Computer Organization and Architecture

Chapter 6

External Memory

Types of External Memory

- Magnetic Disk
  - RAID
  - Removable
- Optical
  - CD-ROM
  - CD-Recordable (CD-R)
  - CD-R/W
  - DVD
- Magnetic Tape
- Flash memories are often used as a “solid-state drives”

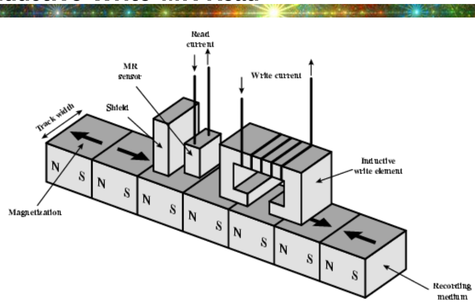
Magnetic Disk

- Disk substrate coated with magnetizable material (iron oxide…rust)
- Substrate used to be aluminium
- Now glass or ceramic
  - Improved surface uniformity
    - Increases reliability
  - Reduction in surface defects
    - Reduced read/write errors
  - Lower flight heights (See later)
  - Better stiffness
  - Better shock/damage resistance

Read and Write Mechanisms

- Recording & retrieval via conductive coil called a head
- May be single read/write head or separate ones
- During read/write, head is stationary, platter rotates
- Write
  - Current through coil produces magnetic field
  - Pulses sent to head
  - Magnetic pattern recorded on surface below
- Read (traditional)
  - Magnetic field moving relative to coil produces current
  - Coil is the same for read and write
- Read (contemporary)
  - Separate read head, close to write head
  - Partially shielded magneto resistive (MR) sensor
  - Electrical resistance depends on direction of magnetic field
  - High frequency operation
    - Higher storage density and speed

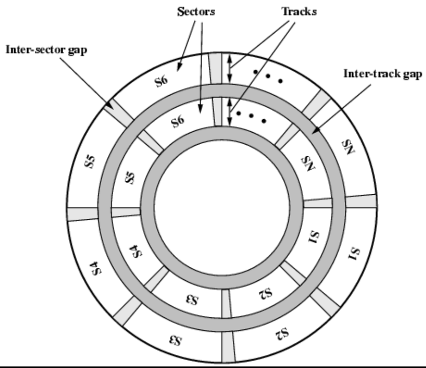
Inductive Write MR Read



Data Organization and Formatting

- Concentric rings or tracks
  - Gaps between tracks
  - Reduce gap to increase capacity
  - Same number of bits per track (variable packing density)
  - Constant angular velocity (rotational speed is constant so linear velocity varies)
- Tracks divided into sectors
- Minimum block size is one sector
- May have more than one sector per block

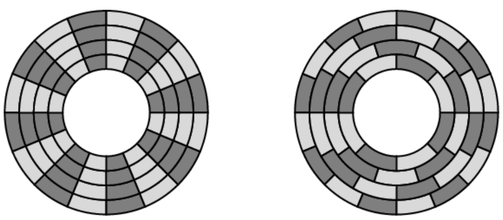
Disk Data Layout



Disk Velocity

- Bit near center of rotating disk passes fixed point slower than bit on outside of disk
- Increased spacing between bits in outer tracks compared to inner
- Rotate disk at constant angular velocity (CAV)
  - Gives pie shaped sectors and concentric tracks
  - Individual tracks and sectors addressable
  - Move head to given track and wait for given sector
  - Waste of space on outer tracks
    - Lower data density
- Can use zones to increase capacity (typical 16)
  - Each zone has fixed bits per track
  - More complex circuitry
  - Common on modern disks

