INVITED PAPER

The History of Storage Systems

This paper reviews the history and development of various data storage systems ranging from the early days of paper and punched cards through digital storage media technologies including storage networking and cloud-based storage systems.

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ABSTRACT | This paper reviews the history of storage systems. The first section begins with the era of early mechanical calculators and the following four sections review historically major storage devices such as magnetic tapes, magnetic disks, optical devices, and solid-state devices. The final two sections focus on recent system technologies such as storage networking and cloud-based storage.

KEYWORDS | Mass storage; storage medium; storage system

I. STORAGE MEDIA IN EARLY COMPUTERS

Earliest computers used paper for their information storage. An archaeological study showed that modern-style paper was already used in China around the 2nd century B.C. After the pulp papermaking process was invented by Cai Lun, a Chinese official, around A.D. 100, paper became widely used all around the world. Compared with earlier media, such as clay tablets and wood strips, paper dramatically facilitated reading and writing and improved information density. Due to these beneficial properties, paper is the standard storage media for most societies today.

The idea of using paper as information storage media for computers can be traced back to Charles Babbage [1], [2], an English mathematician, who invented a mechanical calculator—called the Difference Engine—designated for tabulating polynomial functions in the 1820s. After this successful invention, he began to work on a design to realize more generic calculation. At that time, automatic loom technology had already been established after a series of technical innovations mainly in France since the beginning of the 18th century. One noted example was the Jacquard loom, which could draw a weave pattern by reading punched holes in a given roll sheet and controlling the position of warp threads. Inspired by the loom technology, Babbage came to the idea of providing a calculation program and data using a punched card. He continued work toward building a generic calculator—named the Analytical Engine—but his work was hampered by financial difficulties and he only succeeded in building a partial prototype.

In the 1880s, Herman Hollerith [3], [4], an American statistician, invented a mechanism that could electrically detect a hole in a punched card and he prototyped a machine that could tabulate statistics from a number of punched cards [5]. Coincidentally, the U.S. Census Office was faced with a serious issue brought on by the explosive immigrant population. The census was taken every ten years. The 1880 census took almost eight years to complete tabulation. At the time, it looked like the next census, scheduled for 1890, would be unable to complete before 1900. To resolve this issue, the U.S. Census Office held a contest and called for proposals and finally decided to adopt Hollerith's idea. The Tabulating Machine, developed by Hollerith within a year, was used to tabulate the 1890 census and because of it the census was successfully completed and double checked within 18 months. This marked the first time that information technology amazed society. Hollerith began a business and continued to develop his machine and to lease the machines to census offices and insurance companies around the world. The Tabulating Machine Company he founded formed the basis of IBM through a business merger. After Hollerith's original card with 24 columns and 12 rows, many types of punched cards were designed and manufactured by other companies. The leading card format was the IBM 80-column card with 80 columns by 24 rows. Until the 1950s, punched cards were the most popular media both for data porting and information storage.

Shortly after the electronic computer was invented and became popular, punched cards were replaced with magnetic tape for persistent information storage, whereas

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due to their easy manageability and the legacy compatibility, punched cards still continued to be widely used for porting data and programs to/from computer systems until the mid-1980s. Today, other media such as cheap magnetic disks and broadband networks have become much more popular and punched cards are only used in limited cases.

II. MAGNETIC TAPE AND TAPE LIBRARIES

The original idea of using permanent magnetic impressions for recording information was presented by Oberlin Smith [6], [7], an American mechanical engineer. Originally, he focused on recording sound by magnetizing a thread in which iron particles were fabricated. He finally published his idea in Electrical World, a British engineering magazine, in 1888. In the 1890s, based on Smith's idea, Valdemar Poulsen, a Danish engineer, succeeded in demonstrating the telegraphone, where piano wire was used as magnetic material [6], [8]. He began a business selling the telegraphone but it never became very popular. Thomas Edison's phonograph, however, was commonly used in those days.

