CS 33

Memory Hierarchy II

Most of the slides in this lecture are either from or adapted from slides provided by the authors of the textbook "Computer Systems: A Programmer's Perspective," 2^{nd} Edition and are provided from the website of Carnegie-Mellon University, course 15-213, taught by Randy Bryant and David O'Hallaron in Fall 2010. These slides are indicated "Supplied by CMU" in the notes section of the slides.

What's Inside A Disk Drive?

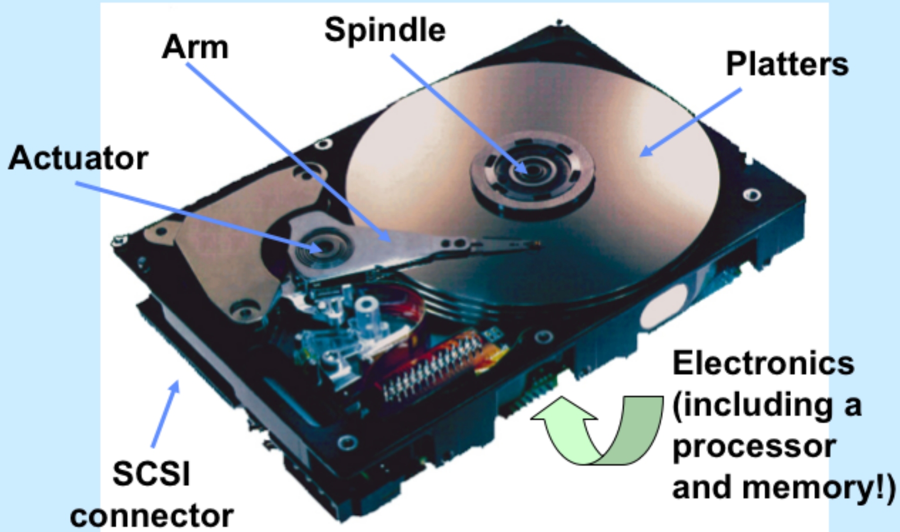
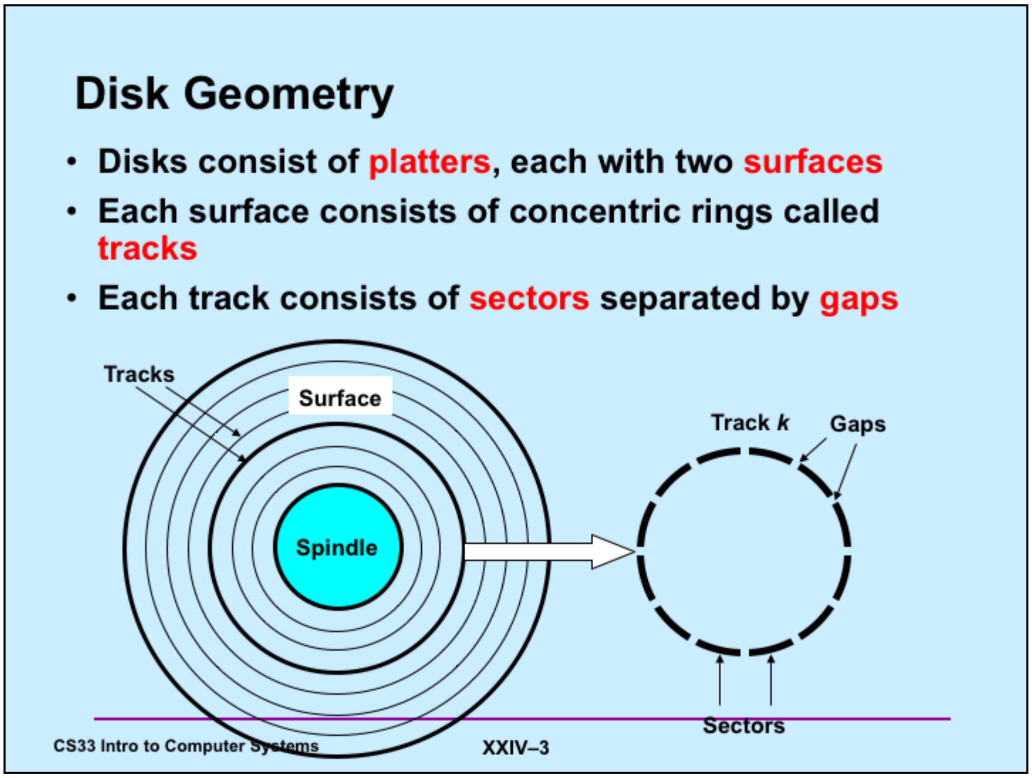


Image courtesy of Seagate Technology

Supplied by CMU.



