

THE ESSENTIALS OF

# Computer Organization *and* Architecture

THIRD EDITION

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## Chapter 7

### Input/Output and Storage Systems

# Chapter 7 Objectives

- Understand how I/O systems work, including I/O methods and architectures.
- Become familiar with storage media, and the differences in their respective formats.
- Understand how RAID improves disk performance and reliability, and which RAID systems are most useful today.
- Be familiar with emerging data storage technologies and the barriers that remain to be overcome.

# 7.1 Introduction

- Data **storage and retrieval** is one of the primary functions of computer systems.
  - One could easily make the argument that computers are more useful to us as data storage and retrieval devices than they are as computational machines.
- All computers have **I/O devices** connected to them, and **to achieve good performance I/O should be kept to a minimum!**
- In studying I/O, we **seek to understand the different types of I/O devices** as well as how they work.

## 7.2 I/O and Performance

- **Sluggish I/O throughput** can have a ripple effect, dragging down overall system performance.
  - This is especially true when virtual memory is involved.
- The **fastest processor** in the world is of little use if it spends most of its time **waiting for data**.
- If we really understand what's happening in a computer system we **can make the best possible use of its resources**.

## 7.3 Amdahl's Law

- The overall performance of a system is a result of the interaction of all of its components.
- System performance is most effectively improved when the performance of the most heavily used components is improved.
- This idea is quantified by Amdahl's Law:

$$S = \frac{1}{(1-f) + \frac{f}{k}}$$


where  $S$  is the overall speedup;  $f$  is the fraction of work performed by a faster component; and  $k$  is the speedup of the faster component.

## 7.3 Amdahl's Law


- Amdahl's Law gives us a handy way to estimate the performance improvement we can expect when we upgrade a system component.
- On a large system, suppose we can upgrade a CPU to make it 50% faster for \$10,000 or upgrade its disk drives for \$7,000 to make them 150% faster.
- Processes spend 70% of their time running in the CPU and 30% of their time waiting for disk service.
- An upgrade of which component would offer the greater benefit for the lesser cost?

## 7.3 Amdahl's Law

- The **processor** option offers a **30%** speedup:

$$\begin{array}{l} f = 0.70, \\ k = 1.5 \end{array} \quad S = \frac{1}{(1 - 0.7) + 0.7/1.5}$$


- And the **disk drive** option gives a **22%** speedup:

$$\begin{array}{l} f = 0.30, \\ k = 2.5 \end{array} \quad S = \frac{1}{(1 - 0.3) + 0.3/2.5}$$


- Each 1% of improvement for the processor costs \$333, and for the disk a 1% improvement costs \$318.

**Should price/performance be your only concern?**

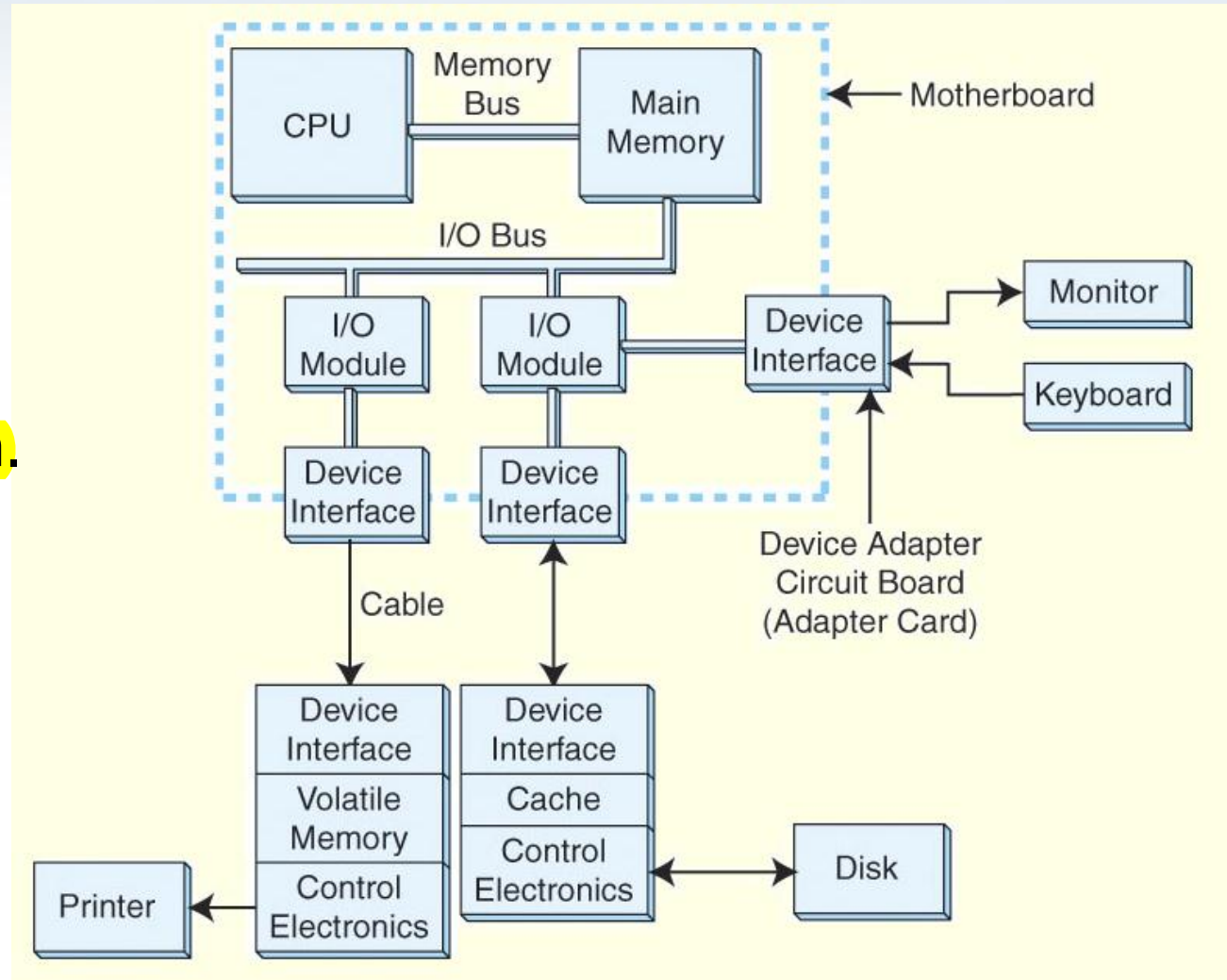
## 7.4 I/O Architectures

- We define input/output as a subsystem of components that moves coded data between external devices and a host system.
- I/O subsystems include:
  - Blocks of main memory that are devoted to I/O functions.
  - Buses that move data into and out of the system.
  - Control modules in the host and in peripheral devices
  - Interfaces to external components such as keyboards and disks.
  - Cabling or communications links between the host system and its peripherals.








## 7.4 I/O Architectures

This is a  
model I/O  
configuration.



## 7.4 I/O Architectures

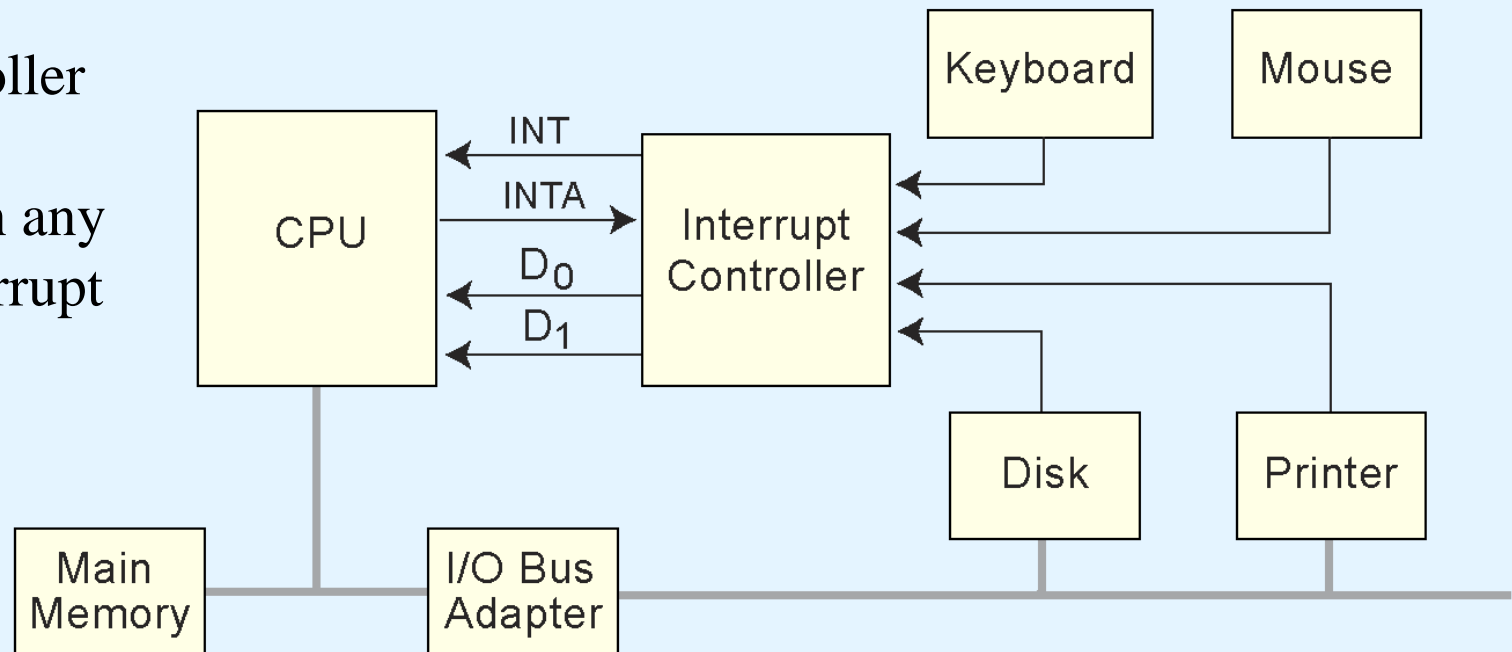
- I/O can be controlled in five general ways.
  - *Programmed I/O* reserves a register for each I/O device. Each register is continually polled to detect data arrival. 
  - *Interrupt-Driven I/O* allows the CPU to do other things until I/O is requested. 
  - *Memory-Mapped I/O* shares memory address space between I/O devices and program memory. 
  - *Direct Memory Access (DMA)* offloads I/O processing to a special-purpose chip that takes care of the details. 
  - *Channel I/O* uses dedicated I/O processors. 

## 7.4 I/O Architectures

This is an idealized I/O subsystem that uses interrupts.

Each device connects its interrupt line to the interrupt controller.

The controller signals the CPU when any of the interrupt lines are asserted.