The magnetic tape that is common today was invented by the German Fritz Pfleumer in 1928 [6], [9], [10]. His original tape was made from ferric-oxide-powder-coated paper designed for sound recording. Based on his idea, AEG, a German electric equipment company, began a business selling the magnetophon, the first magnetic tape recorder for sound recording. Early tape was poor in quality but this was eventually improved by the efforts of many but in particular by the use of acetate plastic tape by BASF, a German chemical company, and the invention of alternate current biasing [6], [9], [10]. Along with phonograph records, magnetic tape was the most popular media for sound recording until they yielded to optical media such as CD not too long ago. All early magnetic tape products placed recording tracks in parallel to the edge of the tape. This technology called linear scan had one problem. It limited recording density and transfer bandwidth but it is still deployed today. In the 1950s, different countries developed yet another technology called helical scan today [6], [9], [10], which placed recording tracks diagonally at a range to the edge of the tape. Dramatically improving recording density, helical scan technology opened the way to using magnetic tape for video recording and is still widely used today.

As previously noted, magnetic tape was originally designed for sound recording. In the 1950s, magnetic tape was being deployed in auxiliary information storage for computers. UNIVAC I of 1951 [11] may be the first computer that used magnetic tape for information storage. A half-inch tape used in the UNIVAC I had eight tracks, each with 128 characters per inch; six for data, one for parity, and one for timing so that the reel speed of 100 in/s yielded an access throughput of 7200 characters per second. After IBM developed its own half-inch tape with a 10.5-in diameter reel and began to support such products in their commercial units in the 1950s [12], magnetic tape came to hold the standard position for information storage in large computer systems.

Early tape products were provided in a reel-to-reel form. When using these products, the user had to load a bare magnetic tape reel to a tape drive. In the 1970s, tape vendors began to provide magnetic tape in a cartridge and such products were soon commonly used in small computers and later replaced reel-to-reel products in large computer systems. Today, magnetic tape is usually used in cartridges for computers except in some cases where legacy compatibility is needed. As a result of much effort on behalf of a number of companies, the tape market has a wide diversity of product specifications [13]. They can be roughly summarized into five groups: 1) half-inch tape formats which have the origin in IBM reel-to-reel tape (IBM cartridges, StorageTek cartridges, DLT and LTO); 2) quarter-inch and 8-mm QIC tape formats (3M QIC, SLR and Travan); 3) large-cassette tape formats originally designed for digital video recording (ID-1, ID-6 and DTF); 4) 8-mm tape formats originally designed for analogue video recording (D8, Exabyte, AIT); and 5) 4-mm tape formats originally designed for digital audio recording (DDS and DAT72).

Since magnetic tape was originally designed for sound recording, recorded information is assumed to be accessed in a sequential manner. Random access requires rewinding the tape and results in unbearably long wait time. In contrast, magnetic disks, commercialized in the 1950s, enabled random accesses with shorter wait time. Magnetic tape eventually came to be replaced with magnetic disks for secondary information storage. However, magnetic tape still held significant advantages in cost-capacity ratios those days. The market did not move away from tape as it continued to be used for tertiary information storage. One example of this is information archiving and information backup. As magnetic tape became popular, a new issue arose regarding the management of cartridges. Tape vendors developed tape library machines (alternatively called robots and jukeboxes) for automatizing the safekeeping of many tape cartridges and loading them on tape drives. One of the earliest tape libraries was the IBM 3850 Mass Storage System released in 1974 [12]. It could store up to 9440 magnetic tape cartridges with a total of 472 GB. Interestingly, the IBM 3850 already had the capability of automatic hierarchical storage management between its own tape cartridges and IBM 3330 magnetic disks.

Magnetic tape technologies have evolved conservatively. In contrast, magnetic disks have achieved dramatic areal density improvements resulting in the reduction of cost per capacity. Magnetic tape's cost effectiveness is relatively small today. Many vendors have proposed virtual tape libraries (VTLs) (physically made of disk arrays but logically working as tape libraries) and disk-to-disk (D2D) systems (utilizing disk arrays directly for tertiary storage) [13]. Pessimists predict that most data centers are moving away from magnetic tape in favor of magnetic disks even for tertiary storage systems [14]. Data centers power awareness, on the other hand, is becoming more pronounced. Magnetic tape consumes much less energy than magnetic disks when archiving data. Such power effectiveness is receiving attention. Careful and continuous investigation will be necessary for the perspective on the billion-dollar market that magnetic tape represents.