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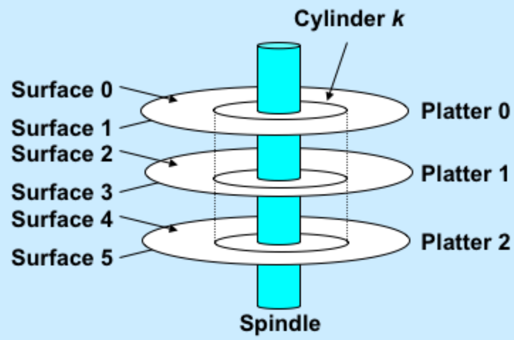
Disk Geometry (Multiple-Platter View)

- Aligned tracks form a cylinder



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Disk Capacity

- **Capacity**: maximum number of bits that can be stored
  - capacity expressed in units of gigabytes (GB), where 1 GB = 2^{30} Bytes ≈ 10^9 Bytes
- Capacity is determined by these technology factors:
  - **recording density** (bits/in): number of bits that can be squeezed into a 1 inch segment of a track
  - **track density** (tracks/in): number of tracks that can be squeezed into a 1 inch radial segment
  - **areal density** (bits/in^2): product of recording and track density
- Modern disks partition tracks into disjoint subsets called **recording zones**
  - each track in a zone has the same number of sectors, determined by the circumference of innermost track
  - each zone has a different number of sectors/track

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Computing Disk Capacity

Capacity = (# bytes/sector) x (avg. # sectors/track) x
(# tracks/surface) x (# surfaces/platter) x
(# platters/disk)

Example:

- 512 bytes/sector
- 600 sectors/track (on average)
- 40,000 tracks/surface
- 2 surfaces/platter
- 5 platters/disk

Capacity = 512 x 600 x 40000 x 2 x 5
= 122,280,000,000
= 113.88 GB

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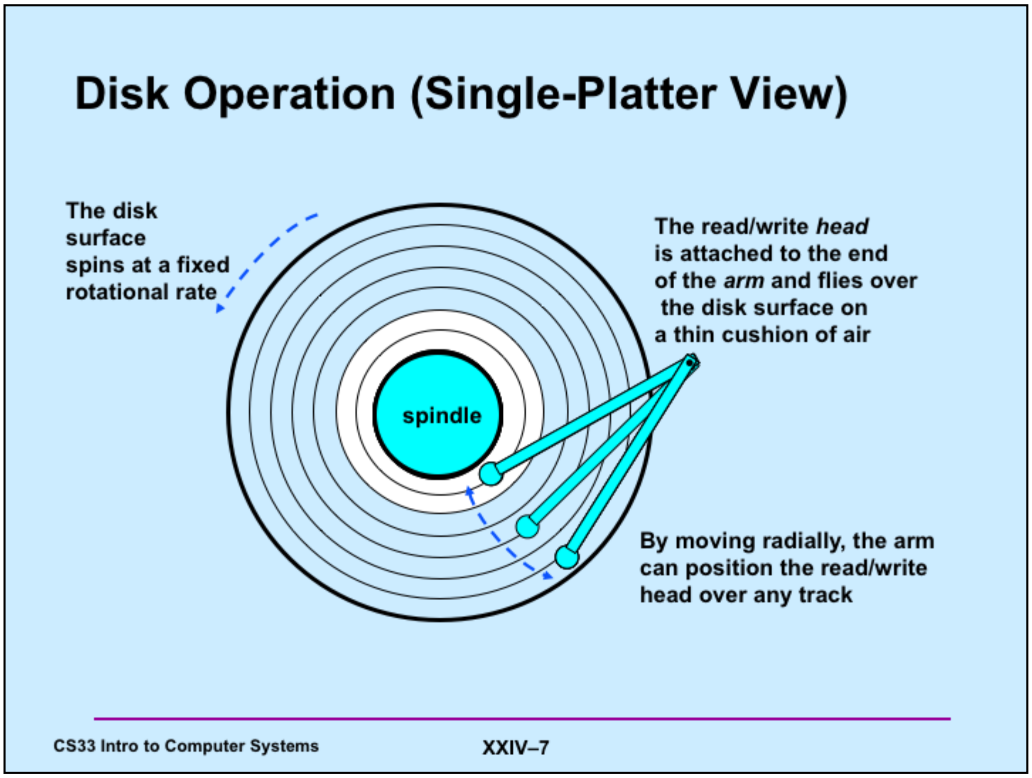
Note that 1GB = 2^{30} bytes.



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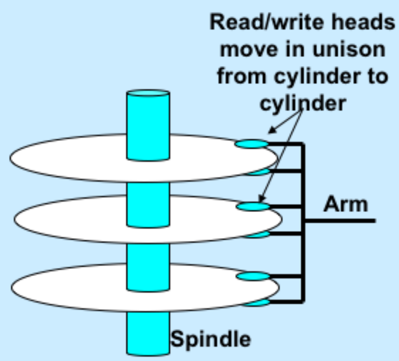
Disk Operation (Multi-Platter View)



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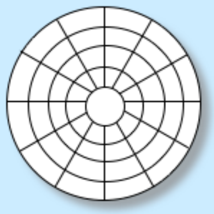
Disk Structure: Top View of Single Platter

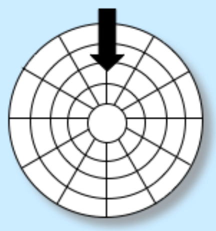


Surface organized into tracks

Tracks divided into sectors

Supplied by CMU.

