugged metal tape, the 726 used a cellulose acetate-based plastic tape coated in iron oxide, similar to what was used in the audio recording industry in the late 1940s. This plastic tape was more prone to break or be damaged than metal tape, but it was much lighter so it required only a fraction of the mechanical inertia needed to spin the reels of a metal tape data storage system like the UNISERVO.<sup>8</sup> It is important to note that this is a relative comparison. Plastic tape drives were less complicated than metal tape drives, but the 726 and other early tape drives were still complex machines.

By the mid-1970s, reel-to-reel tape drives had become a standard for archival data storage, achieving access speeds of just 1ms. And these devices were still quite complex. To operate, a 200-in/s, half-inch tape drive required two reels, a powerful motor, a read/write head, a cleaning head, and various other mechanical and pneumatic subsystems. In this typical, 1970s-era tape drive, the tape reel on the right side of the drive contained the source data. This reel had to be manually mounted or removed. The operator would place the reel over a hub. The hub automatically expanded to grip the reel and initiate the loading process. Next, the right-hand source data reel would rotate clockwise so that the tape was generally moving toward the reel on the left side of the drive. Jets of air—representing the first pneumatic subsystem—gently supported the tape inside the right-hand threading channel. Next, the

Characteristic	Tape System (Year)						
	726 (1953)	727 (1955)	729-3 (1958)	729-6 (1962)	2401-6 (1966)	2420-7 (1969)	3420-8 (1973)
Velocity, in/s	75	75	113	113	113	200	200
Density, b/in	100	200	556	800	1600	1600	6250
Data rate, kB/s	8	15	63	90	180	320	1250
Capacity, MB/reel	3	6	16	23	46	46	180
Interblock gap, in	0.75	0.75	0.75	0.75	0.6	0.6	0.3