III. MAGNETIC DISKS AND DISK ARRAYS

Magnetic disks, the primary component in modern storage systems, began with the IBM 350 Disk File [15] developed by the IBM team led by Reynold B. Johnson. The IBM 350 was incorporated in the IBM 305 RAMAC computer released by IBM in 1956. Its new storage media was composed of 50 24-in-across metal platters coated with magnetic material and two head access arms. The platters could spin at 1200 r/min driven by a spindle motor. The access arms could be dynamically controlled by a servo motor so that the head could move to any desired position and record information by magnetizing the magnetic coating on the platter. Likewise the head could read the recorded magnetic impression. Each side of the platters had 100 recording tracks. The disk could store five million 6-b characters, effectively 3.75 MB of information, and had a transfer rate of 8800 characters per second when disk tracks were accessed sequentially. Random access produced the long latency of around one second to actuate the arm.

The IBM 1301 Disk Storage Unit, released in 1961, introduced a head arm assembly [16]. Previous to this, a single head arm had to move across multiple platters by a servo motor. The IBM 1301 newly incorporated multiple heads, each for a recording surface, which were fixed to a single arm and moved together like a comb. This design contributed to faster seek time. Another major new technology deployed in the IBM 1301 was an aerodynamically designed flying head, which could exploit air drag to fly over a recording surface with very small clearance, then driving improvement of areal density. Another product, the IBM 3340 Direct Access Storage Facility (often called the Winchester Disk from its internal nickname), was released in 1973 and featured the first sealed metal platters along with a head arm assembly and a controlling circuit [16]. The Winchester design reduced the mechanical complexity for disk loading and unloading, thus allowing for size reduction and capacity improvements that came later. Recent magnetic disk products inherited the basic design of the IBM 3340 as magnetic disks and other components are packaged in a metal cover.[1]

Magnetic disks of the 1970s still had large (14- and 8-in) platters requiring large cabinets as well as large-capacity power supplies to operate. The deployment of such disks was limited to large computer systems. After 1980, when Seagate Technology announced a new product named the ST-506 with a 5.25-in platter and 5-MB capacity [17], cheaper reduced-diameter products became available and captured the microcomputer market. Today, 3.5- and 2.5-in products are commonly used in many places such as data centers, desktop computers, and laptops.

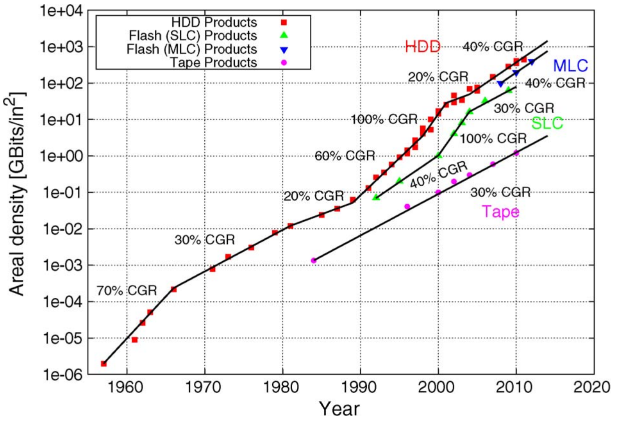

Fig. 1. ***Areal density of magnetic tapes, magnetic disks, and flash memory.***

The idea of leveraging multiple disks can be seen in early articles [18]. But as cheaper reduced-diameter magnetic disks came into the market, many vendors began to actively develop external storage devices, called disk arrays, with a number of cheap small disk drives to achieve large capacity, high access throughput, and high availability at much lower costs rather than expensive large disk drives. Disk arrays became popular in the 1990s in data centers. Some top-end products can operate with more than 1000 disk drives [19]. The redundant array of inexpensive disks (RAID) function is usually implemented at a controller, in most disk arrays,[2] to virtually organize a logical disk drive from multiple physical disk drives [20]. Major standard types can be summarized as follows: block-level striping without parity (RAID-0), mirroring (RAID-1), block-level striping with distributed parity (RAID-5), and any organization type with fault tolerance of two concurrent disk drive failures such as double-parity striping (RAID-6). Further sophistication was also reported by many researchers [21]–[26].

Tremendous growth of areal density and drive capacity seems to lie primarily behind the fact that magnetic disks had kept the primary position in secondary storage media for this half century. Many sustained efforts have realized elegant technologies such as thin recording layers, fine-grain magnetic crystals, giant magnetoresistive (GMR)/tunneling magnetoresistive (TMR) heads and perpendicular recording [27], which have recently allowed areal density of over 100 Gb/in^2 and 3.5-in disk products of 4-TB capacity [28]. Fig. 1 presents areal density evolution of

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[1] Around the same time, floppy disks—from IBM—offered a cheap storage media for distributing program codes to their customers.