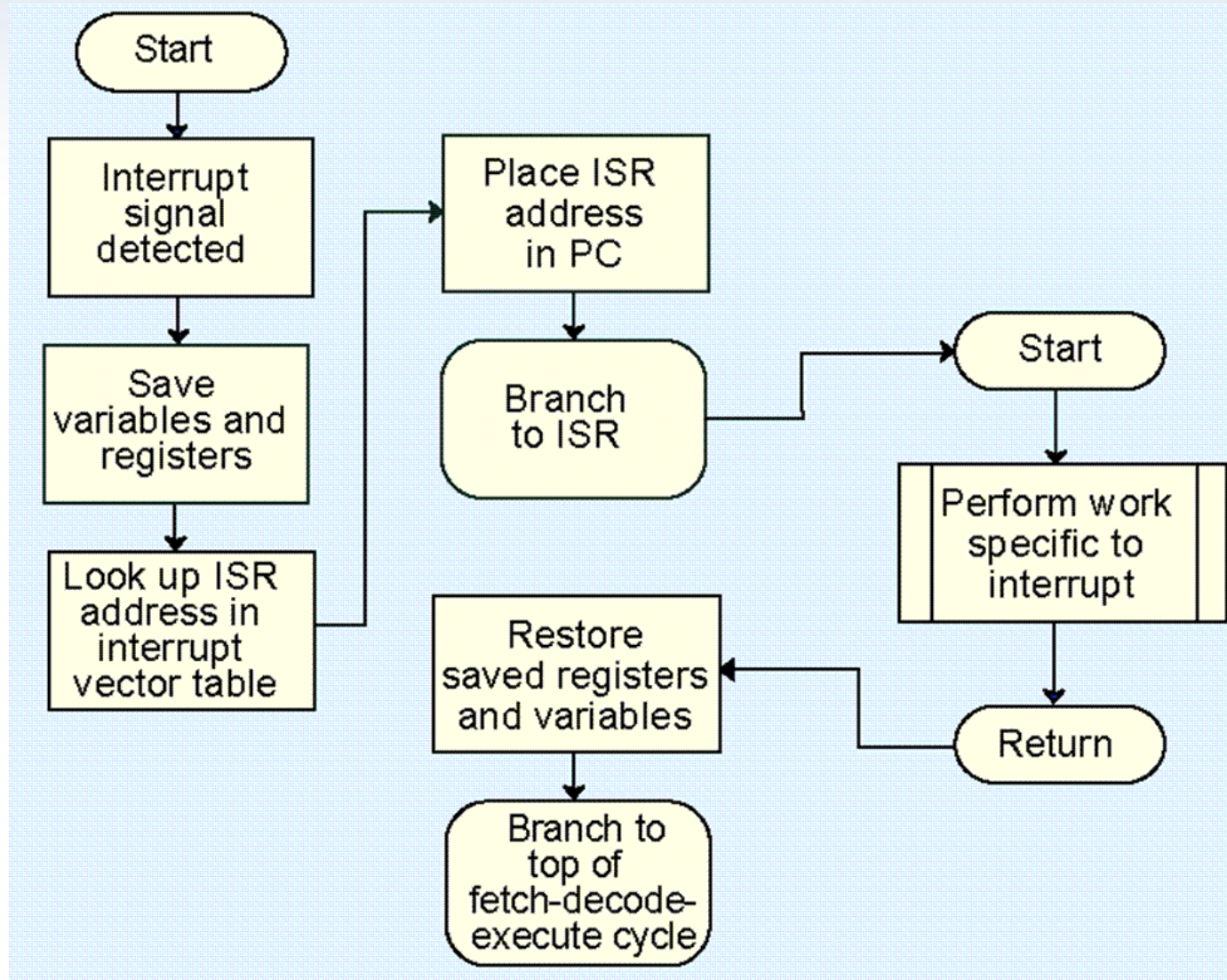


## 7.4 I/O Architectures

- Recall from Chapter 4 that in a system that uses interrupts, the status of the interrupt signal is checked at the top of the fetch-decode-execute cycle.
- The particular code that is executed whenever an interrupt occurs is determined by a set of addresses called *interrupt vectors* that are stored in low memory.
- The system state is saved before the interrupt service routine is executed and is restored afterward.

**We provide a flowchart on the next slide.**

## 7.4 I/O Architectures



## 7.4 I/O Architectures

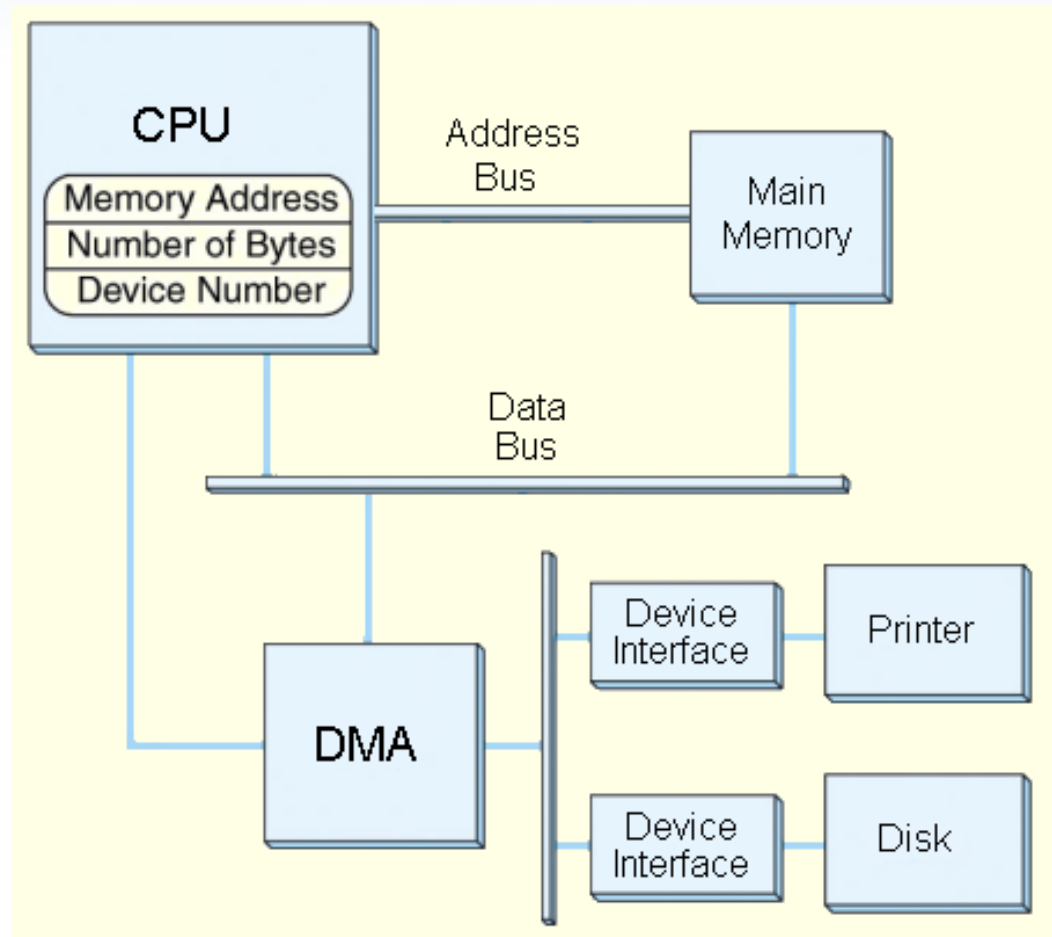
- In memory-mapped I/O devices and main memory share the same address space.
  - Each I/O device has its own reserved block of memory.
  - Memory-mapped I/O therefore looks just like a memory access from the point of view of the CPU.
  - Thus the same instructions to move data to and from both I/O and memory, greatly simplifying system design.
- In small systems the low-level details of the data transfers are offloaded to the I/O controllers built into the I/O devices.

## 7.4 I/O Architectures

This is a **DMA** configuration.

Notice that the **DMA** and the CPU share the bus.

The **DMA** runs at a higher priority and steals memory cycles from the CPU.



## 7.4 I/O Architectures

- Very large systems employ channel I/O.
- Channel I/O consists of one or more I/O processors (IOPs) that control various channel paths.
- Slower devices such as terminals and printers are combined (*multiplexed*) into a single faster channel.
- On IBM mainframes, multiplexed channels are called *multiplexor channels*, the faster ones are called *selector channels*.

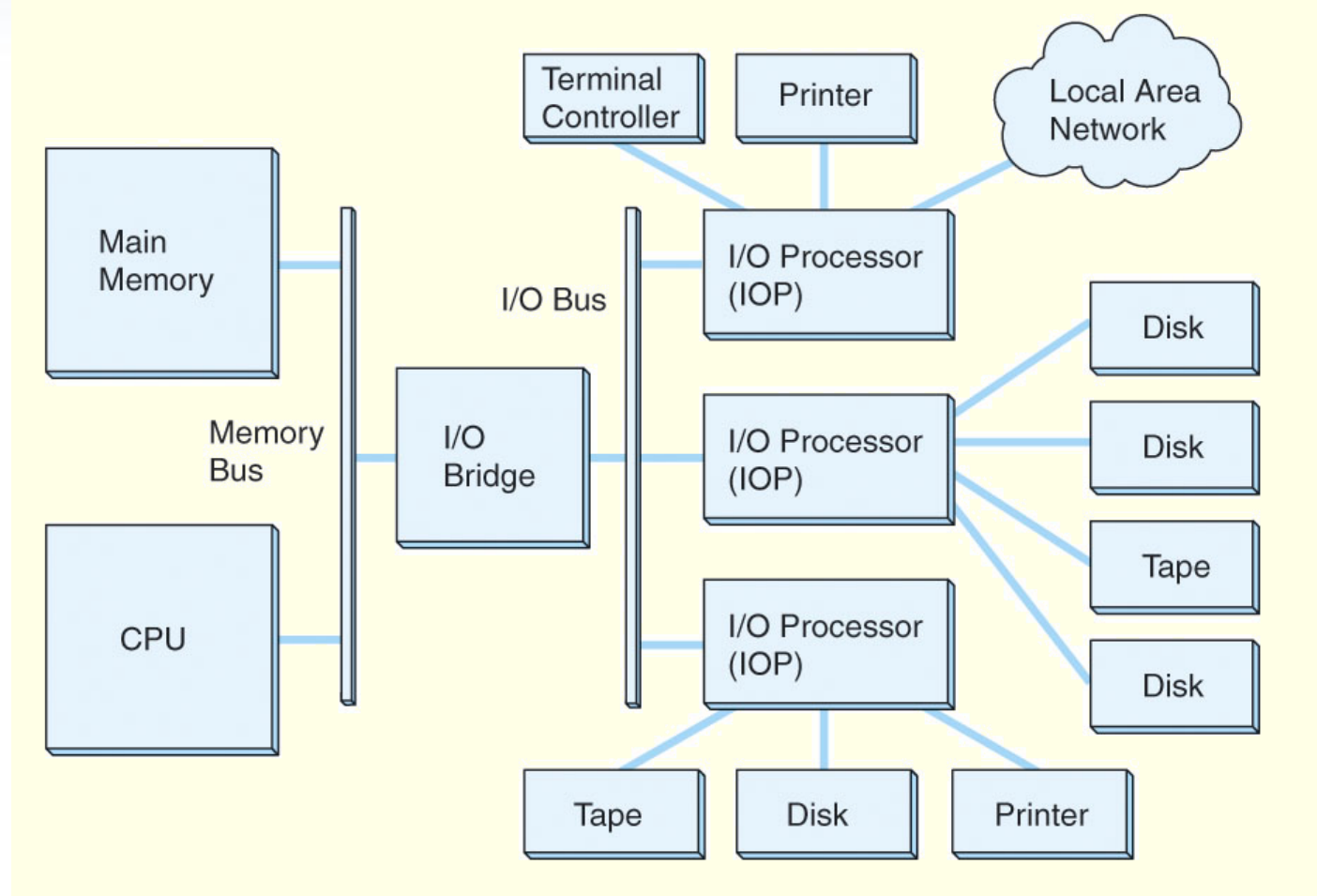


## 7.4 I/O Architectures

- Channel I/O is distinguished from DMA by the intelligence of the IOPs.
- The IOP negotiates protocols, issues device commands, translates storage coding to memory coding, and can transfer entire files or groups of files independent of the host CPU.
- The host has only to create the program instructions for the I/O operation and tell the IOP where to find them.

## 7.4 I/O Architectures

- This is a **channel I/O configuration**.