Disk Access



Head in position above a track

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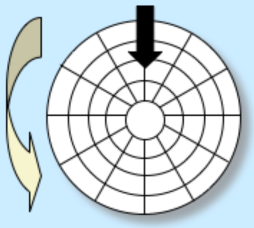
Disk Access



Rotation is counter-clockwise

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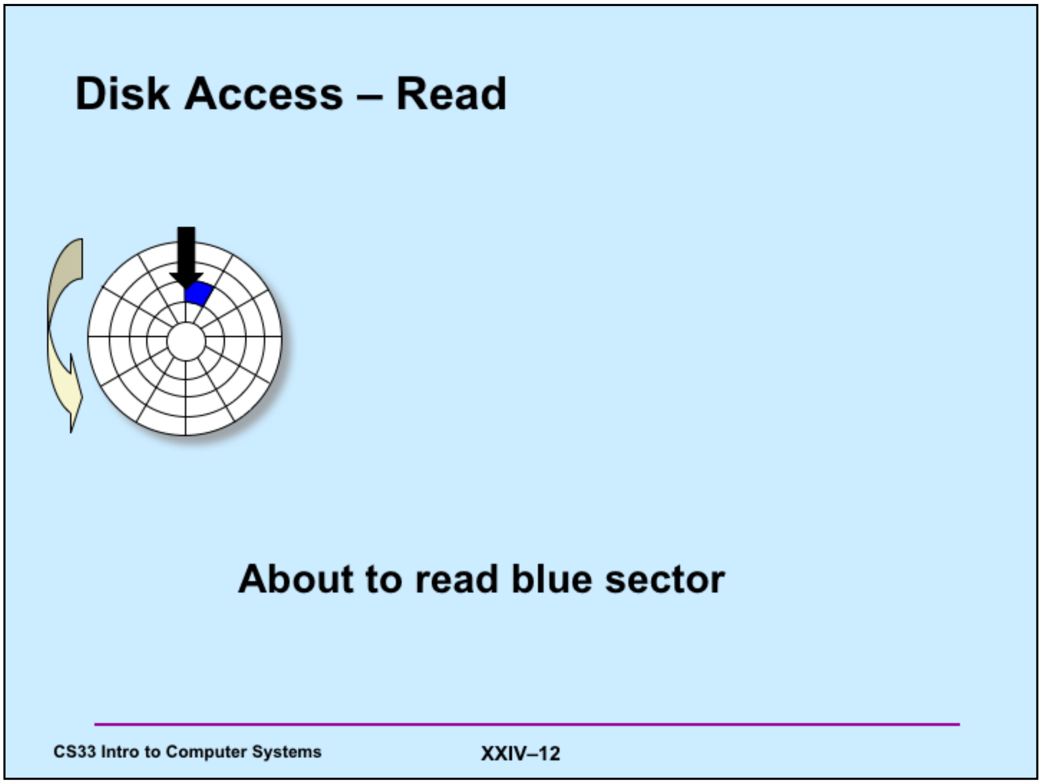

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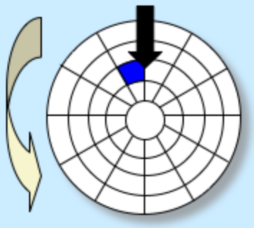
Disk Access – Read



After reading blue sector

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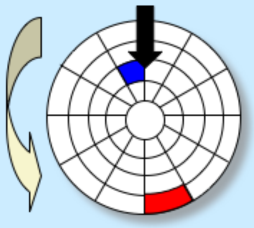
Disk Access – Read



After BLUE
read

Red request scheduled next

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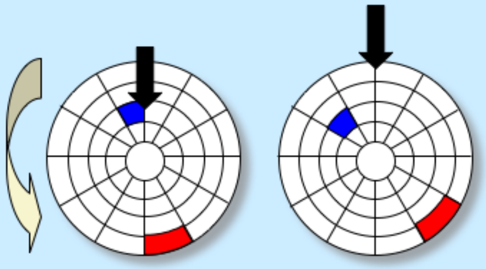
Disk Access – Seek



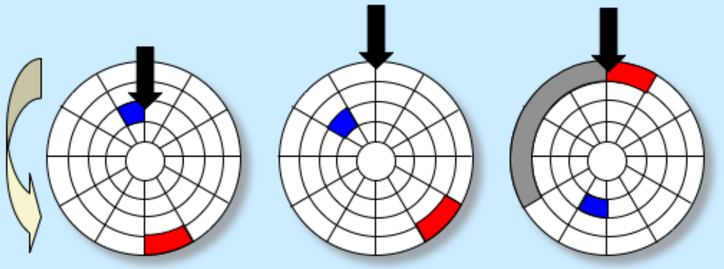
After **BLUE** read

Seek for **RED**

Seek to red's track

Supplied by CMU.