[2] In contrast, a disk array without this functionality is often called just a bunch of disks (JBOD).

magnetic disks. In comparison with the IBM 350 of 1956, magnetic disks have achieved eight orders of magnitude higher areal density and a million times larger drive capacity. Magnetic disk vendors are still actively working on new technologies such as self-heated magnetic recording and self-organized magnetic array to further improve areal density.

In contrast to magnetic tape that has a variety of tape format specifications, magnetic disk interfaces have been relatively standardized and can be grouped into ATA-family interfaces and SCSI-family interfaces [29]. The ATA-family interfaces originate from an interface designed for the ST-506 disk drive from Seagate Technology. Later, ESDI, a revised interface based on the ST-506, was developed and came into wide use by microcomputers of the 1980s. When it came to the 1990s, a further revised interface, IDE (Parallel ATA), was designed and became the standard bus interface for connecting cheap ATA disk drives to IBM PC/AT compatible machines. The ATA-family interfaces benefited from their simplified designs, which allowed rapid capacity growth and cheap manufacturing. However, since the 2000s, when data centers began to use ATA disk drives, disk vendors provided their ATA-interface products with sophisticated functions such as tagged queuing that used to be implemented only in high-end SCSI products. Today, a succeeding interface, Serial ATA, is widely used in data centers mainly for archiving and backup as well as in desktop computers and laptops.

The SCSI-family interfaces evolved from the SASI interface that was originally designed for connecting a floppy disk drive to a microcomputer in the 1970s. Similarly, when the SCSI was standardized in the 1980s, it was originally designed for microcomputers. However, after several improvements SCSI-interface disk drives came to have a variety of sophisticated functions such as rich error correction for signal processing, vibration resistant servo controlling, and access request scheduling, thus holding higher reliability and performance in comparison with ATA-interface products. This led to the use of SCSI interfaces for large computer systems despite its original design. Today, two major revised interfaces, Serial Attached SCSI (SAS) and Fibre Channel Protocol for SCSI (FCP for SCSI), are commonly used in data centers.

Interface evolution has eventually improved transfer rates. Some recent disk drives have transferring capabilities of around 100 MB per second. However, improvements have not kept up with the rapid capacity growth since 1990. In other words, drive transfer speed has eventually slowed down relatively to drive capacity. Worse, when a magnetic disk is accessed in a random fashion, the disk head has to suspend for waiting for seeking time and rotation latency. Reduction of seeking time has been limited merely to around 70% from 1990 to 2000. Rotation speeds of spindle motors have hit the ceiling at 15 000 r/min; further improvements are almost surely impossible due to heat capacity problems even in high-end products. Improvement of random access speeds is definitely far behind capacity growth and the gap has grown larger. Unfortunately, no substantial work has been reported to change these trends. Instead, data centers are beginning to leverage storage class memory such as flash memory for high-end applications that require low-latency random accesses. Magnetic disks are continuously evolving to improve drive capacity, recoding density, and reliability. Future disks might be much more specialized for sequential accesses.

IV. OPTICAL/MAGNETO-OPTICAL STORAGE MEDIA

Optical disks and magneto-optical disks are storage media that can record information by changing photo-physical forms on their recording surfaces and read the recorded information by emitting light beams against the surface and sensing their reflection. Their origin can be traced back to the video recording method invented by David Paul Gregg [30], but their practical use began with the first LaserDisc (LD), announced in 1980. Optical and magneto-optical disks later became very popular media for recording audio and visual content. A number of commercial products have been announced, but they can be roughly categorized into four groups in terms of their recording methods [31], [32]. The first category is read-only optical disks, on which manufacturers provide very small holes, called bits, on a recording surface for recording information when pressing media. Major products are CD and its succeeding media DVD and Blu-ray Disc (BD). The second category is write-once-read-many (WORM) optical disks, on which a disk drive can record information only once by emitting a laser beam to irreversibly burn pigments on a metal recording surface. Major products are CD-R, DVD-R, and BD-R. The third category is rewritable optical disks, on which a disk drive can record multiple times by emitting a laser beam to change the crystal forms of an amorphous recording surface. CD-RW, DVD-RW/RAM, and BD-RE belong in this category. The last category is rewritable magneto-optical disks, on which a disk drive instead emits a laser beam and magnetic field to change optical properties on a recording face.