## 7.4 I/O Architectures

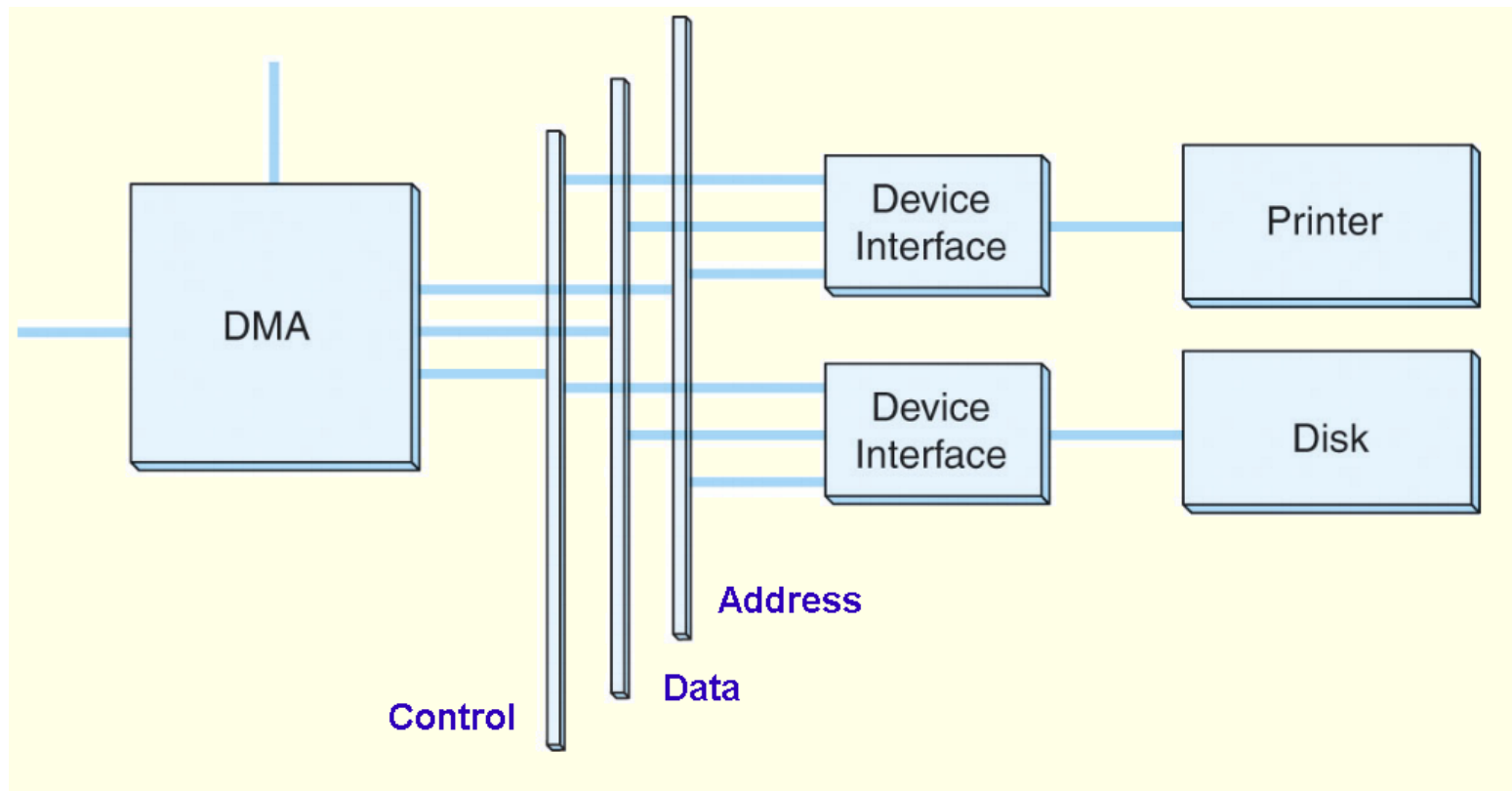
- Character I/O devices process one byte (or character) at a time.
  - Examples include modems, keyboards, and mice.
  - Keyboards are usually connected through an interrupt-driven I/O system.
- Block I/O devices handle bytes in groups.
  - Most mass storage devices (disk and tape) are block I/O devices.
  - Block I/O systems are most efficiently connected through DMA or channel I/O.

## 7.4 I/O Architectures

- I/O buses, unlike memory buses, operate asynchronously. Requests for bus access must be arbitrated among the devices involved.
- Bus control lines activate the devices when they are needed, raise signals when errors have occurred, and reset devices when necessary.
- The number of data lines is the *width* of the bus.
- A bus clock coordinates activities and provides bit cell boundaries.

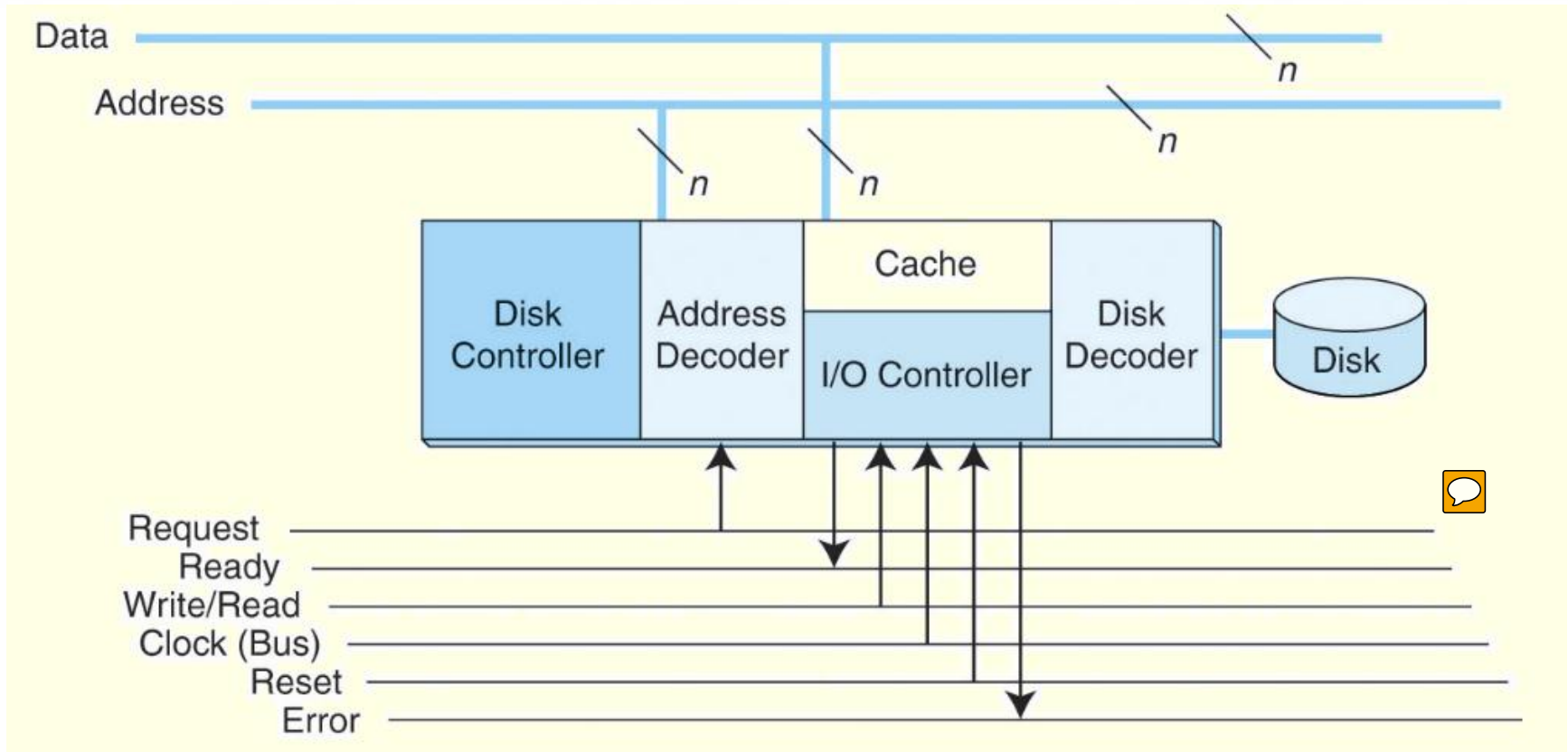
## 7.4 I/O Architectures

This is a generic DMA configuration showing how the DMA circuit connects to a data bus.

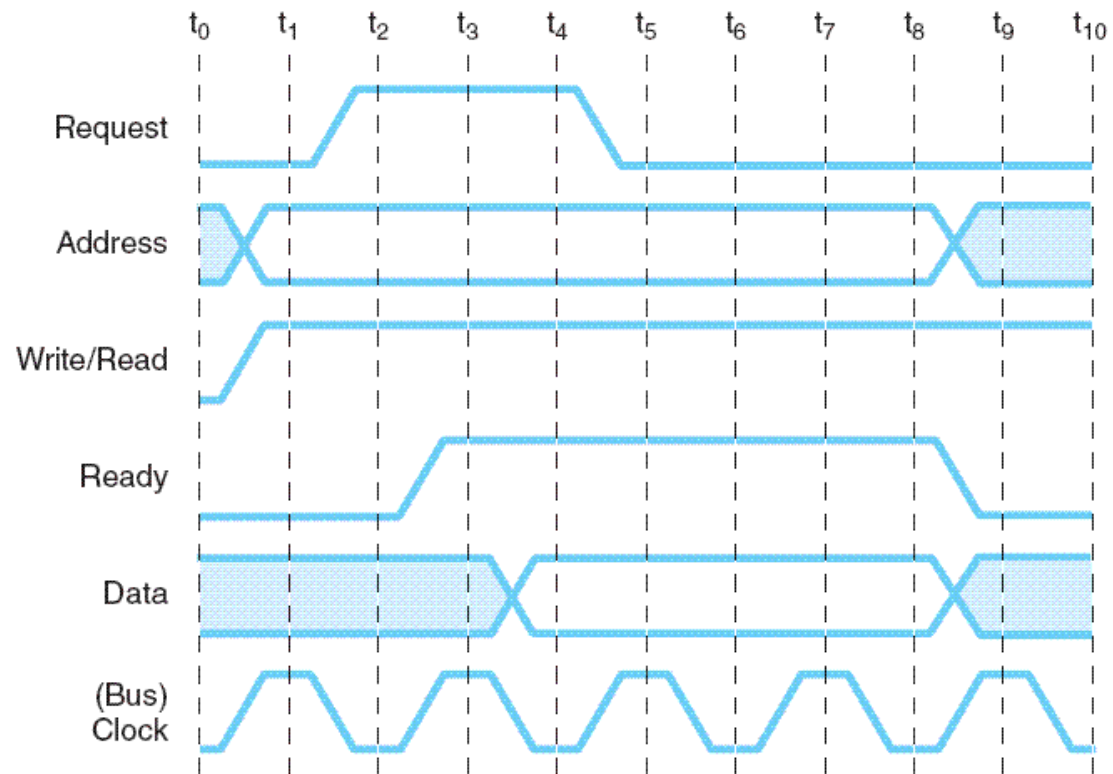


## 7.4 I/O Architectures

This is how a bus connects to a disk drive.



Timing diagrams, such as this one, define bus operation in detail.

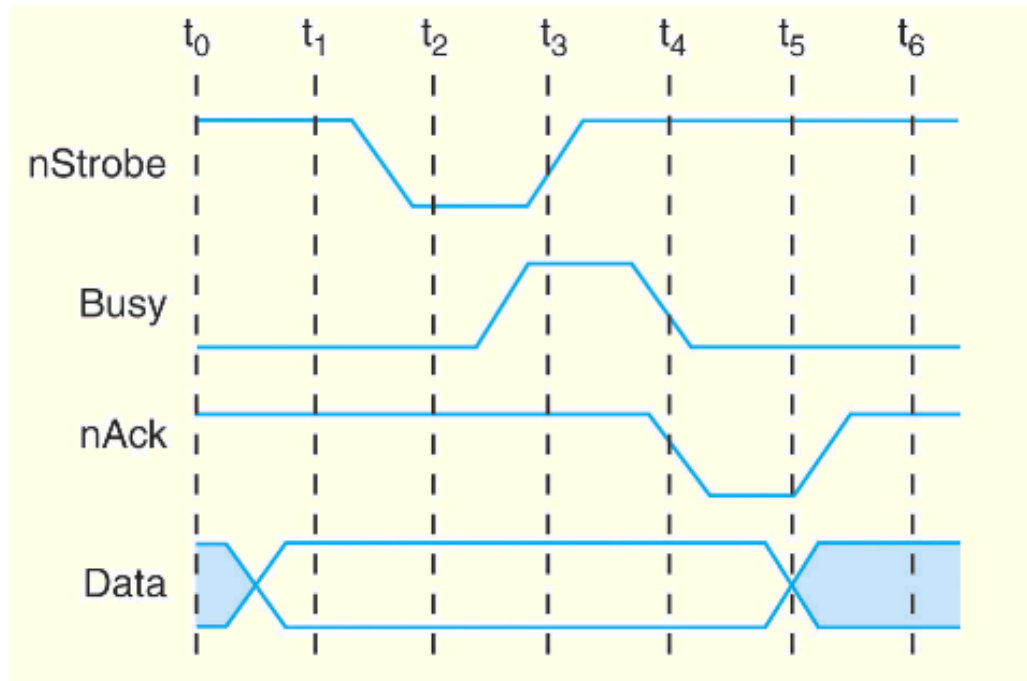


Time	Salient Bus Signal	Meaning
$t_0$	Assert Write	Bus is needed for writing (not reading)
$t_1$	Assert Address	Indicates where bytes will be written
$t_2$	Assert Request	Request write to address on address lines
$t_3$	Assert Ready	Acknowledges write request, bytes placed on data lines
$t_4$ – $t_7$	Data Lines	Write data (requires several cycles)
$t_8$	Lower Ready	Release bus

## 7.5 Data Transmission Modes

- Bytes can be conveyed from one point to another by sending their encoding signals simultaneously using *parallel data transmission* or by sending them one bit at a time in *serial data transmission*.