Disk Access – Rotational Latency



After BLUE read

Seek for RED

Rotational latency

Wait for red sector to rotate around

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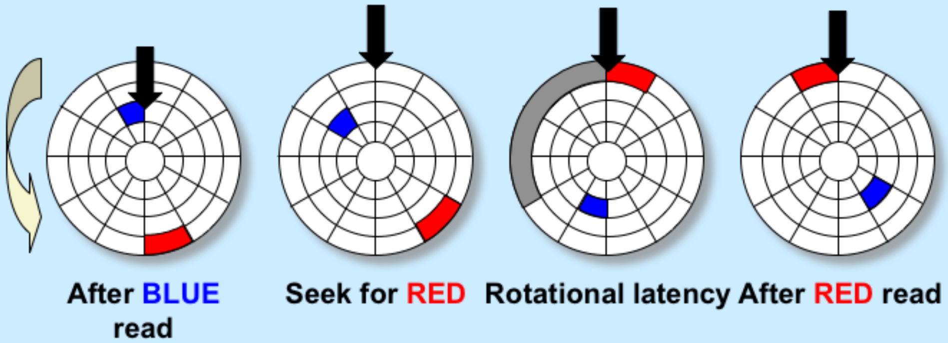
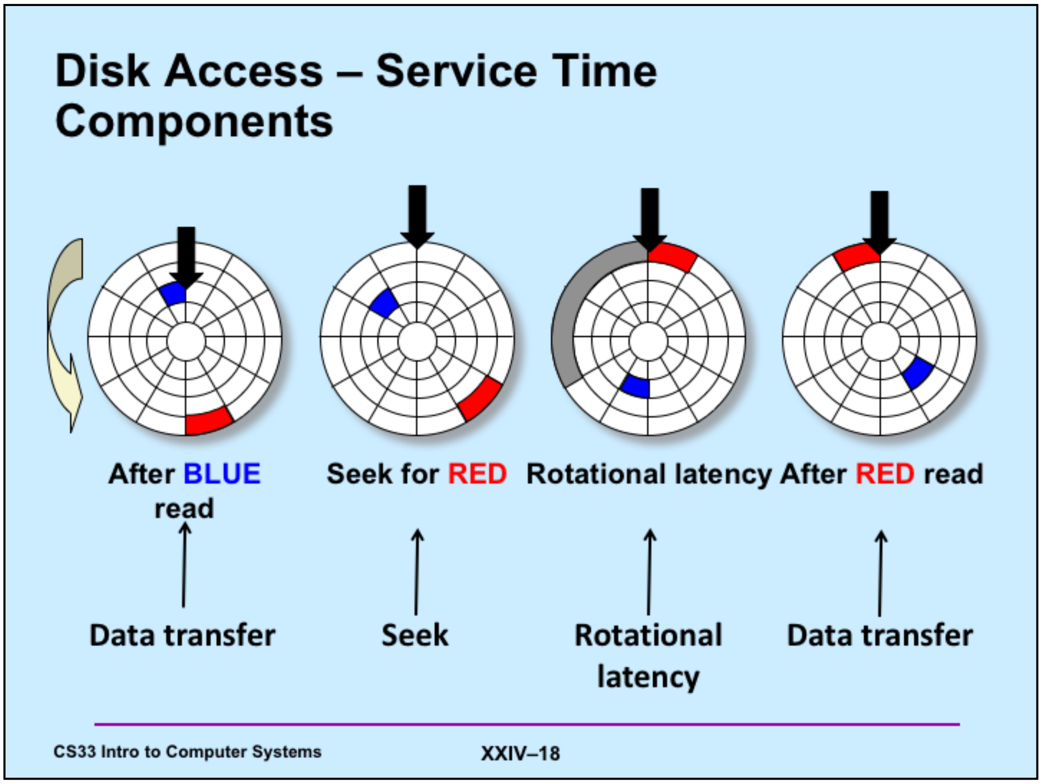
Disk Access – Read



Complete read of red

Supplied by CMU.



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Disk Access Time

- Average time to access some target sector approximated by :
  - Taccess = Tavg seek + Tavg rotation + Tavg transfer
- **Seek time** (Tavg seek)
  - time to position heads over cylinder containing target sector
  - typical Tavg seek is 3–9 ms
- **Rotational latency** (Tavg rotation)
  - time waiting for first bit of target sector to pass under r/w head
  - typical rotation speed R = 7200 RPM
  - Tavg rotation = 1/2 x 1/R x 60 sec/1 min
- **Transfer time** (Tavg transfer)
  - time to read the bits in the target sector
  - Tavg transfer = 1/R x 1/(avg # sectors/track) x 60 secs/1 min

Supplied by CMU.

Disk Access Time Example

- **Given:**
  - rotational rate = 7,200 RPM
  - average seek time = 9 ms
  - avg # sectors/track = 600
- **Derived:**
  - Tavg rotation = 1/2 x (60 secs/7200 RPM) x 1000 ms/sec = 4 ms
  - Tavg transfer = 60/7200 RPM x 1/600 sects/track x 1000 ms/sec = 0.014 ms
  - Taccess = 9 ms + 4 ms + 0.014 ms
- **Important points:**
  - access time dominated by seek time and rotational latency
  - first bit in a sector is the most expensive, the rest are free
  - SRAM access time is about 4 ns/doubleword, DRAM about 60 ns
    - » disk is about 40,000 times slower than SRAM
    - » 2,500 times slower than DRAM

Supplied by CMU.