Optical and magneto-optical disks are commonly used for distributing contents because they are easy to use and can be manufactured at low cost. CD has been the standard media for audio contents and DVD and BD have been the standard for visual contents. CD and DVD have also been widely used to distribute computer software. Recently, however, broadband networks are increasingly allowing online distribution. Currently, computer software is very often distributed online and a number of online distributors are emerging for audio and visual contents. On the other hand, optical and magneto-optical disks were also deployed for mass storage in large computer systems. Vendors developed several library machines, sometimes called optical jukeboxes, which could manage a number of optical and magneto-optical disks in one place. However, recording density of optical and magneto-optical disks is still far behind magnetic tape and their deployment into mass storage is not yet widespread.

A new type of optical media under research is holographic memory, which allows 3-D recording in crystal material [33]. If successfully developed, holographic memory may significantly improve recording density in comparison with conventional disk media. However, to our knowledge, commercialization has yet to be reported.

V. STORAGE CLASS MEMORY

Nonmechanical storage media, such as flash memory, are currently deployed for secondary storage in computer systems. Those storage media have recently been named storage class memory (SCM). But the use of such storage media is not limited to recent systems. Vacuum-tube computers of the 1950s allowed external memory units made of nonvolatile magnetic core memory to be attached. Some later systems also used magnetic bubble memory and battery backed-up memory. However, the use of storage class memory only became popular for secondary storage after flash memory, invented by Toshiba engineer Fujio Masuoka in the 1980s [34], became widely commercialized.

Flash memory is a sort of electrically erasable programmable read-only memory (EEPROM) [35], [36]. The memory controller can program/erase information by putting/removing an electron to/from a solid-state cell made of a floating gate and read information by measuring voltage of the floating gate. To manipulate an electron to the floating gate requires tunnel electron transfer called Fowler–Nordheim effect; as more electron manipulations are conducted, an oxide layer on the floating gate eventually degrades. Product lifetime is limited by this phenomenon. Two design options for connecting multiple floating gates, NOR and NAND, are known; out of these the NAND design is commonly used because it easily improves integration density. Information can be programmed and read in a unit of page (often several kilobytes long). A page once written cannot be programmed again and has to be erased in advance. Erasing is usually allowed in a unit of blocks (often hundreds of kilobytes long) thus consuming relatively longer time than programming and reading. Early products deployed only a single-level cell (SLC) design, which could record only a bit in each cell. Later improvement enabled a multiple-level cell (MLC) design, which could record more than a bit in each cell. SLC memory is often deployed in systems requiring high performance and high reliability, whereas MLC is usually found in systems requiring large capacity. In contrast to magnetic disks that take latencies of several milliseconds even in high-end products, flash memory has dramatically reduced latencies between tens to hundreds of microseconds and holds much better balances between power consumption and access throughput.

Early flash memory products found their way into consumer electronics like compact flash and SD cards. From the 2000s, large-capacity products became available in the market and they came to be used as secondary storage in computer systems, even though flash memory is far behind magnetic disks in terms of per-capacity cost. In many cases, flash memory is used in solid-state drives (SSDs), where flash memory chips and a controlling circuit are packed. The controlling circuit has the emulating capability of making attached flash memory work like a magnetic disk. This emulation enables computer systems to use SSDs via existing interfaces such as SATA and has led to SSDs popularity. Early SSD products had limited controlling capabilities, but some recent products have sophisticated functions such as wear leveling to extend product life by balancing programming times over cells and deferred write scheduling to absorb long erasing latencies by using large buffer memory [37]. In other uses, existing interconnects were designed to connect magnetic disks but not always optimized for flash memory. The market is witnessing new types of flash memory products like so-called PCI Express SSDs that can be connected via PCI Express to provide much smaller access latency and external flash memory arrays made of a number of flash memory chips and strong controlling circuits.

Flash memory is currently a dominant technology for storage class memory. Active research is being conducted to further improve performance, reliability, and recording density. These new attempts include new material cells such as SONOS and TaNoS, and 3-D gates. At the same time developers are investing in many new types of memory devices, including FeRAM, MRAM, PCRAM, RRAM, and Solid Electrolyte [38], [39].