- Parallel data transmission for a printer resembles the signal protocol of a memory bus:





## 7.5 Data Transmission Modes

- In **parallel data transmission**, the interface requires **one conductor for each bit**.
- Parallel cables are **fatter** than serial cables.
- Compared with parallel **data interfaces**, serial communications **interfaces**:
  - **Require fewer conductors.**
  - Are **less susceptible to attenuation.**
  - **Can transmit data farther and faster.**

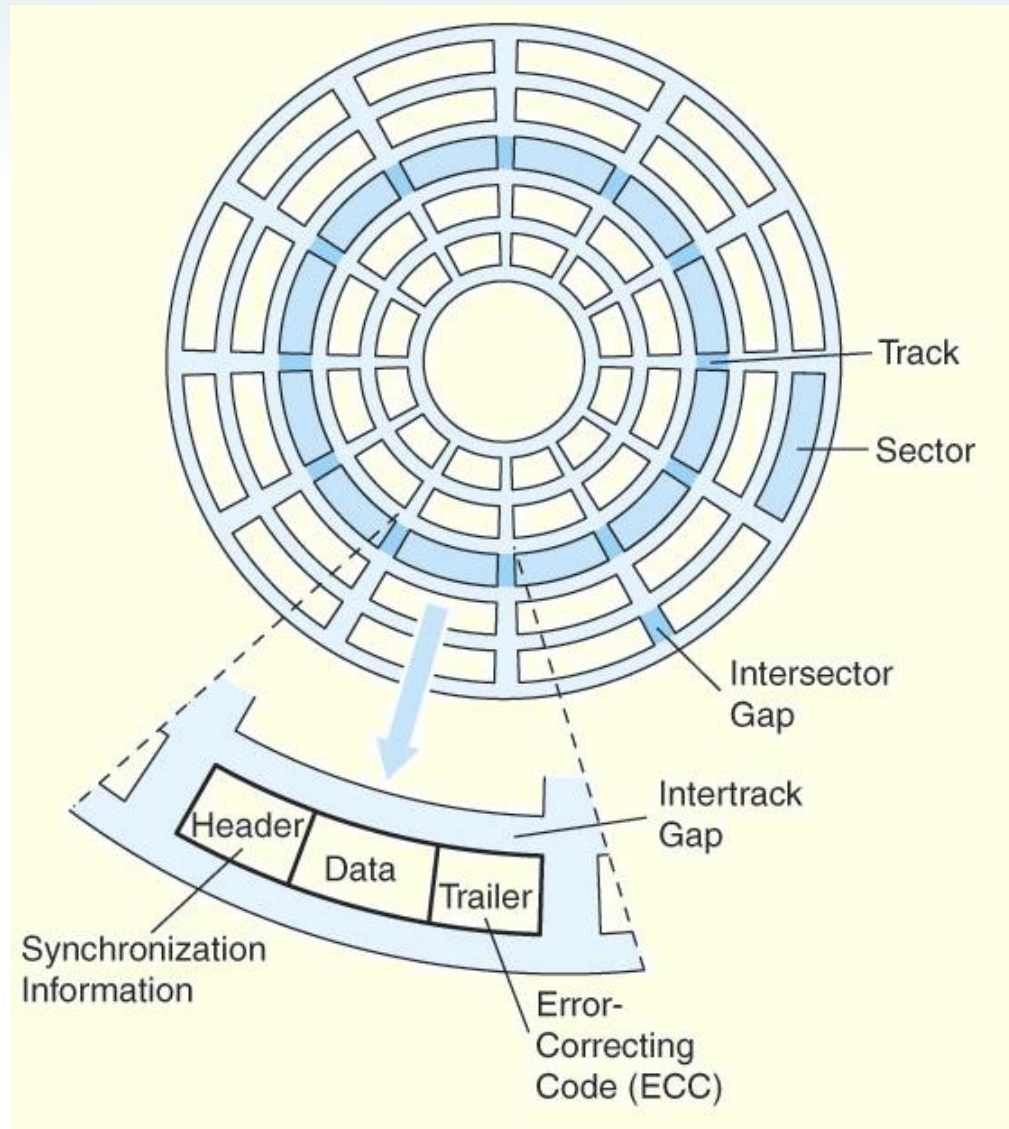
**Serial communications interfaces are **suitable** for time-sensitive (*isochronous*) data **such as voice and video.****

## 7.6 Magnetic Disk Technology

- Magnetic disks offer large amounts of durable storage that can be accessed quickly.
- Disk drives are called *random* (or *direct*) access storage devices, because blocks of data can be accessed according to their location on the disk.
  - This term was coined when all other durable storage (e.g., tape) was sequential.
- Magnetic disk organization is shown on the following slide.

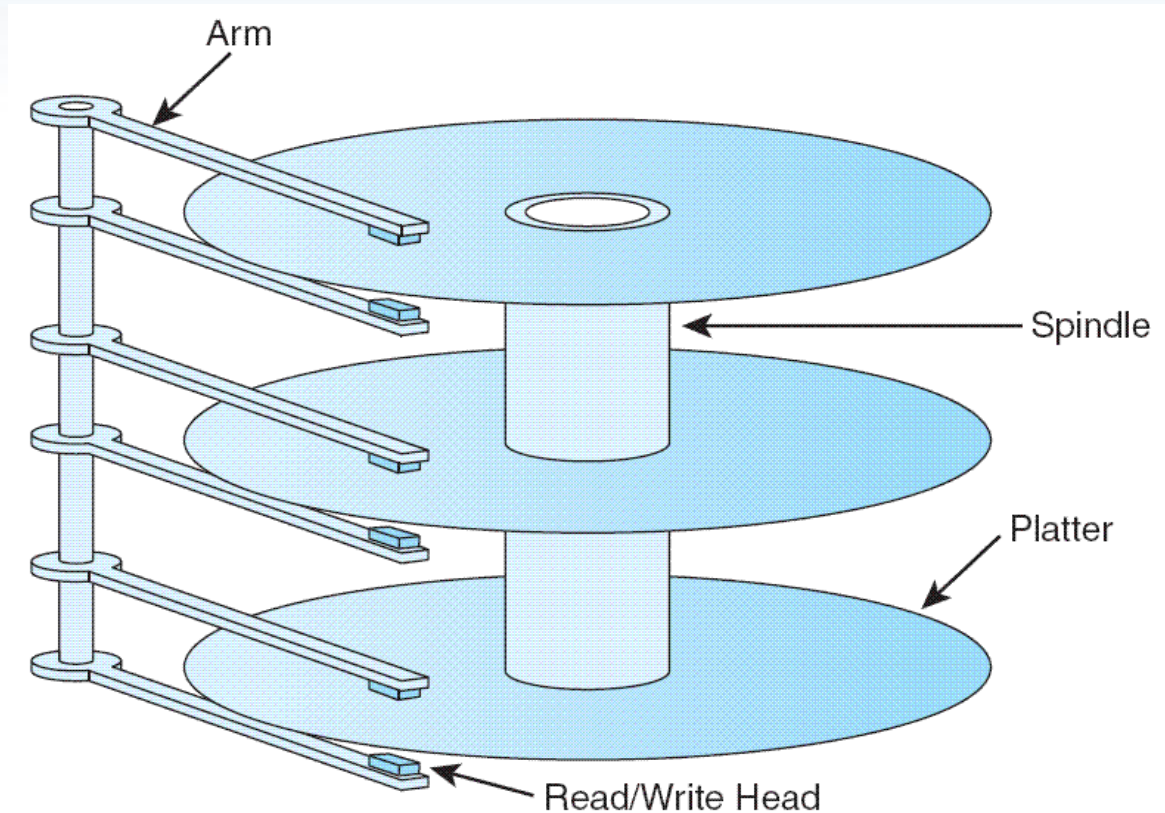
# 7.6 Magnetic Disk Technology

Disk tracks are numbered from the outside edge, starting with zero.



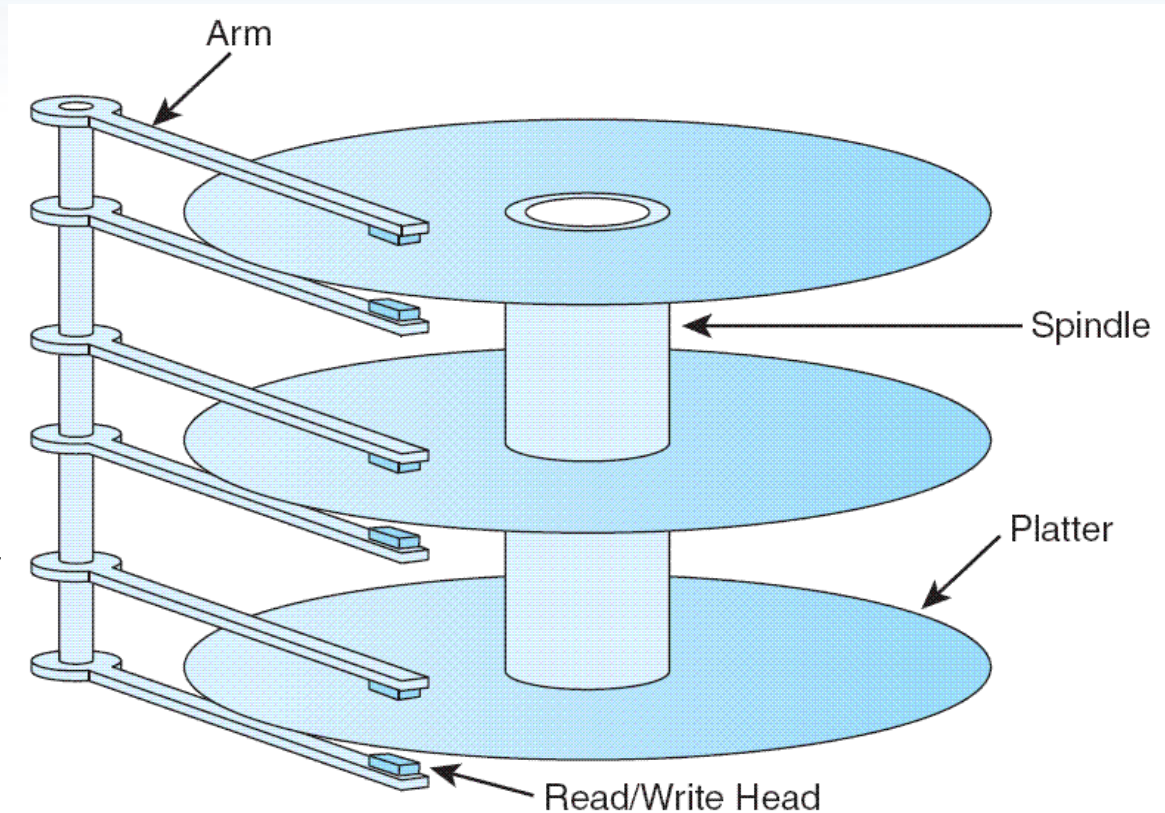
## 7.6 Magnetic Disk Technology

- **Hard disk platters** are mounted on spindles.
- **Read/write heads** are mounted on a comb that swings radially to read the disk.



## 7.6 Magnetic Disk Technology

- The rotating disk forms a logical cylinder beneath the read/write heads.
- Data blocks are addressed by their cylinder, surface, and sector.



## 7.6 Magnetic Disk Technology

- There are a number of electromechanical properties of hard disk drives that determine how fast its data can be accessed.
- *Seek time* is the time that it takes for a disk arm to move into position over the desired cylinder.
- *Rotational delay* is the time that it takes for the desired sector to move into position beneath the read/write head.
- $\text{Seek time} + \text{rotational delay} = \text{access time}$ .



## 7.6 Magnetic Disk Technology

- *Transfer rate* gives us the rate at which data can be read from the disk.
- *Average latency* is a function of the rotational speed:
$$\frac{\frac{60 \text{ seconds}}{\text{disk rotation speed}} \times \frac{1000 \text{ ms}}{\text{second}}}{2}$$
- *Mean Time To Failure* (MTTF) is a statistically-determined value often calculated experimentally.
  - It usually doesn't tell us much about the actual expected life of the disk. *Design life* is usually more realistic.