Quiz 1

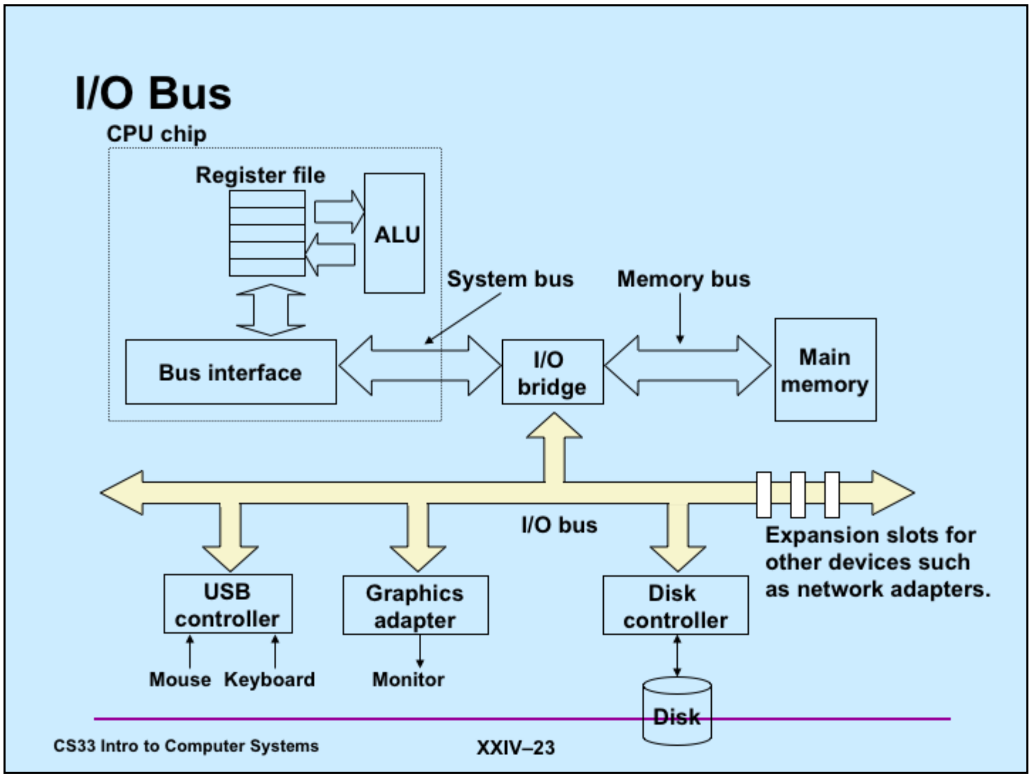
Assuming a 5-inch diameter disk spinning at 10,000 RPM, what is the approximate speed at which the outermost track is moving?

a) faster than a speeding bullet (i.e., supersonic)
b) roughly the speed of a pretty fast car (250 kph/155 mph)
c) roughly the speed of a pretty slow car (50 mph)
d) roughly the speed of a world-class marathoner (13.1 mph)

Logical Disk Blocks

- Modern disks present a simpler abstract view of the complex sector geometry:
  - the set of available sectors is modeled as a sequence of b-sized **logical blocks** (0, 1, 2, ...)
- Mapping between logical blocks and actual (physical) sectors
  - maintained by hardware/firmware device called disk controller
  - converts requests for logical blocks into (surface, track, sector) triples
- Allows controller to set aside spare cylinders for each zone
  - accounts for the difference in “formatted capacity” and “maximum capacity”

Supplied by CMU.



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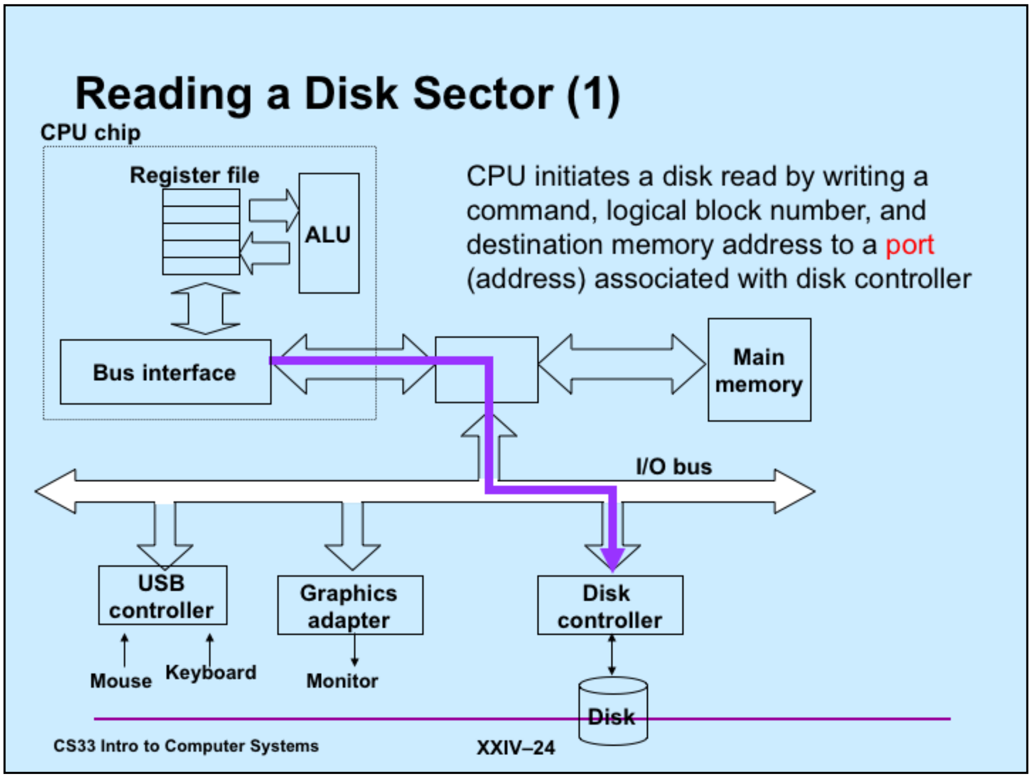