Disk Layout Methods



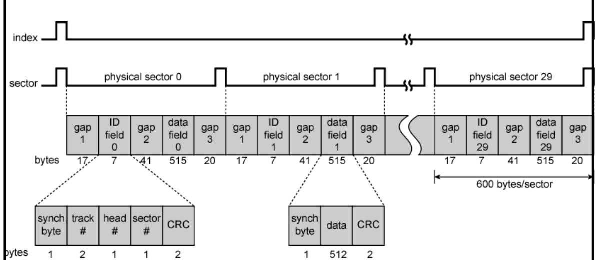
(a) Constant angular velocity

(b) Multiple zoned recording

Finding Sectors

- Must be able to identify start of track and sector
- Format disk
  - Additional information not available to user
  - Marks tracks and sectors

Winchester Disk Format
Seagate ST506



Characteristics

- Fixed (rare) or movable head
- Disk is removable or fixed
- Single or double (usually) sided
- Single or multiple platter
- Head mechanism
  - Contact (Floppy)
  - Fixed gap
  - Flying (Winchester)

Fixed/Movable Head Disk

- Fixed head
  - One read write head per track
  - Heads mounted on fixed ridged arm
- Movable head
  - One read write head per side
  - Mounted on a movable arm

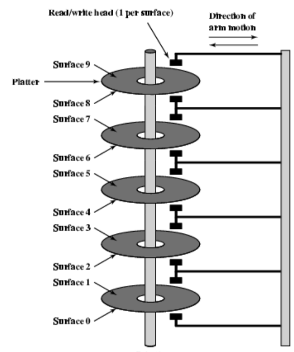
Removable or Not

- Removable disk
  - Can be removed from drive and replaced with another disk
  - Provides unlimited storage capacity
  - Easy data transfer between systems
- Nonremovable disk
  - Permanently mounted in the drive

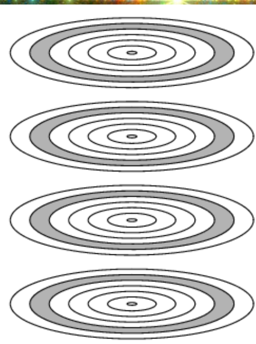
Multiple Platters

- One head per side
- Heads are joined and aligned
- Aligned tracks on each platter form cylinders
- Data is striped by cylinder
  - reduces head movement
  - Increases speed (transfer rate)

Multiple Platters



Tracks and Cylinders



Floppy Disk

- 8” (175kb), 5.25” (360kb/720kb), 3.5”(1440kb, 2880kb)
- Small capacity
  - Aside: 3.5” are almost always described as 1.44Mb but they are really 1.40625Mb
- Slow, cheap, universal, almost obsolete
- With Windows 2000 Microsoft modified the floppy driver to be much faster (and also much less reliable)
- Omitted from most current computers
- To access old data floppy drives can be attached through USB ports

Winchester Hard Disk (1)

- Developed by IBM in Winchester (USA)
- Sealed unit
- One or more platters (disks)
- Heads fly on boundary layer of air as disk spins, rest on disk when power off
- Very small head to disk gap
- Getting more robust
  - Automatic correction of errors, remapping of bad sectors

Winchester Hard Disk (2)

- Universal
- Cheap
- Fastest external storage
- Getting larger all the time
  - Hundreds of gigabytes now easily available

Speed

- Seek time
  - Time to move head to correct track
  - Typically < 10ms today
- (Rotational) latency
  - Waiting for data to rotate under head
  - Speeds of 3,600 to 15,000 rpm common
  - Floppies 300-600 rpm
- Access time = Seek + Latency
- Transfer rate
- Operating system queuing adds additional time

Transfer Time and Rates

- Transfer time T = b / rN

  b = bytes to transfer, r = revolutions/sec, N = number of bytes/track

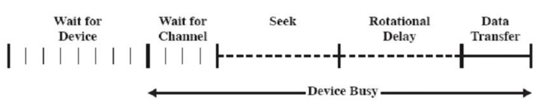
- Average access time T_a

  $T_a = T_s + 1/2r + b/rN$

  Where T_s is average seek time

Operating system queuing

- Operating system queuing adds additional time
- But queues increase overall I/O throughput



Disk scheduling algorithms

- Improve performance with efficient scheduling
- Covered in Operating Systems
- Examples:
  - Shortest Seek Time First
  - SCAN head continually moves innermost to outermost and back to center

Rotational Position Sensing

- Used in servers
- Channel released when seek command issued
- Device attempts to reestablish communication when seek is complete

Typical Specs (Now a bit old...)