**Figure 7.15 in the text shows a sample disk specification.**

## 7.6 Magnetic Disk Technology

- **Low cost** is the major advantage of hard disks.
- But their limitations include:
  - **Very slow compared** to main memory
  - **Fragility**
  - **Moving parts** wear out
- **Reductions in memory cost** enable the widespread adoption of **solid state drives, SSDs**.
  - Computers "see" SSDs as just another disk drive, but **they store data in non-volatile *flash* memory** circuits.
  - Flash memory is also found in memory sticks and MP3 players.



## 7.6 Magnetic Disk Technology

- SSD access time and transfer rates are *typically* 100 times faster than magnetic disk, but slower than onboard RAM by a factor of 100,000.
  - These numbers vary widely among manufacturers and interface methods.
- Unlike RAM, flash is block-addressable (like disk drives).
  - The duty cycle of flash is between 30,000 and 1,000,000 updates to a block.
  - Updates are spread over the entire medium through *wear leveling* to prolong the life of the SSD.

## 7.7 Optical Disks

- Optical disks provide large storage capacities very inexpensively.
- They come in a number of varieties including CD-ROM, DVD, and WORM.
- Many large computer installations produce document output on optical disk rather than on paper. This idea is called COLD-- *Computer Output Laser Disk*.
- It is estimated that optical disks can endure for a hundred years. Other media are good for only a decade-- at best.

## 7.7 Optical Disks

- CD-ROMs were designed by the music industry in the 1980s, and later adapted to data.
- This history is reflected by the fact that data is recorded in a single spiral track, starting from the center of the disk and spanning outward.
- Binary ones and zeros are delineated by bumps in the polycarbonate disk substrate. The transitions between pits and lands define binary ones.
- If you could unravel a full CD-ROM track, it would be nearly five miles long!

## 7.7 Optical Disks

- The logical data format for a CD-ROM is much more complex than that of a magnetic disk. (See the text for details.)
- Different formats are provided for data and music.
- Two levels of error correction are provided for the data format.
- Because of this, a CD holds at most 650MB of data, but can contain as much as 742MB of music.

## 7.7 Optical Disks

- DVDs can be thought of as quad-density CDs.
  - Varieties include single sided, single layer, single sided double layer, double sided double layer, and double sided double layer.
- Where a CD-ROM can hold at most 650MB of data, DVDs can hold as much as 17GB.
- One of the reasons for this is that DVD employs a laser that has a shorter wavelength than the CD's laser.
- This allows pits and lands to be closer together and the spiral track to be wound tighter.

## 7.7 Optical Disks

- A shorter wavelength light can read and write bytes in greater densities than can be done by a longer wavelength laser.
- This is one reason that DVD's density is greater than that of CD.
- The 405 nm wavelength of blue-violet light is much shorter than either red (750 nm) or orange (650 nm).
- The manufacture of blue-violet lasers can now be done economically, bringing about the next generation of laser disks.

## 7.7 Optical Disks


- The **Blu-Ray disc** format won market dominance over HD-CD owing mainly to the influence of Sony.
  - HD-CDs are backward compatible with DVD, but hold less data.
- Blu-Ray was developed by a consortium of nine companies that includes Sony, Samsung, and Pioneer.
  - **Maximum capacity** of a single layer Blu-Ray disk is **25GB**.
  - **Multiple layers** can be "stacked" up to **six deep**.
  - Only **double-layer disks** are available for **home use**.

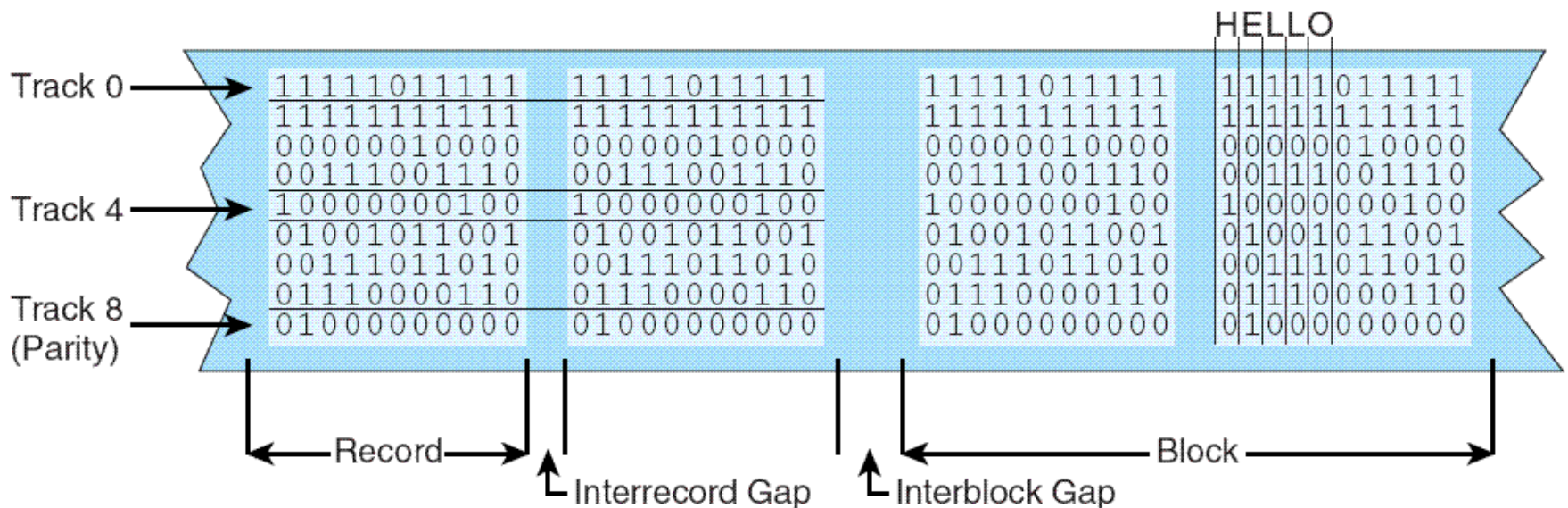
## 7.7 Optical Disks

- Blue-violet laser disks are also used in the data center.
- The intention is to provide a means for long term data storage and retrieval.
- Two types are now dominant:
  - Sony's Professional Disk for Data (PDD) that can store 23GB on one disk and
  - Plasmon's Ultra Density Optical (UDO) that can hold up to 30GB.
- It is too soon to tell which of these technologies will emerge as the winner.



## 7.8 Magnetic Tape

- **First-generation** magnetic tape was not much more than **wide analog recording tape**, having capacities under **11MB**.
- Data was usually written in **nine vertical tracks**: 

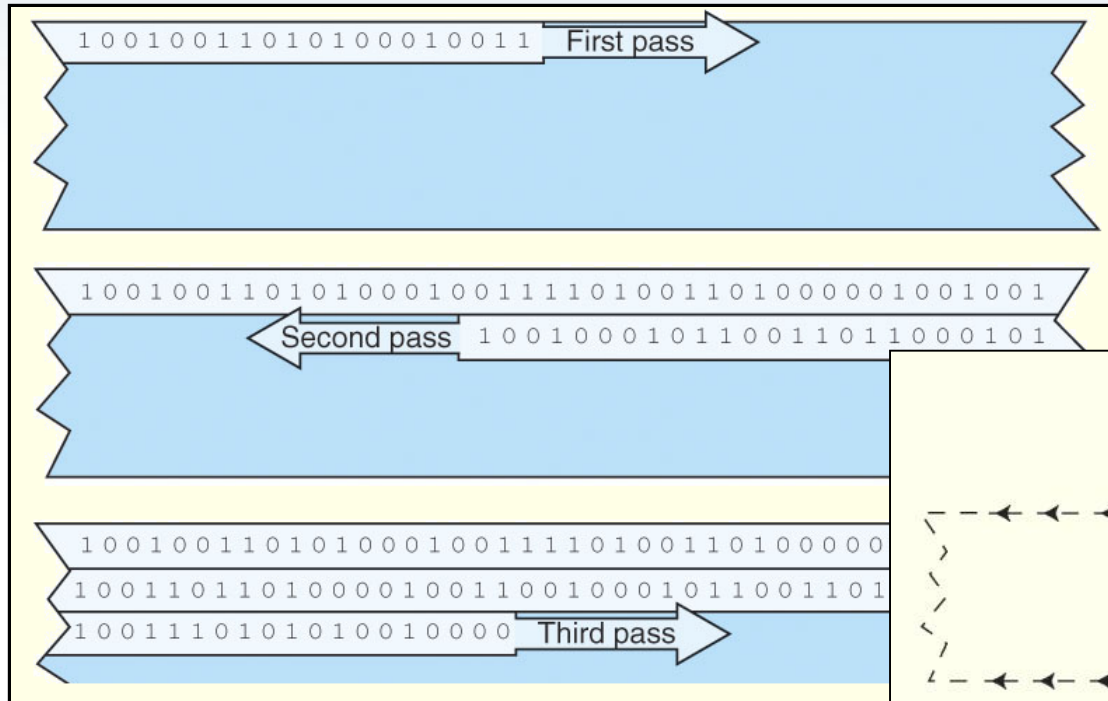


## 7.8 Magnetic Tape

- Today's tapes are digital, and provide multiple gigabytes of data storage.
- Two dominant recording methods are *serpentine* and *helical scan*, which are distinguished by how the read-write head passes over the recording medium.
- Serpentine recording is used in *digital linear tape* (DLT) and *Quarter inch cartridge* (QIC) tape systems.
- *Digital audio tape* (DAT) systems employ helical scan recording.

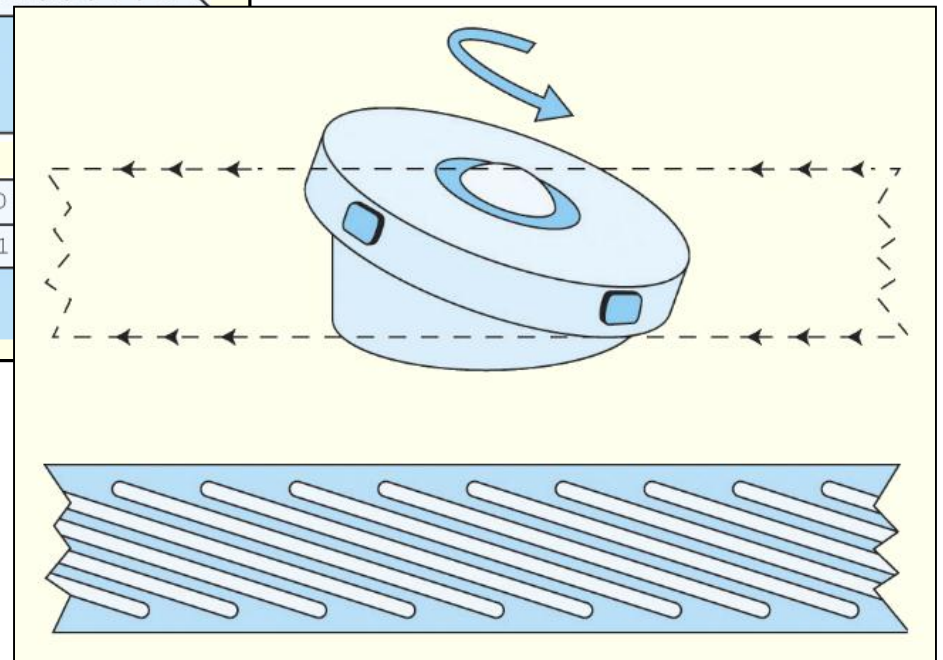
**These two recording methods are shown on the next slide.**

# 7.8 Magnetic Tape



← **Serpentine**

**Helical Scan →**



## 7.8 Magnetic Tape

- Numerous incompatible tape formats emerged over the years.
  - Sometimes even different models of the same manufacturer's tape drives were incompatible!
- Finally, in 1997, HP, IBM, and Seagate collaboratively invented a best-of-breed tape standard.
- They called this new tape format *Linear Tape Open* (LTO) because the specification is openly available.