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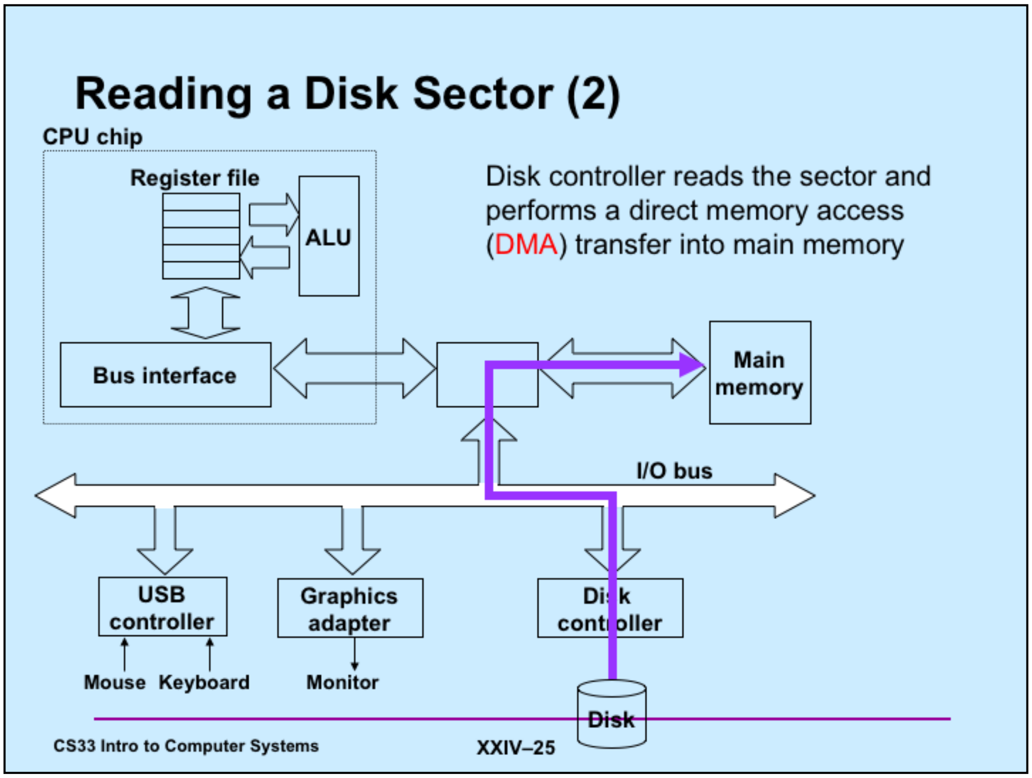

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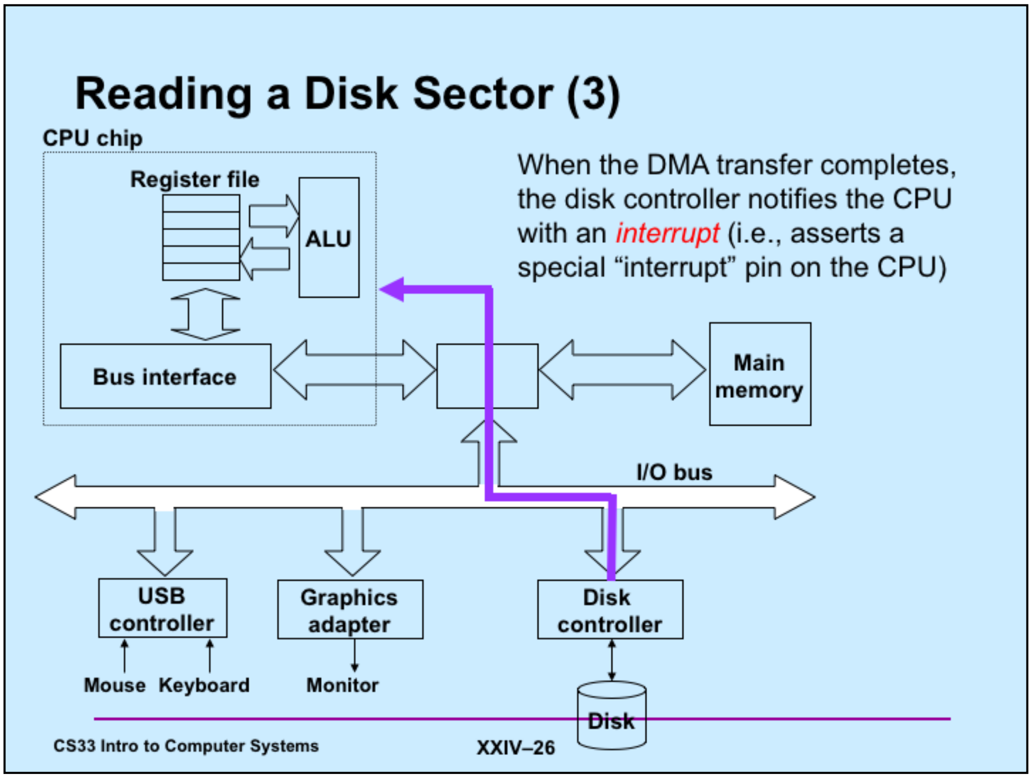

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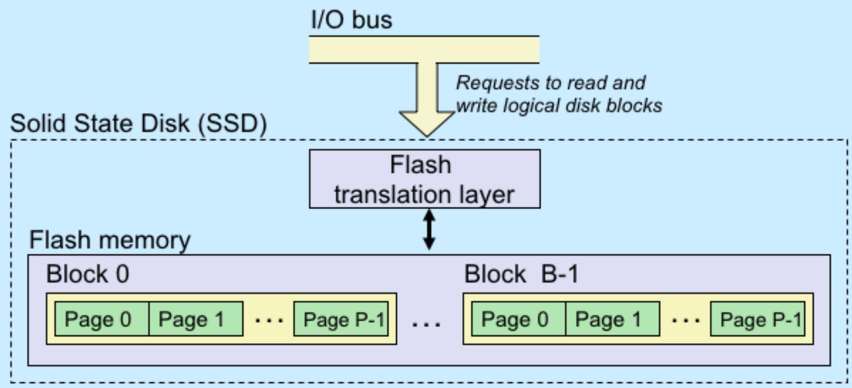
Solid-State Disks (SSDs)