Characteristics	Seagate Barracuda ES.2	Seagate Barracuda 7200.10	Seagate Barracuda 7200.9	Seagate	Hitachi Microdrive
Application	High-capacity server	High-performance desktop	Entry-level desktop	Laptop	Handheld devices
Capacity	1 TB	750 GB	160 GB	120 GB	8 GB
Minimum track-to-track seek time	0.8 ms	0.3 ms	1.0 ms	—	1.0 ms
Average seek time	8.5 ms	3.6 ms	9.5 ms	12.5 ms	12 ms
Spindle speed	7200 rpm	7200 rpm	7200	5400 rpm	3600 rpm
Average rotational delay	4.16 ms	4.16 ms	4.17 ms	5.6 ms	8.33 ms
Maximum transfer rate	3 GB/s	300 MB/s	300 MB/s	150 MB/s	10 MB/s
Bytes per sector	512	512	512	512	512
Tracks per cylinder (number of platter surfaces)	8	8	2	8	2

For more detailed information...

- See
  http://www.pcguide.com/ref/hdd/index.htm

RAID

- Two interpretations of acronym:
  - Redundant Array of Independent Disks
  - Redundant Array of Inexpensive Disks
  - 2nd interpretation probably more common
- 7 levels defined
  - NOT a hierarchy
  - Levels 2 and 4 not implemented in practice
- 3 principles in common:
  - Set of physical disks viewed as single logical drive by O/S
  - Data distributed across physical drives
  - Can use redundant capacity to store parity information for error detection and correction

Why RAID?

- Improve I/O throughput through parallelism
- Improve recoverability
  - Note that multiple devices actually decreases the reliability of a system
  - Disks are independent, so probability of failure is the sum of the individual probabilities

Overview of RAID Levels

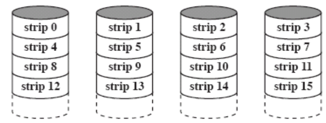
Category	Level	Description	Disks required	Data availability	Large I/O data transfer capacity	Small I/O request rate
Striping	0	Nonredundant	N	Lower than single disk	Very high	Very high for both read and write
Mirroring	1	Mirrored	$2N$, $3N$, etc.	Higher than RAID 2, 3, 4, or 5; lower than RAID 6	Higher than single disk for read; similar to single disk for write	Up to twice that of a single disk for read; similar to single disk for write
Parallel access	2	Redundant via Hamming code	$N + m$	Much higher than single disk; higher than RAID 3, 4, or 5	Highest of all listed alternatives	Approximately twice that of a single disk
	3	Bit-interleaved parity	$N + 1$	Much higher than single disk; comparable to RAID 2, 4, or 5	Highest of all listed alternatives	Approximately twice that of a single disk
Independent access	4	Block-interleaved parity	$N + 1$	Much higher than single disk; comparable to RAID 2, 3, or 5	Similar to RAID 0 for read; significantly lower than single disk for write	Similar to RAID 0 for read; significantly lower than single disk for write
	5	Block-interleaved distributed parity	$N + 1$	Much higher than single disk; comparable to RAID 2, 3, or 4	Similar to RAID 0 for read; lower than single disk for write	Similar to RAID 0 for read; generally lower than single disk for write
	6	Block-interleaved dual distributed parity	$N + 2$	Highest of all listed alternatives	Similar to RAID 0 for read; lower than RAID 5 for write	Similar to RAID 0 for read; significantly lower than RAID 5 for write