Table 1: Operating Characteristics of the Early IBM Half-Inch Tape Drives



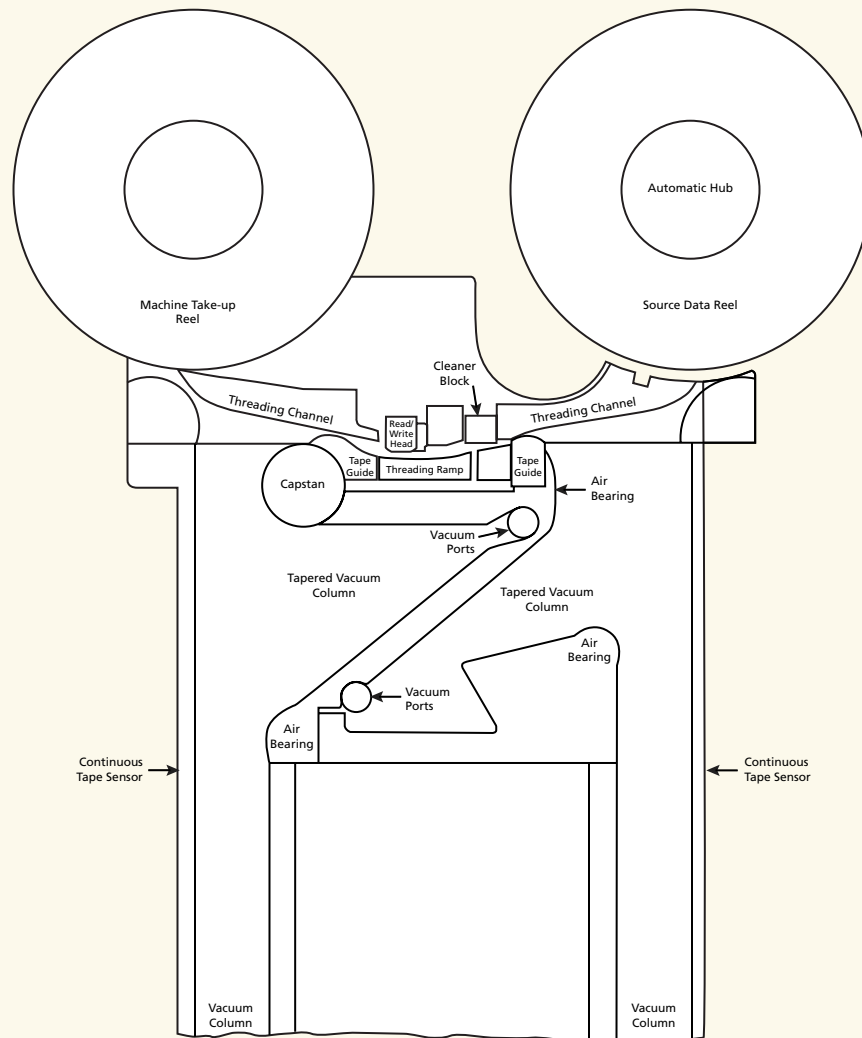


Figure 1: Typical Tape Path for a Magnetic Tape Unit, circa 1975

tape moved across the read/write head and advanced toward the left-hand threading channel where another set of air jets waited to lift the tape toward the second reel—on the left side of the drive. The hub in the left reel used a vacuum to attract the tape and hold it in place for the first few revolutions. After enough of the tape had been positioned on the left-hand reel sensors, the hub shut down the vacuum and reversed the left reel so that it began to turn counterclockwise, slackening the tape. At this point, two vacuum columns drew the tape down and into position. Finally, the capstan positioned a special beginning-of-tape marker and the machine was ready for use.<sup>9</sup>

## Improving Access Speed in Reel-to-Reel Tape Drives

Early magnetic tape storage units commonly employed two capstans with constant-speed, synchronous motors that worked in tandem with an air and vacuum system that attracted or repelled the tape as the head searched the tape for data. These systems could take several milliseconds to start before the tape even began to move, and it might take an additional 2ms for the drive to reach operating speeds. And getting to the right data could take much, much longer—tens of seconds or more.

Beginning in the 1960s, synchronous motors were being replaced with a new kind of DC motor that used a rotating cylindrical shell to encase the armature conductors and a concentric iron core that did not rotate. This design was an important improvement over the standard armature made of wires and embedded in a solid iron cylinder. These newer motors had a much better torque-to-inertia ratio and they boosted access time. They also enabled designers to use only one capstan instead of two.<sup>11</sup>

## Enclosed Tape Drives

Competition from semiconductor technology and hard disk drives and the advent of the personal computer forced tape to move to new form factors. Although tape cartridges had been around for years, they were unable to gain popularity in the 1980s because size and cost were the dominant market forces.<sup>12</sup>

## Tape Drive Technology Lags Behind Computer Advances

Magnetic tape storage has played an important part in the evolution of digital storage and is still a good, low-cost storage media for some applications. And while engineers at drive and tape manufacturers have developed new techniques to improve density and access speed, in general, tape storage has not kept pace with the storage capacity or performance of other new—more evolved—technologies.<sup>13</sup>

## Magnetic Drum Memory: A Forerunner of the Modern Hard Drive

Almost in parallel to tape drive development, magnetic drum memory was finding use as a data storage media. While working under a contract with IBM (The Tabulating Machine Company) in 1928<sup>14</sup>, Austrian engineer, Gustav Tauschek, who was self-taught<sup>15</sup>, developed the first electromagnetic drum storage device. He received a U.S. patent for his work on drum storage in 1932, but his invention would not become generally popular until the 1950s and 1960s.

In its most basic form, magnetic drum memory is simply a metal drum or cylinder coated with a ferromagnetic material. Stationary write heads emit an electrical pulse, changing the magnetic orientation of a particle at a given position on the drum. The read heads, which are

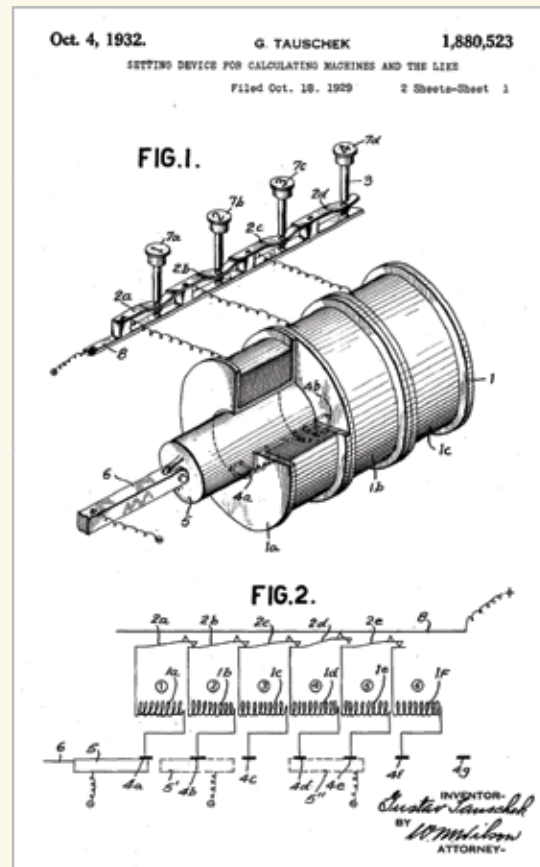


Figure 2: Setting Device for Calculating Machines and the Like from Tauschek's 1932 U.S. Patent