- **Pages: 512KB to 4KB; blocks: 32 to 128 pages**
- **Data read/written in units of pages**
- **Page can be written only after its block has been erased**
- **A block wears out after 100,000 repeated writes**

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SSD Performance Characteristics

Sequential read tput	250 MB/s	Sequential write tput	170 MB/s
Random read tput	140 MB/s	Random write tput	14 MB/s
Random read access	30 us	Random write access	300 us

- Why are random writes so slow?
  - erasing a block is slow (around 1 ms)
  - modifying a page triggers a copy of all useful pages in the block
    - » find a used block (new block) and erase it
    - » write the page into the new block
    - » copy other pages from old block to the new block

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SSD Tradeoffs vs Rotating Disks

- **Advantages**
  - no moving parts → faster, less power, more rugged
- **Disadvantages**
  - have the potential to wear out
    - » mitigated by “wear-leveling logic” in flash translation layer
    - » e.g. Intel X25 guarantees 1 petabyte (10^{15} bytes) of random writes before they wear out
  - in 2010, about 100 times more expensive per byte
  - in 2017, about 6 times more expensive per byte
- **Applications**
  - smart phones, laptops
  - Apple “Fusion” drives

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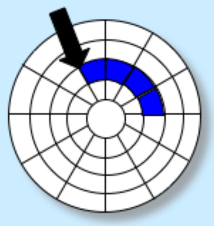
Reading a File on a Rotating Disk

- Suppose the data of a file are stored on consecutive disk sectors on one track
  - this is the best possible scenario for reading data quickly
    - » single seek required
    - » single rotational delay
    - » all sectors read in a single scan



Quiz 2

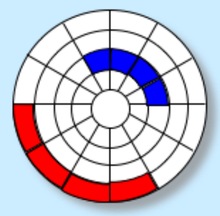
We have two files on the same (rotating) disk. The first file's data resides in consecutive sectors on one track, the second in consecutive sectors on another track. It takes a total of *t* seconds to read all of the first file then all of the second file.

Now suppose the files are read concurrently, perhaps a sector of the first, then a sector of the second, then the first, then the second, etc. Compared to reading them sequentially, this will take

a) less time

b) about the same amount of time

c) more time



Quiz 3

You've replaced the rotating disk on your computer with a solid-state disk. The data of the two files are again each in consecutive locations. Suppose it still takes a total of *t* seconds to read the first file then the second. Suppose it took *u* seconds to read the two files concurrently on the rotating disk. It takes *v* seconds to read them concurrently on the SSD.

a) $v < u$ **(faster on the SSD)**

b) $v \approx u$ **(about the same)**

c) $v > u$ **(slower on the SSD)**

Storage Trends

SRAM

Metric	1980	1985	1990	1995	2000	2005	2010	*2010:1980*
$/MB	19,200	2,900	320	256	100	75	60	*320*
access (ns)	300	150	35	15	3	2	1.5	*200*

DRAM

Metric	1980	1985	1990	1995	2000	2005	2010	*2010:1980*
$/MB	8,000	880	100	30	1	0.1	0.06	*130,000*
access (ns)	375	200	100	70	60	50	40	*9*
typical size (MB)	0.064	0.256	4	16	64	2,000	8,000	*125,000*

Disk

Metric	1980	1985	1990	1995	2000	2005	2010	*2010:1980*
$/MB	500	100	8	0.30	0.01	0.005	0.0003	*1,600,000*
access (ms)	87	75	28	10	8	*4*	*3*	*29*
typical size (MB)	1	10	160	1,000	20,000	160,000	1,500,000	*1,500,000*

Supplied by CMU.

Current (late 2017) prices for SRAM vary a fair amount. As of 10/31, they range from $11.99/MB to $23.08/MB (the latter is via Amazon prime and includes free 2nd-day shipping).

CPU Clock Rates

Inflection point in computer history
when designers hit the “Power Wall”

	1980	1990	1995	2000	2003	2005	2010	*2010:1980*
CPU	8080	386	Pentium	P-III	P-4	Core 2	Core i7	---
Clock rate (MHz)	1	20	150	600	3300	2000	2500	2500
Cycle time (ns)	1000	50	6	1.6	0.3	0.50	0.4	2500
Cores	1	1	1	1	1	2	4	4
Effective cycle time (ns)	1000	50	6	1.6	0.3	0.25	0.1	10,000