I/O Transfer Rate and I/O Request Rate

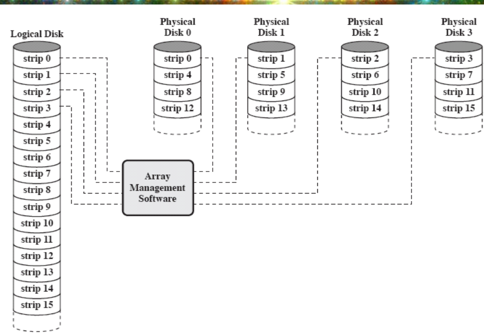
- Note the last two columns in table
  - Transfer Rate and I/O Request Rate are not the same!
  - High transfer rate useful when large blocks of data have to read (or written); e.g., large database
  - Ability to satisfy high I/O request rate useful when many small independent requests have to satisfied; e.g., web server, mail server, database server, multi-user computing, other transaction-oriented environments

RAID 0

- No redundancy
- Appears as logical disk on which all data is stored: an abstraction of the real disk(s)
- Data is placed in segments called *strips*
  - A *stripe* is all of the strips at the same location on all of the disks
  - Strips are placed on disks in round-robin:



RAID 0 Logical to Physical Mapping



RAID 0 Performance

- Depends on
  - High transfer capacity on entire path to memory
  - Application data requests need to drive I/O efficiently, either:
    - Large requests for logically contiguous data that can be satisfied by parallel access to different disks, or
    - Many small requests, each of which requires access to a single strip of a disk
  - Strip size has to be balanced with typical I/O patterns
  - Depends on whether you want large transfer capacity or high I/O request rate

Raid 0 Request Patterns

- Transfer capacity increases:
  - When the strip size is smaller than a single request, and requests are made for contiguous data, so that a single request is handled by multiple disks (in parallel)
- Request Rate
  - Multiple data requests probably not on same disk so provides increased request rate
  - Strip size should be larger than average request size

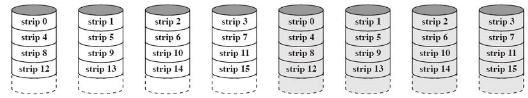
Redundancy

- RAID 0 does not provide redundant storage
- RAID 1 provides redundant storage in the simplest form: data is duplicated on mirrored disks
- RAID 2-6 provide redundancy through parity calculations

RAID 1

- Mirrored Disks
- Data is (usually) striped across disks
  - Each logical stripe mapped to 2 disks
- Read from either
- Write to both
- Recovery is simple
  - Swap faulty disk & re-mirror
  - No down time
- Relatively expensive: double disks

RAID 1 Layout



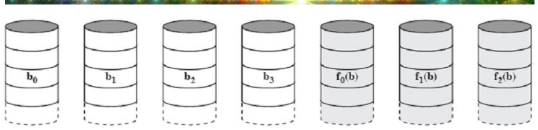
RAID 1 Pros and Cons

- Expensive (2 disks per logical disk)
  - usually used for system or other highly critical data only
- Can achieve very high transfer rates (2 x RAID0) in transaction-oriented environment but only if most requests are Reads
- Write are limited to the slower of the two drives

RAID 2

- Parallel access across all disks for each I/O request
  - Requires synchronized disks and specialized controllers
- Very small strips, single byte/word
  - Data split at bit level across disks
- Error correction calculated across corresponding bits on disks
  - Multiple parity disks store Hamming code error correction in corresponding positions
- Lots of redundancy
  - Expensive
  - No longer used; most disks incorporate ECC already

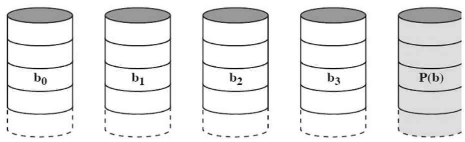
RAID 2 Layout



RAID 3

- Similar to RAID 2, but only one redundant disk, no matter how large the array
- Data is striped at the byte level; a block of data has parts written to each drive
- Simple parity bit for each set of corresponding bits
- Data on failed drive can be reconstructed from surviving data and parity info
- Very high transfer rates, but low I/O request rates (1 at a time, because all disks are involved in each I/O)
- RAID 3 is not common; poor I/O request performance