also stationary, recognize a particle's orientation as either a binary 1 or 0. Tauschek's prototype could store 500,000 bits across the drum's total surface for a capacity of about 62.5KB.<sup>16</sup>

## The Workhorse of Modern Industry

In the 1950s, the world of computers was changing, and while it would be decades before the personal computer completely revolutionized the business world, companies like IBM were making huge strides in electronic data processing. It was against this backdrop that the engineers at IBM's Endicott, New York, laboratory launched the 650 Magnetic Drum Data Processing Machine in 1953.<sup>17</sup>

Originally, IBM believed that the total market for 650's might be 50 installed units. But in less than two years, 75



of the drum-based machines had been installed and the company expected to install more than 700 more units over the next few years.<sup>18</sup>

“The development requirement underlying the 650 was for a small, reliable machine offering the versatility of a stored-program computer that could operate within the traditional punched card environment. IBM—and the industry—wanted a machine capable of performing arithmetic, storing data, processing instructions and providing suitable read-write speeds at reasonable cost. The magnetic drum concept was seen as the answer to the speed and storage problems.”<sup>19</sup>

By 1962, when IBM stopped manufacturing the 650, more than 2,000 units had been sold, making it the most popular computing machine of the era.<sup>20</sup>

The principles at work in magnetic drum memory would help to lead researchers to another and perhaps even more important innovation: the hard disk drive.

## IBM's RAMAC: The Birth of the Hard Drive

The hard disk drive (HDD) is the workhorse of modern storage systems, from personal computers to enterprise networks. To record data, HDDs change the polarity of tiny sections (magnetic domains) of a magnetic platter. Flipped one way, a domain represents the binary 0; flipped the opposite way, it represents a 1. Domains are arranged in a circumferential fashion around the platters so that a read/write head driven by a servomechanical actuator can track the binary bits.<sup>21</sup> This sort of storage was nothing less than a modern marvel when IBM first introduced the 350 Disk Storage Unit in 1956.

“The 350 Disk Storage Unit consisted of the magnetic disk memory unit with its access mechanism, the electronic and pneumatic controls for the access mechanism, and a small air compressor. Assembled with covers, the 350 was 60 inches long, 68 inches high, and 29 inches deep. It was configured with 50 magnetic disks containing 50,000 sectors, each of which held 100 alphanumeric characters, for a total capacity of 5 million characters.”

“Disks rotated at 1,200rpm, tracks (20 to the inch) were recorded at up to 100 bits per inch, and typical head-to-disk spacing was 800 microinches. The execution of a ‘seek’ instruction positioned a read-write head to the track that contained the desired sector and selected the

sector for a later read or write operation. Seek time averaged about 600 milliseconds.”<sup>22</sup>

The 350 was one of six components in IBM's 305 Random Access Memory Accounting (RAMAC) system, which also included an IBM 305 Processing Unit, an 80-position serial-output printer called the 370, a card punch, a console, and a huge power supply. Two years after it was introduced, IBM began offering the 305 RAMAC with an optional second 350 Disk Storage Unit, which doubled capacity. The 305 RAMAC originally leased for \$3,200 per month.<sup>23</sup>

As an interesting aside, each of the RAMAC's 50 aluminum platters was coated with magnetic iron oxide, derived from the same chemical formula as the primer paint used on the Golden Gate Bridge.<sup>24</sup>

In 1973, IBM introduced the 3340 or Winchester Direct Access Storage Facility. Certainly IBM had not been inactive. The company developed several models between the 305 and the 3340, but the smaller and lighter 3340 marked the next real evolutionary step in hard disk storage.