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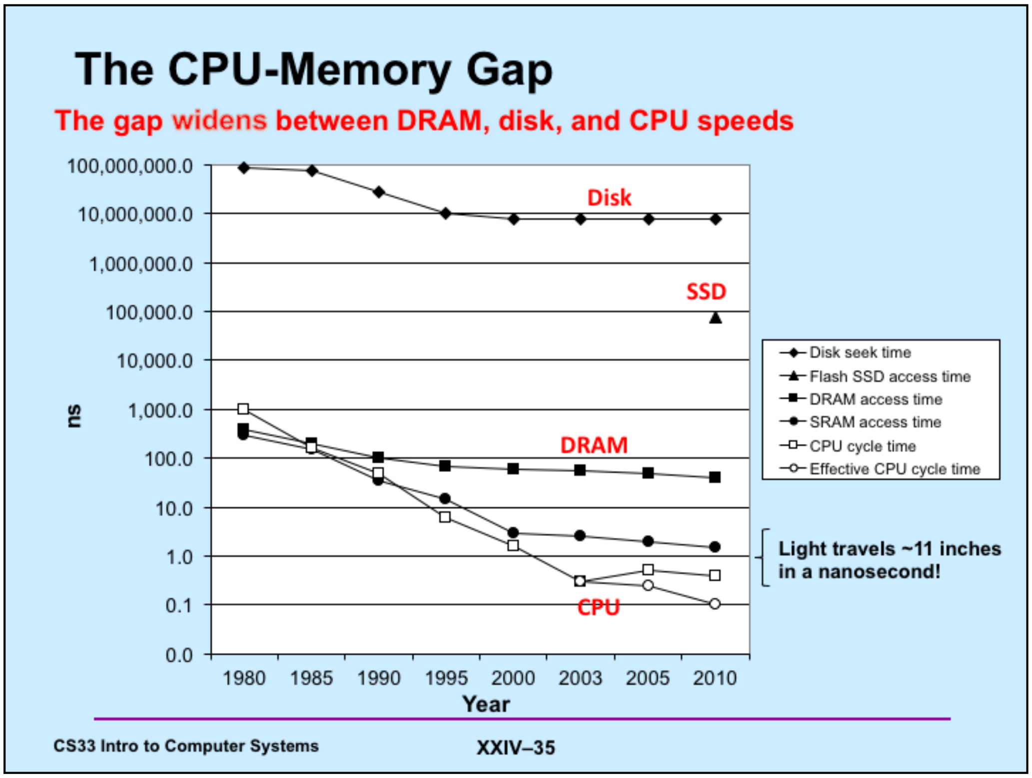

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Memory Hierarchies

- Some fundamental and enduring properties of hardware and software:
  - fast storage technologies cost more per byte, have less capacity, and require more power (heat!)
  - the gap between CPU and main memory speed is widening
  - well written programs tend to exhibit good locality
- These fundamental properties complement each other beautifully
- They suggest an approach for organizing memory and storage systems known as a **memory hierarchy**

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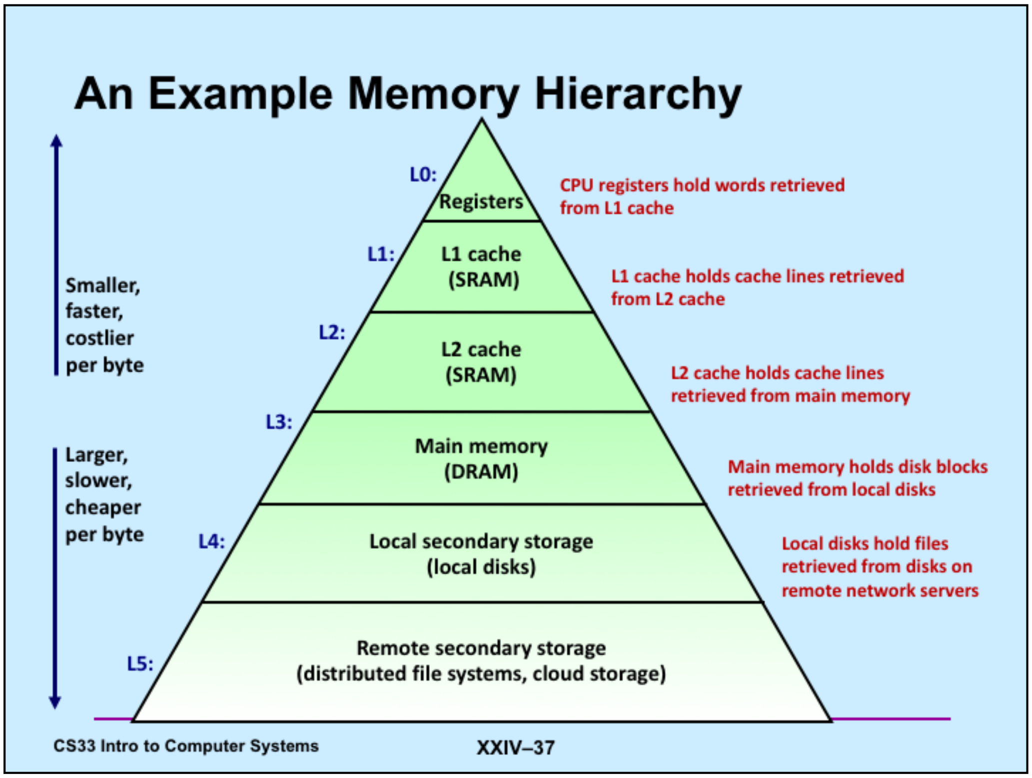

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Putting Things Into Perspective ...

- Reading from:
  - ... the L1 cache is like grabbing a piece of paper from your desk (3 seconds)
  - ... the L2 cache is picking up a book from a nearby shelf (14 seconds)
  - ... main system memory is taking a 4-minute walk down the hall to talk to a friend
  - ... a hard drive is like leaving the building to roam the earth for one year and three months

This analogy is from http://duartes.org/gustavo/blog/post/what-your-computer-does-while-you-wait (definitely worth reading!).