VI. STORAGE NETWORKING

The literature reporting on the exponential growth of digital information has steadily increased since we entered this century [40]. This phenomenon seems to have been fueled by the rapid evolution of IT devices and broadband networks. Storage technologies should be one of the major contributors. Emerging sensor network technology is likely to drive further rapid growth. Let us think about how to manage the growing information in IT systems. As digital information matures, storage capacity has to keep pace too. However, it is almost impossible to expand administrative personnel at the same pace. The consequence is that the management burden per administrator is rapidly growing. Today, one primary concern of system owners is often how to manage large storage resources efficiently. Storage networking is a promising solution.

In conventional systems, each storage device was recognized as a peripheral device dedicated to a particular computer via bus technology such as SCSI. In contrast, storage networking can connect arbitrary storage devices and computers via a network often designed for connecting storage devices. Being networked, storage resources are becoming more easily shared and consolidated into one place, where a number of sophisticated functions have come to be built on top of storage virtualization infrastructure. This section briefly summarizes such storage networking technologies [41] that are rapidly evolving today.

A. Storage Area Network and Network Attached Storage

Storage area network (SAN) and network attached storage (NAS) are two major types of storage network architectures[3] [42]. SAN originally referred to any type of network designed for connecting storage devices. In reality, this term came to refer to a storage network to provide block-level access service.

When the term SAN is used without any modifications, the term often refers to Fibre Channel, developed in the late 1990s for transferring massive amounts of data for scientific calculations and image processing. Its sophisticated design allows Fibre Channel frames to efficiently encapsulate SCSI commands and transfer them on a network. Fibre channel was soon deployed at data centers to connect storage devices and was later recognized as the standard SAN technology from the early 2000s. Implementation for connecting magnetic disks to multiple computers was realized before Fibre Channel was announced but only in very limited cases.

As Fibre Channel became common in data centers, two issues were being focused on. First, transmission distance using Fibre Channel was limited and another network technology had to be developed to bridge two distant Fibre Channel networks. Second, Fibre Channel was an expensive technology in comparison with other network technologies such as Ethernet. Several technologies were proposed to resolve these issues by utilizing the IP technology, which could relatively easily allow distant communication and could build network infrastructure at lower costs [43]. Major proposals were iFCP, FCIP, and iSCSI. iFCP and FCIP were network gateway technologies specially designed for encapsulating Fibre Channel frames in IP packets, thus easily bridging two remote Fibre Channel networks via an IP network. These bridged Fibre Channel networks could work virtually as one system and its transparency was helpful to relieve data center operation. In reality, FCIP and iFCP are deployed in many data centers for remote bridging. In contrast, iSCSI was another IP-based SAN technology designed for more general storage networking. iSCSI has the capability of encapsulating SCSI commands in IP packets, which allows end-to-end SCSI communication over an IP network as well as remote SAN bridging. This technology is rapidly becoming popular in entry-class data centers. The market is witnessing another emerging network technology, FCoE, for transferring Fibre Channel frames over an Ethernet network.

NAS is a networked storage device that provides a file-level access service. Despite its original meaning, the term NAS is also used to refer to a storage network that provides a file-level access service and its storage network architecture. Major NAS protocols are NFS and CIFS that were originally designed for file sharing between networked computers and are still used in recent data centers. Similar to iSCSI, the NAS technology is usually implemented over an IP network. It gained popularity in entry-class data centers due to its cost effectiveness. As the NAS technology also became widely used in midrange systems, vendors began to develop gigantic NAS machines, which are made of a number of file servers with many magnetic disks.

B. Storage Consolidation and Storage Virtualization

Before storage networking technology arose, storage resources were distributed among computers and managed separately. Suppose that computer X has consumed most of its storage space but another computer Y has much unused space. It was not easy for computer X to access the unused storage space of computer Y. After storage networking has been developed, storage resources can be shared among computers and these resources can be allocated in a flexible fashion [44]. Consolidating storage resources over a storage network in one place improved the efficiency of storage resource management. Storage networking soon became popular in many data centers.