“The 3340 featured a smaller, lighter read/write head that could ride closer to the disk surface—on an air film 18-millionths of an inch thick, and with a load of less than 20 grams. The Winchester disk file's low-cost head slider structure made it feasible to use two heads per surface, cutting the stroke length in half. The disks, the disk spindle and bearings, the carriage, and the head-arm assemblies were incorporated into a removable, sealed cartridge called the IBM 3348 Data Module. A track density of 300 tracks per inch and an access time of 25 milliseconds were achieved.”<sup>25</sup>

Over the next several years the HDD would replace earlier storage technologies. Essentially, storage memory had evolved and HDDs represented the next new, more adaptable species. In 1980, Seagate Technology introduced the world's first 5.25-inch hard drive, bringing HDDs to a broader audience; prior to 1980 only large and well funded companies could afford the technology.

At each step along this evolutionary cycle, storage enabled new applications and greatly increased productivity. Over the next several years, as storage memory continued to evolve, the HDD would emerge as the next new, more adaptable solution and would replace many of the earlier, groundbreaking storage technologies.



## The First 5.25-Inch HDD

In 1980, Seagate Technology introduced the world's first 5.25-inch hard drive, bringing HDDs to a broader audience; prior to 1980 only large and well funded companies could afford the technology.

HDD capacity grew as much as 30% each year in the 1980s before accelerating to more than 60% per year in the 1990s. By 1999, HDD capacity was doubling every nine months.<sup>26</sup>

## The SPE Barrier – HDD Innovation

To achieve the HDD's nearly exponential density growth, scientists and engineers miniaturized the magnetic grains or bits on the platter's surface, squeezing more bits into the same or even smaller physical space.<sup>27</sup> These same researchers also developed more sensitive read/write heads (the giant-magnetoresistive head introduced in 1997, for example), capable of detecting faint magnetic fields.<sup>28</sup>

Since its inception, HDDs have faced a density-growth challenge in the form of the superparamagnetic effect (SPE). "Superparamagnetism occurs when the microscopic magnetic grains on the disk become so tiny that random thermal vibrations at room temperature cause them to lose their ability to hold their magnetic orientations. What results are 'flipped bits' – bits whose

magnetic north and south poles suddenly and spontaneously reverse—that corrupt data, rendering it and the storage device unreliable."<sup>29</sup>

Temperature plays a role in the SPE since another way to describe the effect is to say that when the ambient thermal energy equals the amount of energy needed to change a bit's polarity, that bit can flip and lose the data it was storing.

As bits are compressed, they become more susceptible to SPE, meaning that larger and faster HDDs have the potential to become less reliable.<sup>30</sup> For several decades, HDD developers have searched for ways to stave off the eventuality of reaching the density and reliability limits of HDDs.

One of the chief ideas proffered was to align bits perpendicularly rather than longitudinally. Famed inventor Valdemar Poulsen, who is sometimes called the Danish Edison, was one of the first researchers to experiment with perpendicular recording nearly 100 years ago,<sup>31</sup> but it took modern engineers at leading HDD makers to actually produce HDDs with perpendicular bits like Hitachi Global Storage Solutions first introduced in 2006.

In longitudinal magnetic recording, each bit is oriented horizontally on the platter, whereas perpendicular recording orients bits vertically on the platter and