RAID 3 Layout

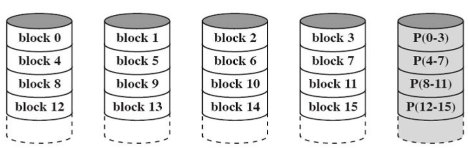


(a) RAID 3 (bit-interleaved parity)

RAID 4

- Each disk operates independently
- Good for high I/O request rate
- Large strips (e.g., 16k or 32k)
- Bit by bit parity calculated across stripes on each disk
- Parity stored on parity disk
- Poor write performance on small requests
- The single parity drive is a bottleneck

RAID 4 Layout

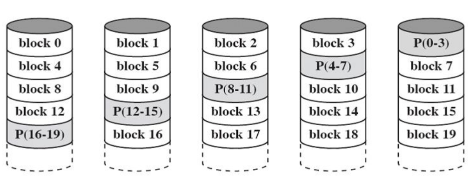


(b) RAID 4 (block-level parity)

RAID 5

- One of the most widely used RAID schemes
- Similar to RAID 4, but parity striped across ALL disks
- Round robin allocation for parity stripe
- Avoids RAID 4 bottleneck at parity disk
- Commonly used in network servers

RAID 5 Layout

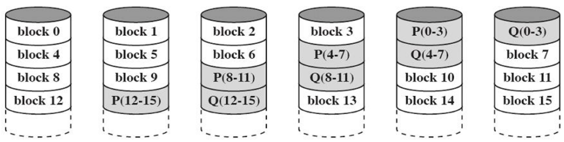


(c) RAID 5 (block-level distributed parity)

RAID 6

- Two parity calculations
- Stored in separate blocks on different disks
- User requirement of N disks needs N+2
- High data availability
  - Three disks need to fail for data loss
  - Significant write penalty
- Rarely used because possibility of multiple simultaneous disk failure is very slim
- Catastrophic events would normally destroy most or all disks

RAID 6 Layout



(d) RAID 6 (dual redundancy)

Other RAID systems

- The list above is not all-inclusive
- Some systems combine levels, for example RAID 0+1
- Some are proprietary, such as RAID 7

RAID Comparison

Level	Advantages	Disadvantages	Applications
0	I/O performance is greatly improved by spreading the I/O load across many channels and drives No parity calculation overhead is involved Very simple design Easy to implement	The failure of just one drive will result in all data in an array being lost	Video production and Editing Image editing Pre-press applications Any application requiring high bandwidth
1	100% redundancy of data means no rebuild is necessary in case of a disk failure, just a copy to the replacement disk Under certain circumstances, RAID 1 can sustain multiple simultaneous drive failures Simplest RAID storage subsystem design	Highest disk overhead of all RAID types (100%) - inefficient	Accounting Payroll Financial Any application requiring very high availability
2	Extremely high data transfer rates possible The higher the data transfer rate required, the better the ratio of data disks to ECC disks Relatively simple controller design compared to RAID levels 3,4 & 5	Very high ratio of ECC disks to data disks with smaller word sizes - inefficient Entry level cost very high - requires very high transfer rate requirement to justify	No commercial implementations exist / not commercially viable