## 7.8 Magnetic Tape

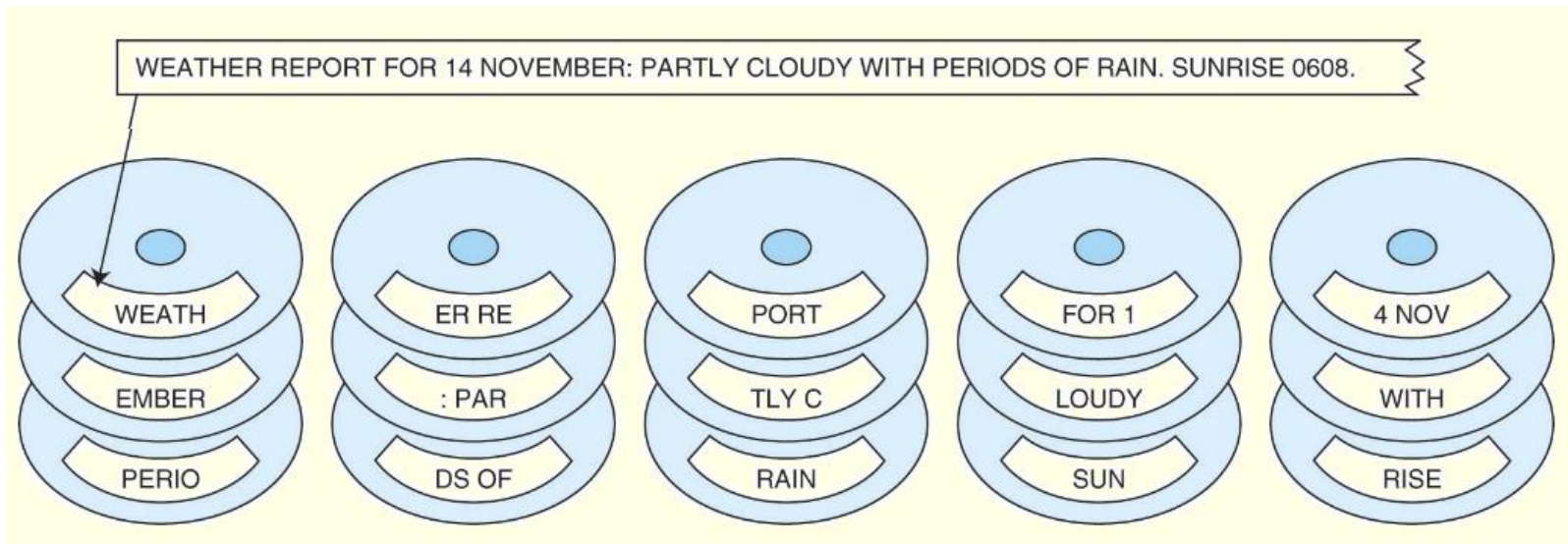
- LTO, as the name implies, is a linear digital tape format.
- The specification allowed for the refinement of the technology through four “generations.”
- Generation 5 was released in 2010.
  - Without compression, the tapes support a transfer rate of 208MB per second and each tape can hold up to 1.4TB.
- LTO supports several levels of error correction, providing superb reliability.
  - Tape has a reputation for being an error-prone medium.

## 7.9 RAID

- RAID, an acronym for *Redundant Array of Independent Disks* was invented to address problems of disk reliability, cost, and performance.
- In RAID, data is stored across many disks, with extra disks added to the array to provide error correction (redundancy).
- The inventors of RAID, David Patterson, Garth Gibson, and Randy Katz, provided a RAID taxonomy that has persisted for a quarter of a century, despite many efforts to redefine it.

# 7.9 RAID

- **RAID Level 0**, also known as *drive spanning*, provides improved performance, but no redundancy.
  - Data is written in blocks across the entire array

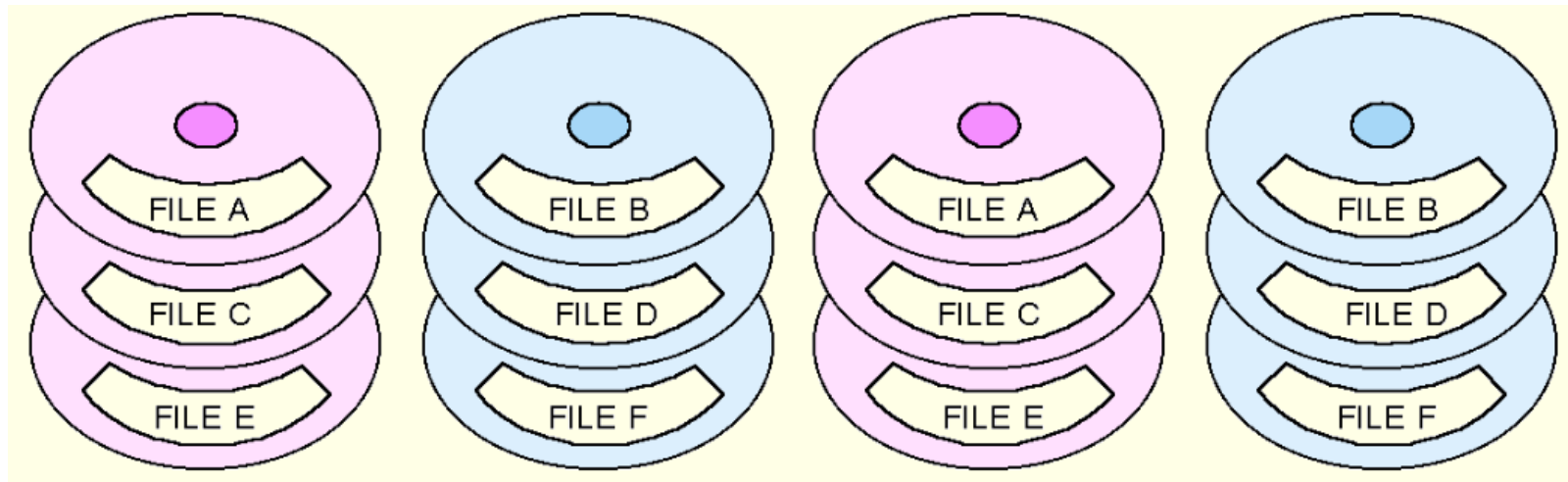


- The **disadvantage** of RAID 0 is in its **low reliability**.



# 7.9 RAID

- **RAID Level 1**, also known as *disk mirroring*, provides **100% redundancy, and good performance.**
  - **Two matched sets of disks contain the same data.**

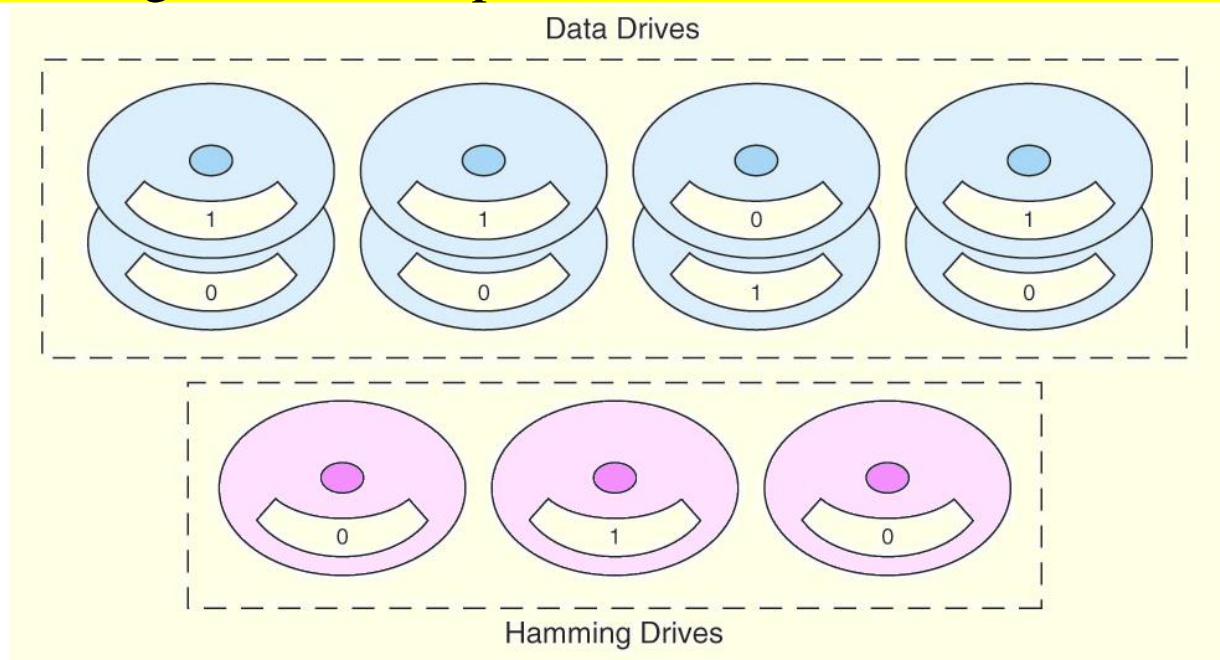


- The **disadvantage** of RAID 1 is cost.



# 7.9 RAID

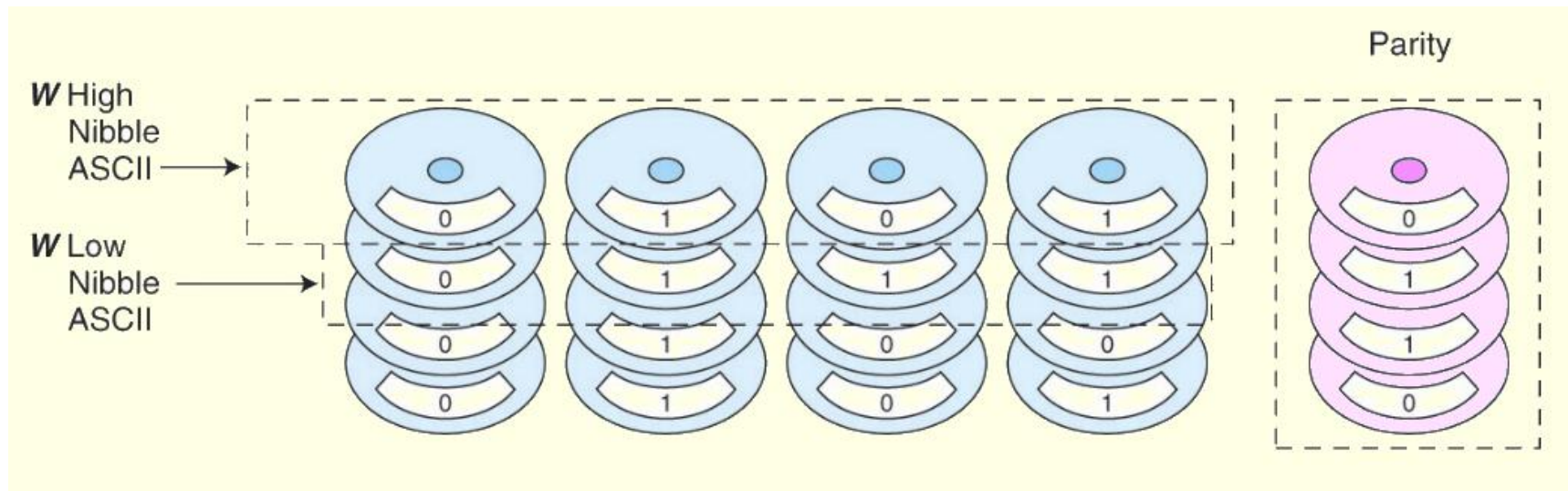
- A RAID Level 2 configuration consists of a set of data drives, and a set of Hamming code drives.
  - Hamming code drives provide error correction for the data drives.



- RAID 2 performance is poor and the cost is relatively high.