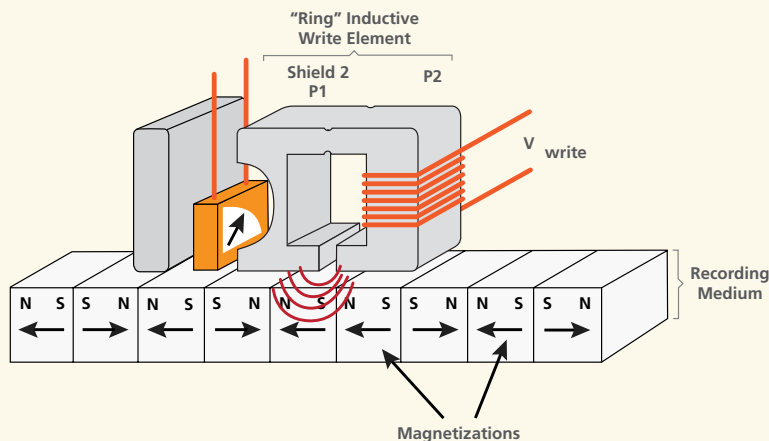


Figure 3: Longitudinal Recording

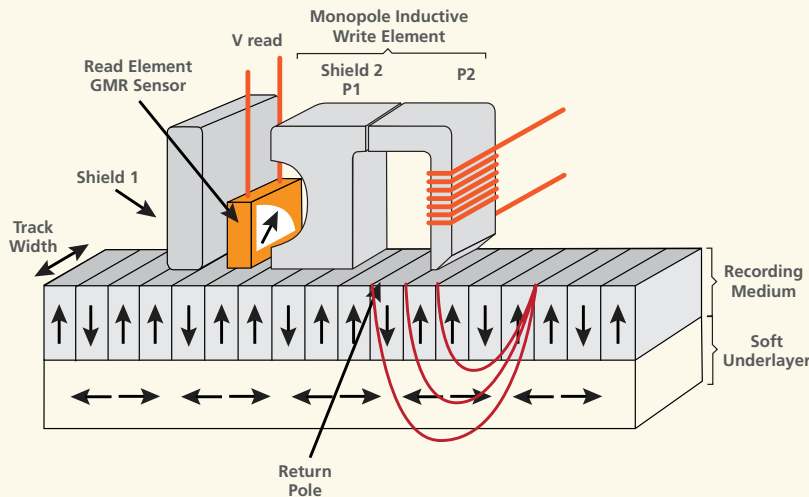


Figure 4: Perpendicular Recording

actually increases the number of bits that can be aligned on the disk.<sup>32</sup> Perpendicular recording is also inherently more stable across temperature ranges<sup>33</sup> because its poles are arranged south pole to south pole and north pole to north pole. In this way, bits naturally repel each other, reducing the likelihood of the SPE occurring.<sup>34</sup>

Several of the world's leading HDD makers now offer perpendicularly aligned HDDs.

## Heat-Assisted Magnetic Recording

Heat-assisted magnetic recording (HAMR) is a hybrid of magnetic and optical technology that represents the latest innovation in HDD development. HAMR has the potential to increase HDD density by an order of magnitude while still avoiding the SPE's limitations.<sup>35</sup>

With HAMR, engineers use a laser to briefly heat an area of an HDD's platter. The heat lowers that area's coercivity so it is below the coercivity of the magnetic field that the recording head is producing, essentially making it easier to flip a given bit's magnetic orientation in a stable magnetic material and allowing for "smaller thermally stable grains."<sup>36</sup>

## An HDD's Mechanical Limitations

In spite of new technologies like perpendicularly aligned bits and HAMR, HDDs are mechanical devices at heart and, as such, they face many performance challenges. Indications are that, ultimately, as storage systems continue to evolve, HDDs will be replaced.

Mechanical devices cannot improve as quickly as solid state technologies can. For example, "over the past 20 years, microprocessor technology—which plays a key role in data storage efficiency and function—has enabled CPU performance to nearly double every 18 months. Put another way, CPU performance has increased 16,800 times between 1988 and 2008, but HDD performance has increased by just 11 times."<sup>37</sup>

Even leading HDD manufacturers recognize the HDD performance problem. When Seagate Technology introduced faster, 15,000-RPM disk drives in 2004, it released a white paper describing the need for better HDD performance.

"Dramatic advances in processor speed, RAM size and RAM speed have combined to accelerate system performance to levels unthinkable just a few years ago. Such powerful hardware resources have made feasible software solutions with increasingly sophisti-

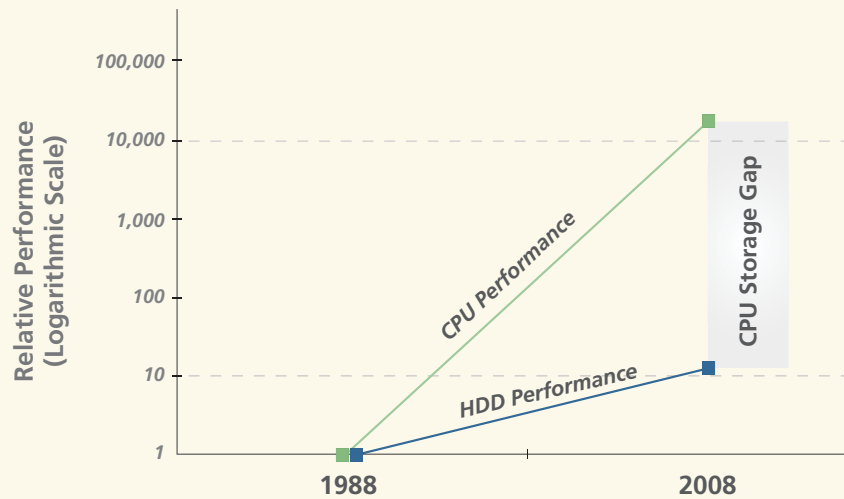


Figure 5: Relative Performance Improvement for CPUs and HDDs

cated and comprehensive capabilities, enabling business productivity to climb at a remarkable rate. Yet one aspect of system evolution has historically lagged behind: disc drive performance. While impressive advances in density have yielded exponential growth in disc drive capacity, disc drive speed has achieved only modest gains over the years,”<sup>38</sup> Seagate said.