RAID Comparison

3	Very high read data transfer rate Very high write data transfer rate Disk failure has an insignificant impact on throughput Low ratio of ECC (parity) disks to data disks means high efficiency	Transaction rate equal to that of a single disk drive at best (if spindles are synchronized) Controller design is fairly complex	Video production and live streaming Image editing Video editing Prepress applications Any application requiring high throughput
4	Very high Read data transaction rate Low ratio of ECC (parity) disks to data disks means high efficiency	Quite complex controller design Worst write transaction rate and Write aggregate transfer rate Difficult and inefficient data rebuild in the event of disk failure	No commercial implementations exist / not commercially viable
5	Highest Read data transaction rate Low ratio of ECC (parity) disks to data disks means high efficiency Good aggregate transfer rate	Most complex controller design Difficult to rebuild in the event of a disk failure (as compared to RAID level 1)	File and application servers Database servers Web, e-mail, and news servers Intranet servers Most versatile RAID level
6	Provides for an extremely high data fault tolerance and can sustain multiple simultaneous drive failures	More complex controller design Controller overhead to compute parity addresses is extremely high	Perfect solution for mission critical applications

Optical Storage

- Primarily CD and DVD
- Other technologies exist:
  - Magneto-optical
  - Floptical

Optical Storage Products

CD
Compact Disk. A nonerasable disk that stores digitized audio information. The standard system uses 12-cm disks and can record more than 60 minutes of uninterrupted playing time.

CD-ROM
Compact Disk Read-Only Memory. A nonerasable disk used for storing computer data. The standard system uses 12-cm disks and can hold more than 650 Mbytes.

CD-R
CD Recordable. Similar to a CD-ROM. The user can write to the disk only once.

CD-RW
CD Rewritable. Similar to a CD-ROM. The user can erase and rewrite to the disk multiple times.

DVD
Digital Versatile Disk. A technology for producing digitized, compressed representation of video information, as well as large volumes of other digital data. Both 8 and 12 cm diameters are used, with a double-sided capacity of up to 17 Gbytes. The basic DVD is read-only (DVD-ROM).

DVD-R
DVD Recordable. Similar to a DVD-ROM. The user can write to the disk only once. Only one-sided disks can be used.

DVD-RW
DVD Rewritable. Similar to a DVD-ROM. The user can erase and rewrite to the disk multiple times. Only one-sided disks can be used.

Blu-Ray DVD
High definition video disk. Provides considerably greater data storage density than DVD, using a 405-nm (blue-violet) laser. A single layer on a single side can store 25 Gbytes.

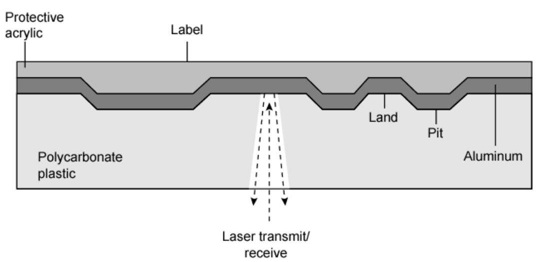
Optical Storage CD-ROM

- Originally designed for audio
- 650-700 MB stores over 70 minutes audio
- Polycarbonate plastic coated with highly reflective coat, usually aluminium
- Data stored as pits and lands
- Read by reflecting laser

Constant Linear Velocity

- Unlike a magnetic disk, CD has only a single track – a very long spiral
- Constant packing density
  - Same numbers of bits/inch on outer edge and inner edge
  - Requires drive to change velocity
  - Higher speeds on inner part of disc
- Complicates seek operation; very slow on CDs

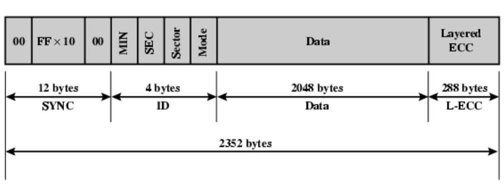
CD Operation



CD-ROM Drive Speeds

- Audio is "single" speed
  - Track (spiral) is 5.27km long
  - Gives 4391 seconds = 73.2 minutes
- Other speeds are quoted as multiples
- e.g. 24x
- Quoted figure is maximum drive can achieve

