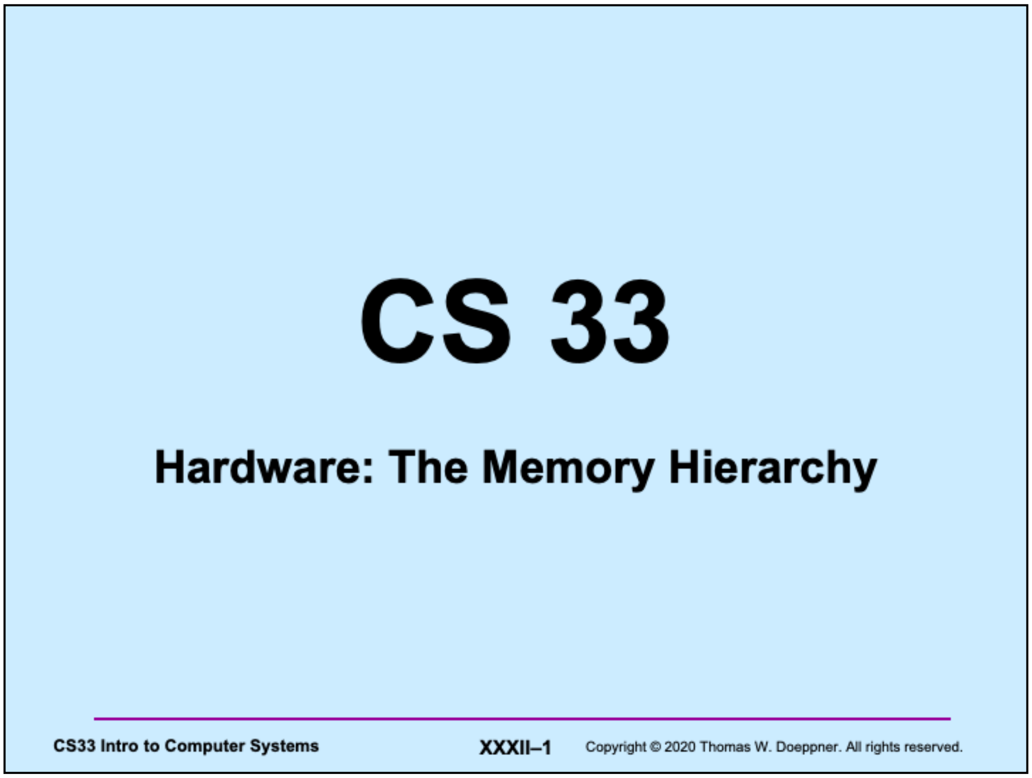


Many of the slides in this lecture are either from or adapted from slides provided by the authors of the textbook "Computer Systems: A Programmer's Perspective," 2nd Edition and are provided from the website of Carnegie-Mellon University, course 15-213, taught by Randy Bryant and David O'Hallaron in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

Random-Access Memory (RAM)

- Key features
  - RAM is traditionally packaged as a chip
  - basic storage unit is normally a cell (one bit per cell)
  - multiple RAM chips form a memory
- Static RAM (SRAM)
  - each cell stores a bit with a four- or six-transistor circuit
  - retains value indefinitely, as long as it is kept powered
  - relatively insensitive to electrical noise (EMI), radiation, etc.
  - faster and more expensive than DRAM
- Dynamic RAM (DRAM)
  - each cell stores bit with a capacitor; transistor is used for access
  - value must be refreshed every 10-100 ms
  - more sensitive to disturbances (EMI, radiation,…) than SRAM
  - slower and cheaper than SRAM