To try to close the HDD performance gap, manufacturers have increased the drive’s rotational speed, added more advanced heads, and used techniques like short stroking, which restricts data to 5%–30% of the platter to boost performance. Western Digital, for example, recently released a speedy 20,000 RPM HDD.

But faster and faster disk rotation cannot be a lasting answer because these high-speed HDDs potentially make more noise, devour more power, and become increasingly less reliable. In addition, these higher-performance HDDs all sacrifice capacity. Each time the CPU issues a command “the hard drive’s mechanical system must then seek the requested data block or file by rotating its spinning platter and reaching out with its actuator.”<sup>39</sup>

To be sure, HDD engineers have continued to improve these devices and thus, stave off their ultimate extinction.

	1988	2008	Increase
CPU Performance	1 MIPS	16,800 MIPS	16,800 x
Memory Device Density	128K	2GB	16,000 x
Disk Drive Performance	60ms	5.3ms	11 x

Table 2: HDD Performance Has Not Kept Pace with Other System Components<sup>4</sup>

## HDD Mean Time Between Failures

"It is estimated that over 90% of all new information produced in the world is being stored on magnetic media, most of it on hard disk drives. Despite their importance, there is relatively little published work on the failure patterns of disk drives and the key factors that affect their lifetime. Most available data are either based on extrapolation from accelerated aging experiments or from relatively modest-sized field studies. Moreover, larger population studies rarely have the infrastructure in place to collect health signals from components in operation, which is critical information for detailed failure analysis."<sup>40</sup>

This seeming lack of information about a modern HDD's mean time between failures is a problem for large data centers and for the potential survival of HDDs. To try and shed light on the subject, Google created the first, large population HDD failure study in 2006 and released their findings at the 5th USENIX Conference on File and Storage Technologies in February 2007.

The Google research categorized dozens of failure types, found a handful of unexplained relationships, and generally showed that HDDs fail more often than manufacturers predict.<sup>41</sup> The study was an important first step since it provided users with foundational data for further research and it gave HDD manufacturers a sort of failure map. Solving some of these issues may result in better HDDs in the near future. If they go unaddressed, however, these failure issues could spell the end of HDDs.

## The RAM Solid State Device: The NAND SSD Forerunner

In 1978, StorageTek introduced the first modern SSD. This pioneering SSD had a maximum storage capacity of 90MB and sold for about \$8,800 per megabyte.<sup>42</sup> "The SSD served the mainframe industry as a virtual memory extension for paging and swapping programs in and out of memory."<sup>43</sup> That same year, Texas Memory Systems began marketing a 16KB RAM SSD to oil companies for a seismic data acquisition system.<sup>44</sup> SSDs were born, but didn't take off. At least not right away.

As far as mainframes were concerned, "the arrival of expanded storage, a bus extension for additional

main memory capacity, signaled the end of the SSD market—for a while," explained Fred Moore, a one-time StorageTek director.<sup>45</sup>

"In the early 1990s, a few small companies were building SSDs for select applications running on Unix, but market visibility was low and price per megabyte was still high. During the 1990s, the popularity of Unix, NT, the Internet, and, later, Linux increased. They became the largest storage markets for databases, and the heavy I/O loads they generated created response time bottlenecks. Twenty-five years after their first appearance, SSDs are still a niche market but are becoming the new stealth weapon for system programmers and storage administrators who struggle to deliver the consistent response times necessary to meet service levels,"<sup>46</sup> Moore wrote in 2002.

"Based on high-density DRAM chips, rather than rotating disk media and moving heads, the variable and lengthy seek and rotational times for rotating disks are eliminated, leaving a very short access and data transfer time to complete an I/O operation. There are no cache misses or back-end data transfers on an SSD. Typical I/O operations on an SSD occur between 30 and 40 times faster than on a rotating disk. SSDs are a quick fix for severe I/O performance problems, and they don't face the ongoing access density challenges of higher-capacity disks. These devices are fault-tolerant architectures and protect data from all types of device failures, not just from the loss of electrical power."<sup>47</sup>

In terms of a storage evolution, the DRAM- or RAM-based SSD was almost too specialized to have a large impact.