Storage virtualization is a fundamental technology in networked storage environments, which can build a resource pool from physical storage devices, organize logical storage devices from the resource pool, and provide computers with the organized logical devices. Today many data centers deploy storage virtualization to enable flexible storage resource management. Most popular examples of storage virtualization are RAID and provisioning (on-demand space allocation) that are often implemented in disk array controllers and logical volume managers (parts of operating systems). Other examples are virtual tape library and hierarchical storage management systems.

When storage networking was born, there were only a limited number of experts. Storage Networking Industry Association (SNIA), a nonprofit organization established in 1997, started to promote this technology and has been composing technical documentation, promoting standardization, and operating educational programs [45]. Their continued efforts are responsible for the current wide use of storage networking.

C. Sophisticated Storage Applications

Storage networking has driven the technology trend for sophisticating storage systems. The concept of executing application code within a magnetic disk drive can be traced

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[3] Direct attached storage (DAS) refers to a storage device that is dedicated to a computer in a conventional way. DAS is also used for such storage network architecture.

back to research on database machines between the 1970s and the 1980s [46]–[49]. Researchers designed and implemented a number of specialized database machines, some of which achieved commercial success. But in the early 1990s, major database vendors moved away from specialized machines and shifted toward software-based solutions for general-purpose machines.

By the late 1990s, a similar idea gained the spotlight in the marketplace. Storage vendors began to incorporate sophisticated functions into their storage products. Storage networking became a popular technology in many data centers, where storage resources became consolidated and more highly virtualized. A design policy for managing storage resources within a storage system became natural and acceptable. In addition, rapid evolution of processor technology provided storage systems with greater processing power, enabling such sophistication. Interestingly, similar ideas were again discussed in academia at around the same time [50]–[52].

One popular function implemented in many storage systems was third-party copy to directly generate a copy within a storage device or between different storage devices. In conventional systems, a specialized computer, called a backup server, was often built for generating and managing copies. But copy generation and management can be decoupled from applications running on computers in many cases. Executing them within a storage system seems natural enough and such a solution is beneficial to simplify system management. In fact, this is deployed into many data centers. Other examples that are popular in recent data centers are point-in-time (PiT) copy for generating consistent copy image, remote replication for enabling disaster recovery solutions, data sharing between mainframes and open systems, WORM for audit trail solutions, deduplication for economizing storage capacity, and continuous data protection (CDP) for automatically saving every version of stored data. Further sophistication of storage systems is under active research.

VII. CLOUD STORAGE AND THE FUTURE

Without long delay from the birth of storage networking, several vendors, originally called storage service providers (SSPs), started to manage customers' storage systems in their data centers, where customers could access their business data via broadband networks. From the customers' viewpoint this trend was rightly regarded as storage management outsourcing, which was enabled by the emerging storage virtualization technology. Vast amounts of storage resources pooled by SSPs help customers to speedy extend or shrink storage capacity and bandwidth in an on-demand manner. Such agility was beneficial in controlling business operations in today's dynamic market. However, SSPs did not rapidly gain acceptance from the early 2000s when they began to be offered by vendors. Around that time, storage virtualization was already popular in many data centers while server virtualization technology for virtualizing application execution environments was in its early stages. Placing business data and business applications in remote data centers came to be a realistic solution for many customers when both virtualization technologies became available. Such solutions were later referred to as cloud computing.

In recent cloud computing contexts, remote storage services that used to be called SSPs are often provided as a part of full-fledged cloud services. Currently major cloud-based storage services include Amazon S3, Windows Azure Storage, and Google Cloud Storage, which are all designed in close coordination with their other cloud services. Cloud-based storage is not limited to enterprise systems and is becoming more popular for new types of consumer electronics such as digital audio/visual players and electric book readers. Apple iCloud and Amazon Cloud are major services that allow customers to store and manage their purchased contents in remote clouds. Cloud computing is an emerging technology. Service providers are trying to resolve complaints and concerns over performance and security issues. Research institutes have reported that much data are moving toward clouds [40].

This paper has reviewed the history of storage technology from early storage devices to recent cloud systems. Due to the recent exponential growth of digital data, data management is gaining more importance. Evolving sensor networking technology is likely to drive this data growth further. Storage system technologies can be expected to play a much wider and deeper in role in future IT systems. ■

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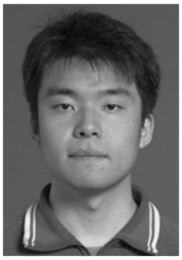

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