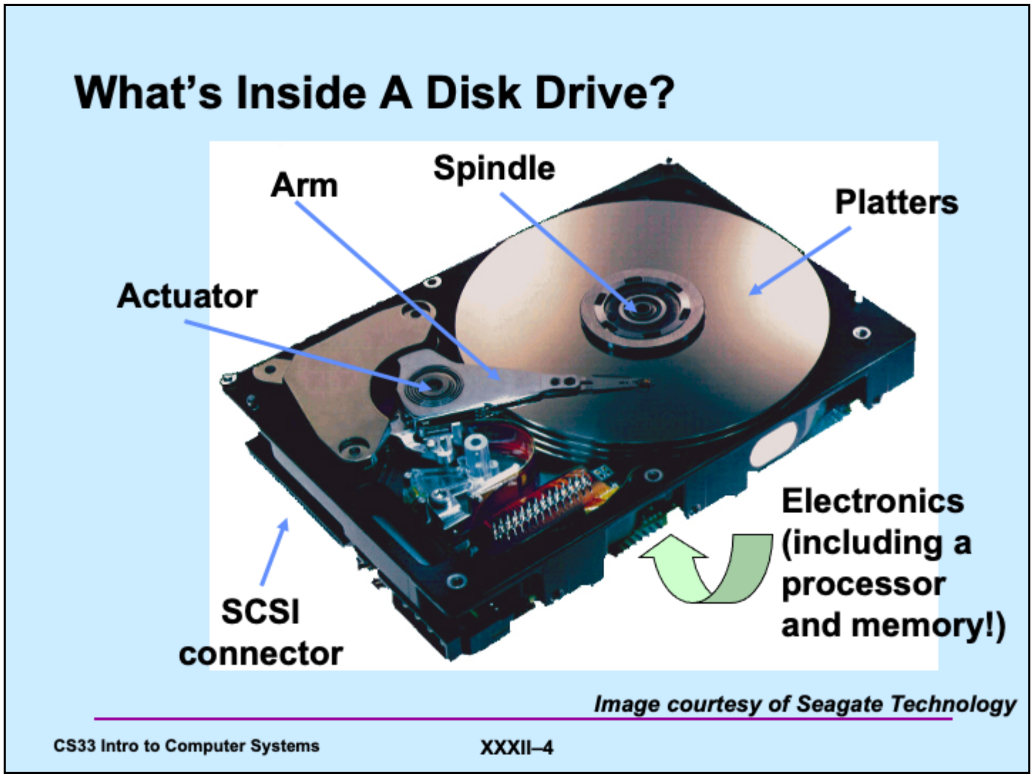
Supplied by CMU.

SRAM vs DRAM Summary

	Trans. per bit	Access time	Needs refresh?	Needs EDC?	Cost	Applications
SRAM	4 or 6	1X	No	Maybe	100x	Cache memories
DRAM	1	10X	Yes	Yes	1X	Main memories, frame buffers

- **EDC = error detection and correction**
  - **to cope with noise, etc.**

Supplied by CMU.



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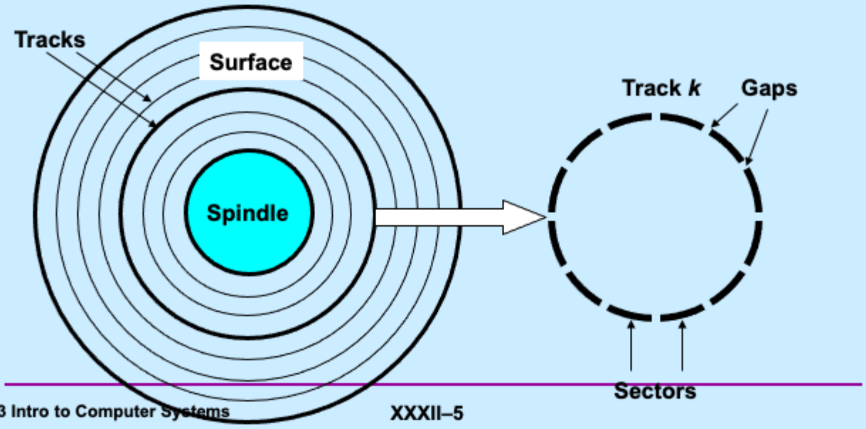
Disk Geometry

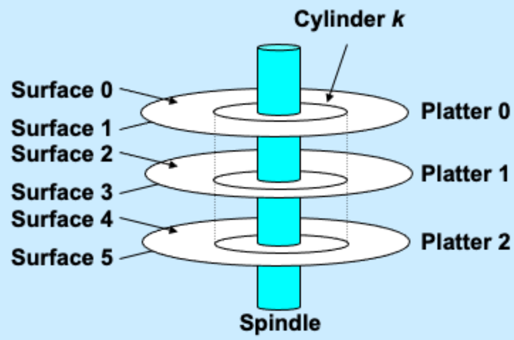
- Disks consist of **platters**, each with two **surfaces**
- Each surface consists of concentric rings called **tracks**
- Each track consists of **sectors** separated by **gaps**



Supplied by CMU.

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

Supplied by CMU.

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
= 122,880,000,000
= 113.88 GB