## NAND Flash Technology

Fujio Masuoka began working on Flash memory cells in the 1970s at Toshiba and received patents for his work in 1980.<sup>48</sup> Masuoka's designs were perhaps the most important semiconductor innovation in the history of storage, but unfortunately, it went poorly for Masuoka. For his work Toshiba gave Masouka "a bonus worth a few hundred dollars"—and promptly let its archrival Intel take control of the market for his invention. Subsequently, Masuoka says, Toshiba tried repeatedly to move him from his senior post to a position where he could do no further research."<sup>49</sup>



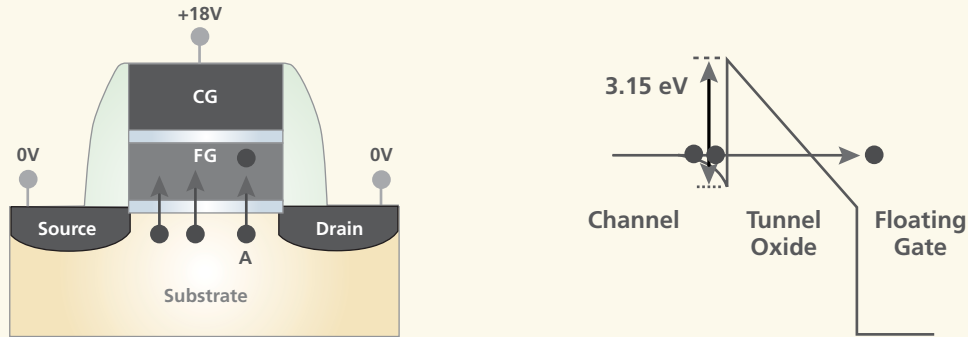


Figure 6: NAND Flash Cell Programming

Masouka’s Flash memory concepts have evolved, and today NAND Flash technology and SSDs have the potential to displace HDDs and force an evolutionary step in storage.

Like all semiconductor devices, NAND Flash memory relies on an electrical current to operate. Specifically, a voltage “is applied to the control gate to draw electrons from the substrate to tunnel through the gate oxide into a polysilicon floating gate layer. To store one bit, two charge levels in the floating gate layer can be stored to distinguish between a 1 and a 0.”<sup>50</sup>

“Single-level cell (SLC) NAND Flash memory stores one bit of information per memory cell. This basic technology enables faster transfer speeds, lower power consumption, and increased endurance. For designs using mid-range densities, SLC NAND Flash will continue to be a good choice. Multiple-level cell (MLC) NAND, by comparison, stores two to four bits of information per memory cell, effectively doubling the amount of data that can be stored in a similar-size NAND Flash device. SLC NAND offers

high performance and reliability, is supported by all controllers, and requires only 1-bit error correction code (ECC). SLC NAND is for applications like high-performance media cards, hybrid disk drives, solid state drives, and other embedded applications with processors, where it is used for code execution. MLC is supported only by controllers that include 4-bit or more ECC.”<sup>51</sup>

MLC is a low-cost file storage solution for consumer applications like media players, cell phones, and media cards (USB, SD/MMC, and CF cards) where density is more important than performance. MLC NAND has also emerged as the dominant Flash memory choice for SSDs targeted at the notebook PC market because they offer such a well balanced price-to-performance solution.

In fact, it is MLC NAND—for the most part—that has powered so many of the recent advances in mobile computing and digital media convergence. MLC NAND has replaced the day planner with the BlackBerry, exchanged film for media cards in cameras, and