CD-ROM Block Format



- Mode 0=blank data field
- Mode 1=2048 byte data+error correction
- Mode 2=2336 byte data
- CD-ROM Error Correction

CD-ROM Error Correction

- CD-ROMs use Reed-Solomon error correction, developed in the late 1960's
  - Theory is based on abstract algebra and the details are beyond the scope of this course
  - Widely used for storage media including hard disks
  - Specific technique is called "Cross-Interleave Reed-Solomon Coding" (CIRC)
- Reed-Solomon error correction is particularly useful for "error bursts"
- For CD-ROMs error bursts as long as 450 bytes can be completely corrected (about 2.5mm on disk surface)

2nd Level Error Correction

- CD Drives in computers have a 2nd level of error correction that is not typically used in audio drives
- 4 byte cyclic redundancy check code in aux header allows detection of errors
- Additional 276 bytes of CIRC is used for correction
- Requires additional hardware on drive (embedded microprocessor) to handle error correction efficiently.

Random Access on CD-ROM

- Difficult to implement because of constant linear velocity

1. Move head to rough position
2. Set correct speed
3. Read address
4. Adjust to required location
5. (Yawn!)

CD-ROM pros and cons

- Large capacity (compared to floppy disks)
- Easy to mass produce
- Removable
- Robust (but not permanent)

- Expensive for small runs
- Slow
- Read only

CD ROM Variants

- CD-Recordable (CD-R)
  - WORM (Write once, read many)
  - Very inexpensive
  - Compatible with CD-ROM drives
- CD-Rewriteable (CD-RW)
  - Erasable
  - Fairly expensive compared to CD-R
  - Mostly CD-ROM drive compatible
  - Phase change
    - Material has two different reflectivities in different phase states
  - Good for 500,000 + erase cycles

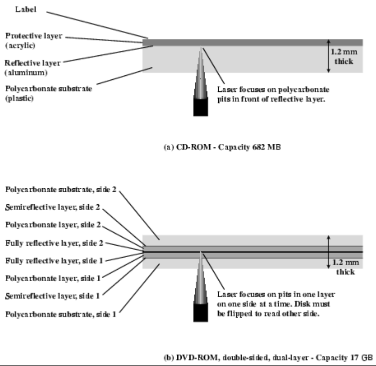
DVD - what's in a name?

- Officially – nothing
- Digital Video Disk
  - Used to indicate a player for movies
    - Only plays video disks
- Digital Versatile Disk
  - Used to indicate a computer drive
    - Will read computer disks and play video disks
- Same size as CD but stores 6 times as much data

DVD - technology

- Multi-layers possible
  - DVDs with 2 layers and two sides can store 17GB
- Very high capacity (4.7G per layer)
- Full length movie on single disk
  - Using MPEG compression
- Finally standardized
- Movies carry regional coding
  - Players only play correct region films

CD and DVD



DVD – Writable

- Many different physical format standards
  - DVD-R
  - DVD+R
  - DVD+RW
  - DVD-RW
  - DVD-RAM
  - ... and more
- These differences are largely irrelevant to most people today
- Many modern drives can handle most formats but not necessarily with the cheapest media
- For more information:
  http://www.digitalfaq.com/guides/media/dvd-formats.htm

High Definition Optical Disks

- Designed for high-def video with greater storage capacity than DVDs.
- Higher density achieved with by using blue-violet laser with shorter wavelength than red lasers
- Two technologies (HD-DVD and Blu-Ray) competed for the market
- 2008 saw the withdrawal of HD-DVD and the dominance of Blu-Ray
- Blu-ray allows 25GB/50GB disks
- 1920×1080 pixel resolution at up to 60 frames per second interlaced or 24 frames per second progressive

Magnetic Tape

- Serial access
- Slow (very!)
- Very cheap
- Backup and archive
- Low cost of backup but high cost to restore
  - 2006 failure of 2-terabyte RAID 0 at Fogler Library required 30 days to restore from tape