## 7.9 RAID

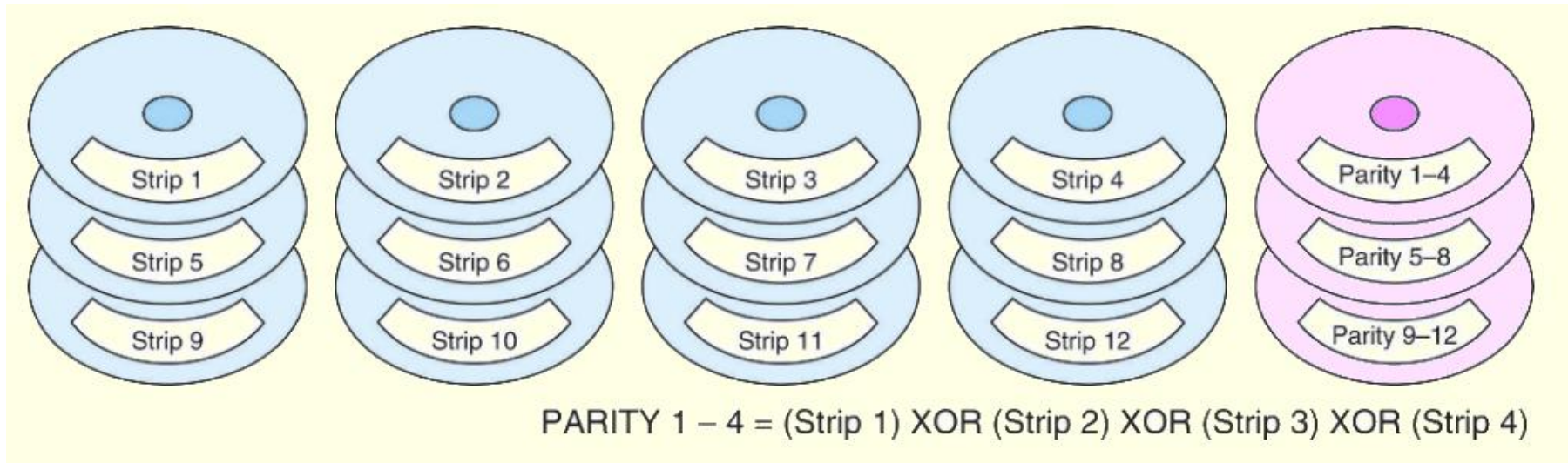
- RAID Level 3 stripes bits across a set of data drives and provides a separate disk for parity.
  - Parity is the XOR of the data bits.



- RAID 3 is not suitable for commercial applications, but is good for personal systems.

# 7.9 RAID

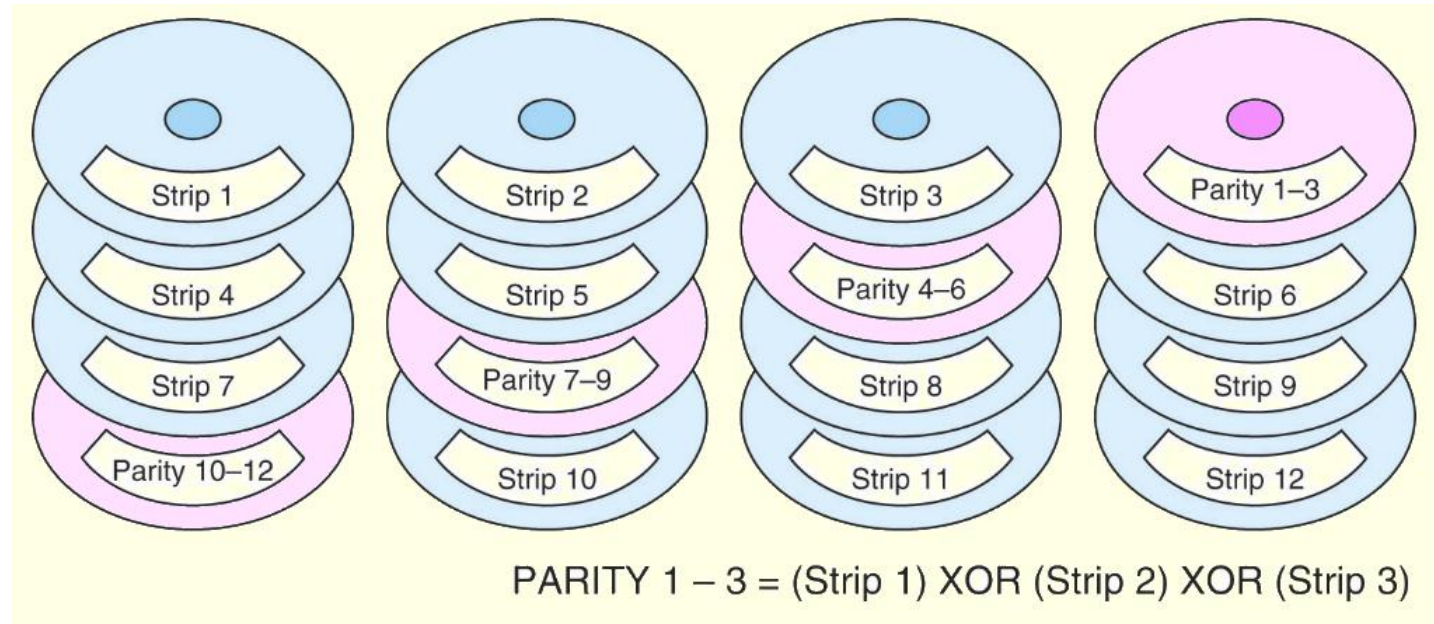
- RAID Level 4 is like adding parity disks to RAID 0.
  - Data is written in blocks across the data disks, and a parity block is written to the redundant drive.



- RAID 4 would be feasible if all record blocks were the same size.

# 7.9 RAID

- **RAID Level 5** is RAID 4 with distributed parity.
  - With **distributed parity**, some accesses can be serviced concurrently, giving good performance and high reliability.

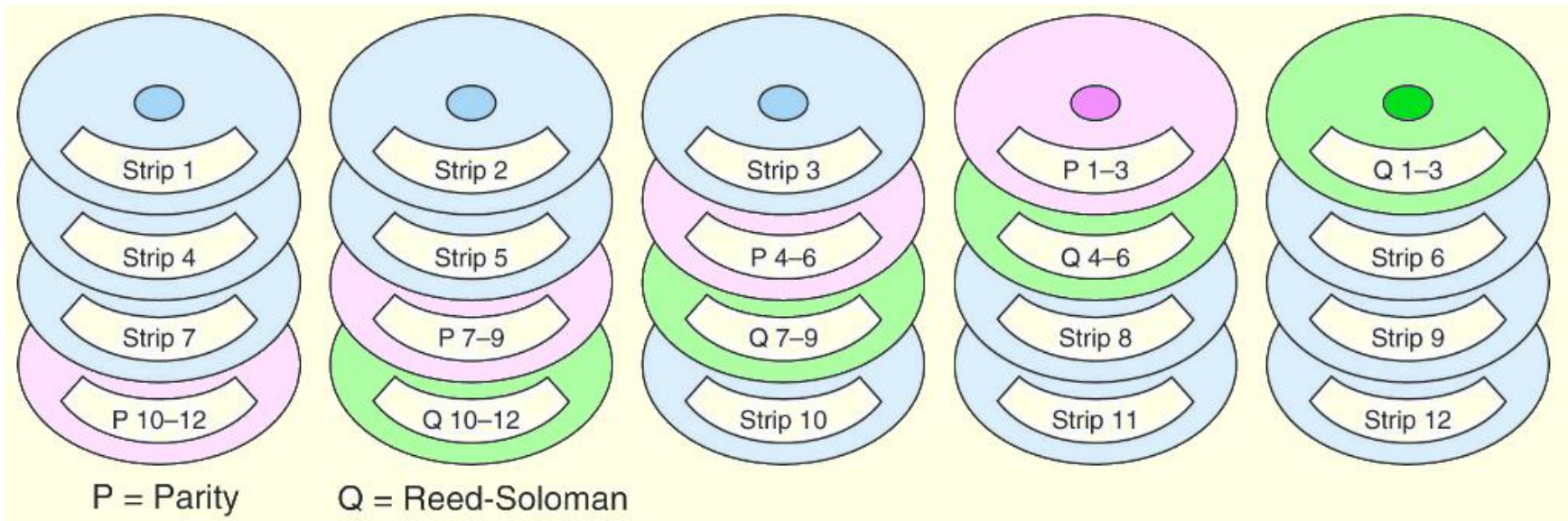


- RAID 5 is **used in many commercial systems.**



# 7.9 RAID

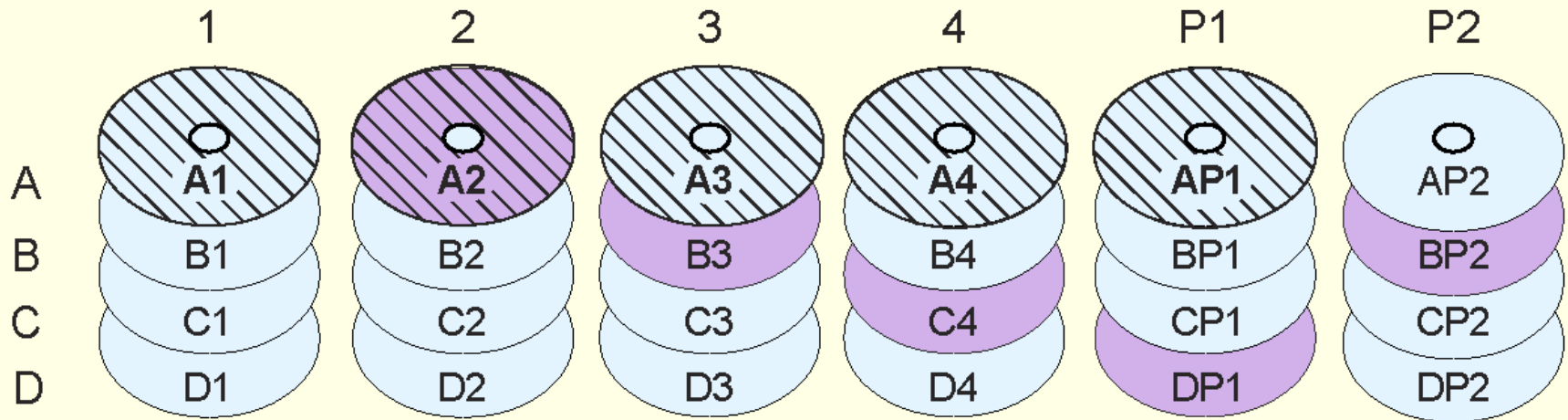
- RAID Level 6 carries two levels of error protection over striped data: Reed-Soloman and parity.
  - It can tolerate the loss of two disks.



- RAID 6 is write-intensive, but highly fault-tolerant.

# 7.9 RAID

- **Double parity RAID** (RAID DP) employs **pairs of overlapping parity blocks** that provide **linearly independent parity functions**.



$$\begin{aligned}AP1 &= A1 \oplus A2 \oplus A3 \oplus A4 \\BP1 &= B1 \oplus B2 \oplus B3 \oplus B4 \\CP1 &= C1 \oplus C2 \oplus C3 \oplus C4 \\DP1 &= D1 \oplus D2 \oplus D3 \oplus D4\end{aligned}$$

$$\begin{aligned}AP2 &= A1 \oplus B2 \oplus C3 \oplus D4 \\BP2 &= A2 \oplus B3 \oplus C4 \oplus DP1 \\CP2 &= A3 \oplus B4 \oplus CP1 \oplus D1 \\DP2 &= A4 \oplus BP1 \oplus C1 \oplus D2\end{aligned}$$

## 7.9 RAID

- Like RAID 6, RAID DP can tolerate the loss of two disks.
- The use of simple parity functions provides RAID DP with better performance than RAID 6.
- Of course, because two parity functions are involved, RAID DP's performance is somewhat degraded from that of RAID 5.
  - RAID DP is also known as EVENODD, diagonal parity RAID, RAID 5DP, advanced data guarding RAID (RAID ADG) and-- erroneously-- RAID 6.

## 7.9 RAID

- Large systems consisting of many drive arrays may employ various RAID levels, depending on the criticality of the data on the drives.
  - A disk array that provides program workspace (say for file sorting) does not require high fault tolerance.
- Critical, high-throughput files can benefit from combining RAID 0 with RAID 1, called RAID 10.
- Keep in mind that a higher RAID level does not necessarily mean a “better” RAID level. It all depends upon the needs of the applications that use the disks.



## 7.10 The Future of Data Storage

- Advances in technology have defied all efforts to define the ultimate upper limit for magnetic disk storage.
  - In the 1970s, the upper limit was thought to be around 2Mb/in<sup>2</sup>.
  - Today's disks commonly support 20Gb/in<sup>2</sup>.
- Improvements have occurred in several different technologies including:
  - Materials science
  - Magneto-optical recording heads.
  - Error correcting codes.