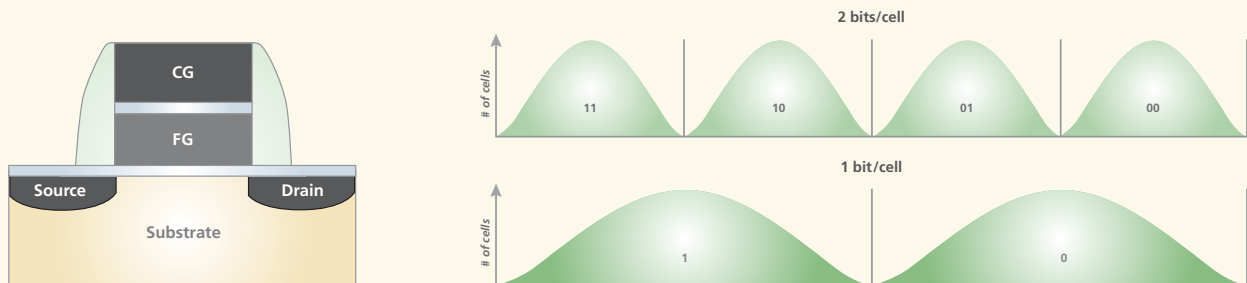


Figure 7: Multilevel Cell Storage in NAND Flash



enabled a musical revolution with the Apple® iPod® and other MP3s. Today, people can carry more memory around in a USB drive on their key chains than an entire room full of early HDDs could have stored.

## The Marriage of NAND Flash and SSDs

NAND technology paved the way for a new breed of SSD that is able to emulate HDDs in most enterprise or consumer applications. These SSDs are far less expensive than DRAM-based SSDs and still offer several advantages over HDDs—particularly in terms of performance and reliability.

Because NAND-based SSDs are a solid state technology, they have no moving parts and offer much better performance than HDDs. When a command is issued

to an HDD, the drive must seek with its actuator, spin its platter, and then transfer the data back to the host. But SSDs have no moving parts (requiring only the time it takes to process the command), and they have random access times as quick as 20µs.<sup>52</sup>

The improved performance of new SSDs equates to 10,000 IOPS compared to less than 450 IOPS for the fastest HDDs.<sup>53</sup> When used in enterprise applications like Internet banking, SSDs might significantly boost information access.

With no moving parts to wear out or break, an SSD will outlast almost any HDD, which typically has only a three- to five-year life expectancy if it is not bumped, banged, or dropped. By comparison, a modern SSD might last twice that long and do so without the sensitivities to mechanical shock and while consuming only a fraction of the power.

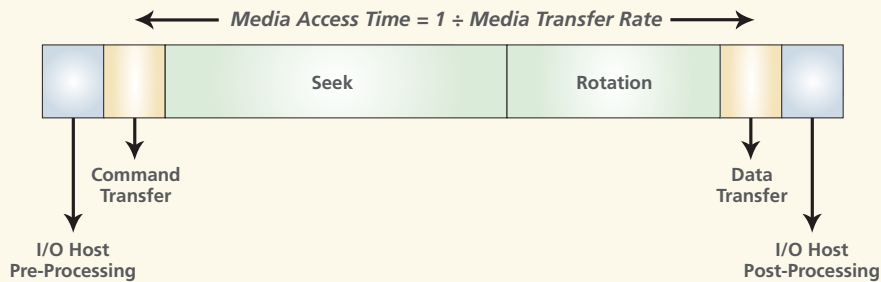


Figure 8: HDD External Storage I/O Timing

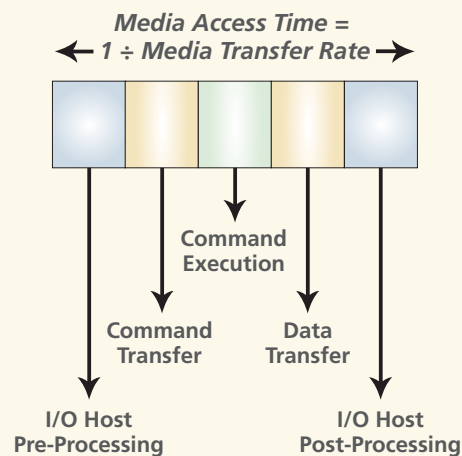


Figure 9: SSD External Storage I/O Timing



## RAIDs, Connections, and the Next Step for SSDs

SSDs can go anywhere an HDD can, so for enterprise and consumer applications alike, SSDs are replacing HDDs—a trend that is sure to continue for the next decade or more. But using an SSD as a drop-in replacement for an HDD is not necessarily using SSDs to their fullest potential. RAID controllers, HDD interfaces, and storage subsystems have been optimized for the characteristics of rotating magnetic media and may be a bottleneck for solid state storage.

Due to the flexibility of NAND solid state storage, SSDs will once again change the picture of storage in computers. NAND-based storage will become more integrated into the computer and will enable new generations of applications. Productivity gains will be measurable and the power savings, dramatic.

## Conclusion

Digital storage has come a long way since 1956, with the most recent innovation being SSDs. And now that SSDs are gaining new ground with the advancements made possible by NAND Flash technology, they represent the next evolutionary step for storage applications.

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