## 7.10 The Future of Data Storage

- As data densities increase, bit cells consist of proportionately fewer magnetic grains.
- There is a point at which there are too few grains to hold a value, and a 1 might spontaneously change to a 0, or vice versa.
- This point is called the superparamagnetic limit.
  - In 2006, the superparamagnetic limit is thought to lie between  $150\text{Gb/in}^2$  and  $200\text{Gb/in}^2$ .
- Even if this limit is wrong by a few orders of magnitude, the greatest gains in magnetic storage have probably already been realized.

## 7.10 The Future of Data Storage

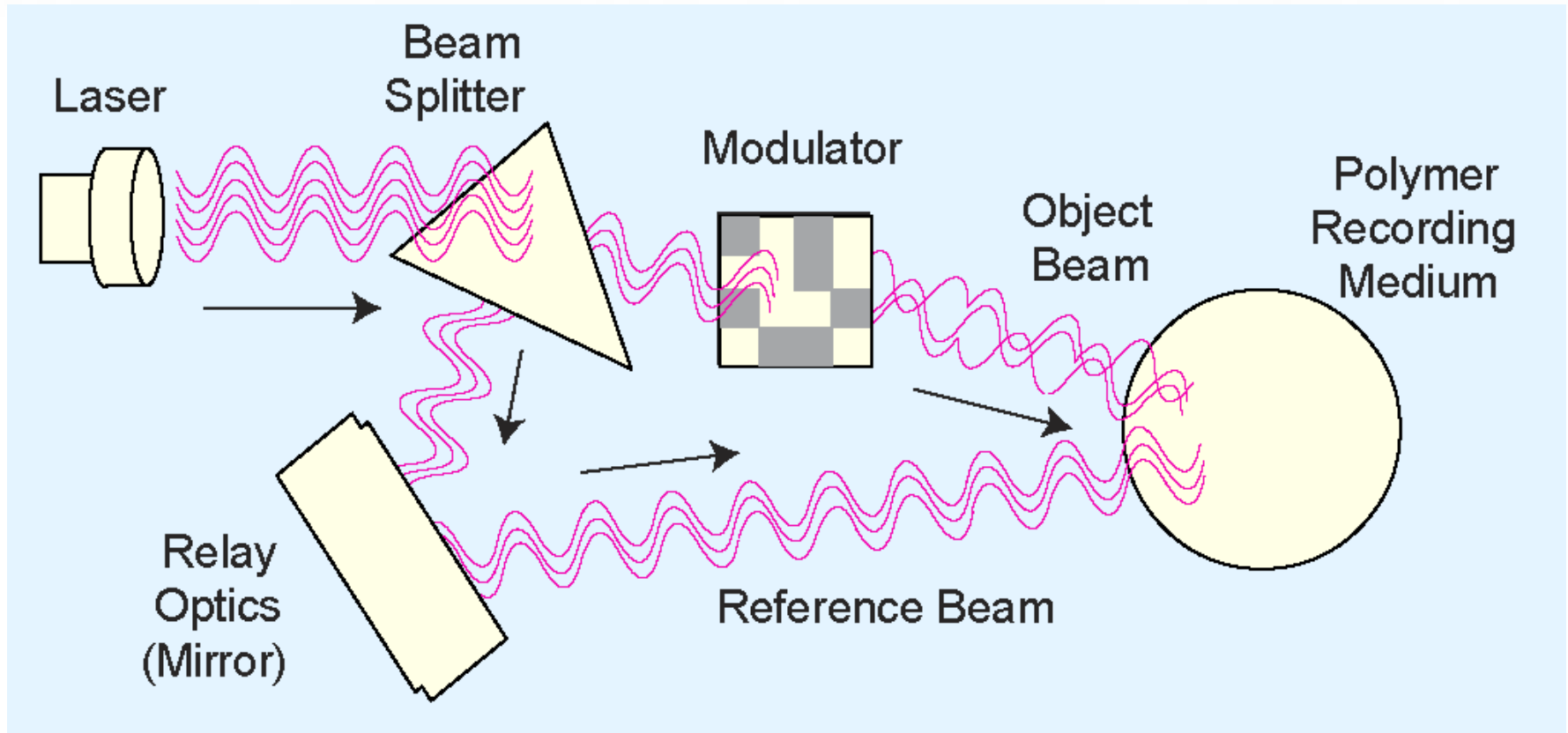
- Future exponential gains in data storage most likely will occur through the use of totally new technologies.
- Research into finding suitable replacements for magnetic disks is taking place on several fronts.
- Some of the more interesting technologies include:
  - Biological materials
  - Holographic systems and
  - Micro-electro-mechanical devices.

## 7.10 The Future of Data Storage

- Present day biological data storage systems combine organic compounds such as proteins or oils with inorganic (magnetizable) substances.
- Early prototypes have encouraged the expectation that densities of 1Tb/in<sup>2</sup> are attainable.
- Of course, the ultimate biological data storage medium is DNA.
  - Trillions of messages can be stored in a tiny strand of DNA.
- Practical DNA-based data storage is most likely decades away.

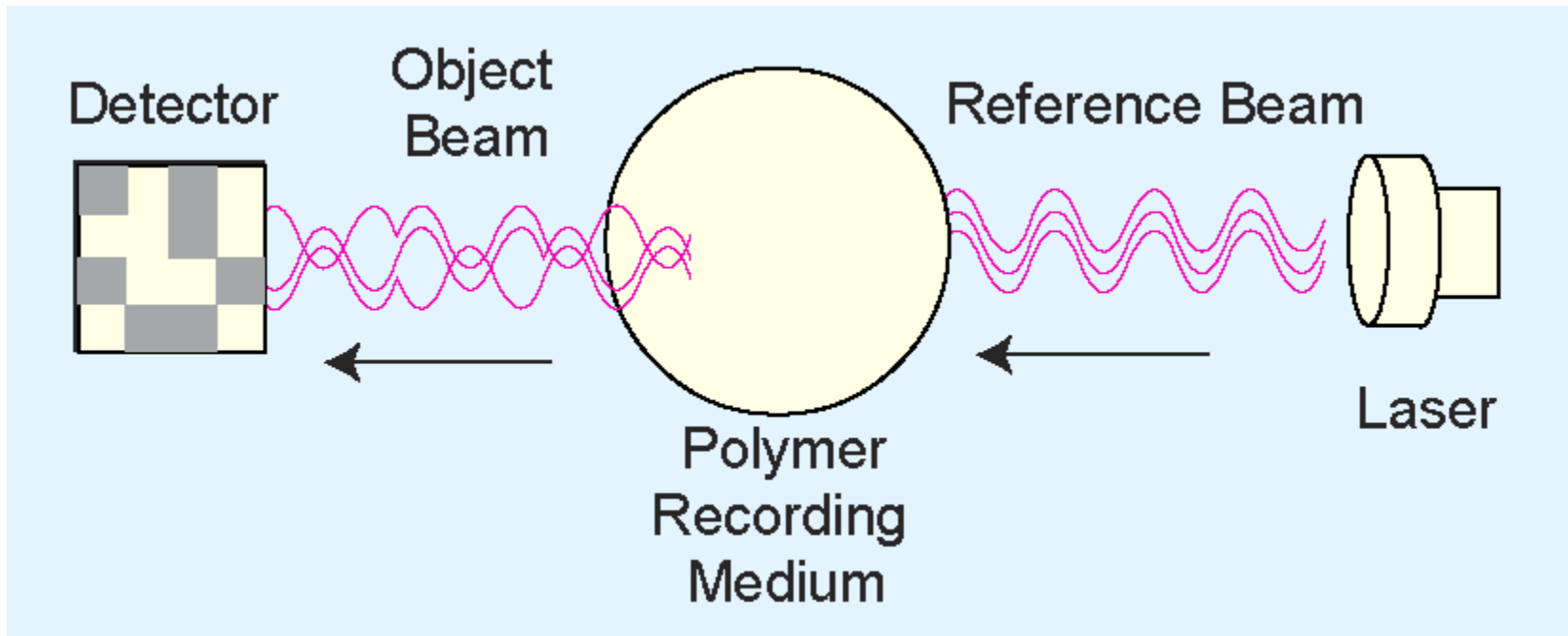
## 7.10 The Future of Data Storage

- Holographic storage uses a pair of laser beams to etch a three-dimensional hologram onto a polymer medium.



## 7.10 The Future of Data Storage

- Data is retrieved by passing the reference beam through the hologram, thereby reproducing the original coded object beam.



## 7.10 The Future of Data Storage

- Because holograms are three-dimensional, tremendous data densities are possible.
- Experimental systems have achieved over 30Gb/in<sup>2</sup>, with transfer rates of around 1GBps.
- In addition, holographic storage is content addressable.
  - This means that there is no need for a file directory on the disk. Accordingly, access time is reduced.
- The major challenge is in finding an inexpensive, stable, rewriteable holographic medium.

## 7.10 The Future of Data Storage

- Micro-electro-mechanical storage (MEMS) devices offer another promising approach to mass storage.
- IBM's Millipede is one such device.
- Prototypes have achieved densities of 100Gb/in<sup>2</sup> with 1Tb/in<sup>2</sup> expected as the technology is refined.

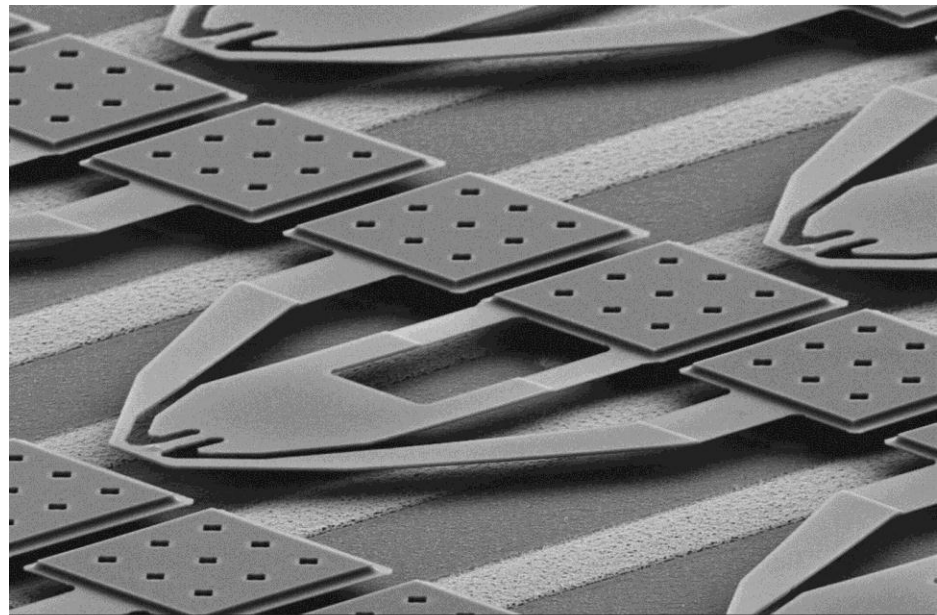
**A photomicrograph of Millipede is shown on the next slide.**



## 7.10 The Future of Data Storage

- Millipede consists of thousands of cantilevers that record a binary 1 by pressing a heated tip into a polymer substrate.
- The tip reads a binary 1 when it dips into the imprint in the polymer

**Photomicrograph courtesy  
of the IBM Corporation.  
© 2005 IBM Corporation**



**H 10 μm**

# Chapter 7 Conclusion

- I/O systems are critical to the overall performance of a computer system.
- Amdahl's Law quantifies this assertion.
- I/O systems consist of memory blocks, cabling, control circuitry, interfaces, and media.
- I/O control methods include programmed I/O, interrupt-based I/O, DMA, and channel I/O.
- Buses require control lines, a clock, and data lines. Timing diagrams specify operational details.

# Chapter 7 Conclusion

- Magnetic disk is the principal form of durable storage.
- Disk performance metrics include seek time, rotational delay, and reliability estimates.
- Optical disks provide long-term storage for large amounts of data, although access is slow.
- Magnetic tape is also an archival medium. Recording methods are track-based, serpentine, and helical scan.

# Chapter 7 Conclusion

- RAID gives disk systems improved performance and reliability. RAID 3 and RAID 5 are the most common.
- RAID 6 and RAID DP protect against dual disk failure, but RAID DP offers better performance.
- Any one of several new technologies including biological, holographic, or mechanical may someday replace magnetic disks.
- The hardest part of data storage may be end up be in locating the data after it's stored.

## End of Chapter 7