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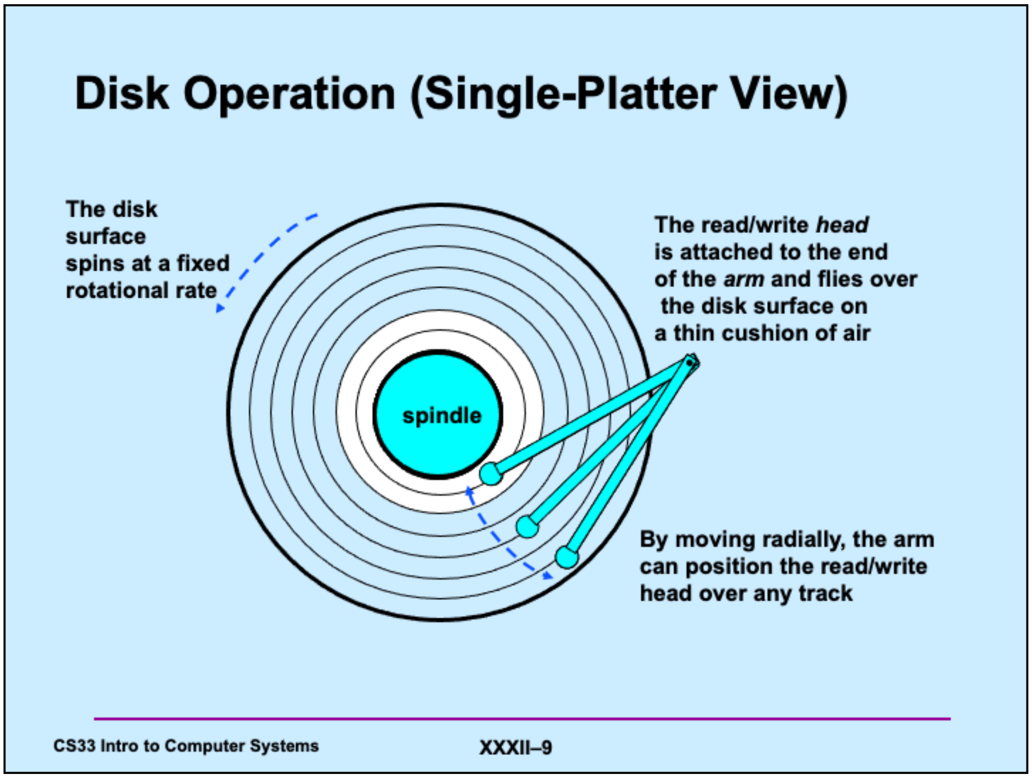
Note that 1GB = 2^{30} bytes.



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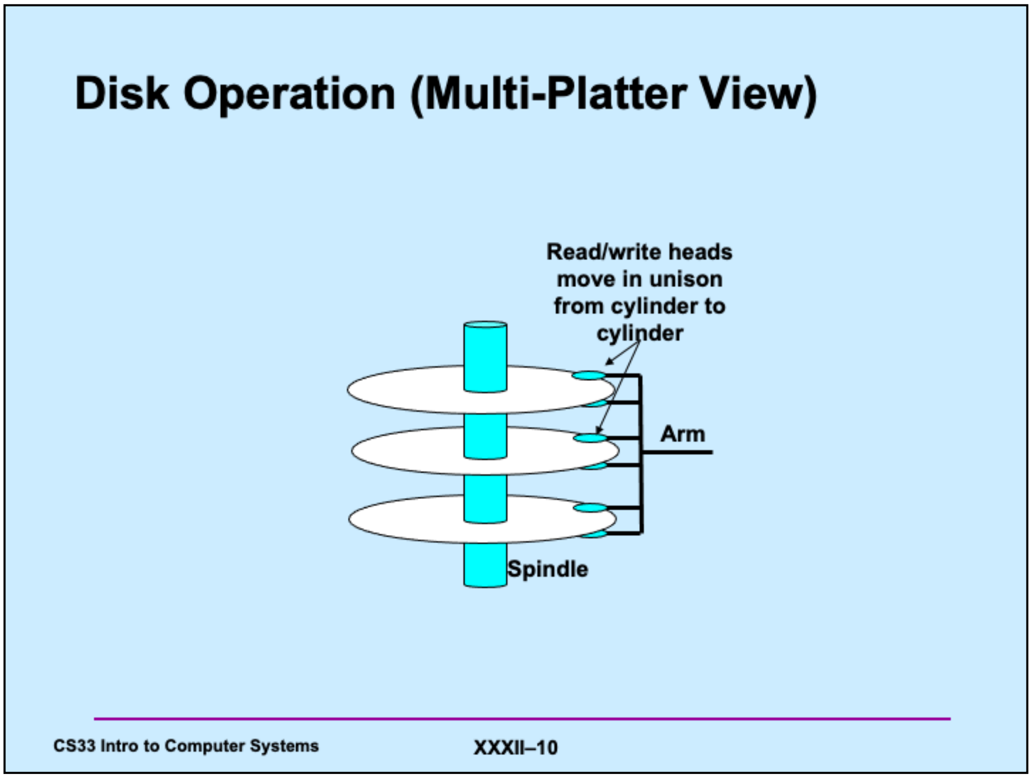

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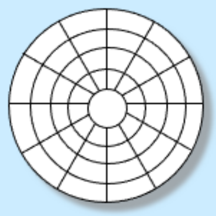
Disk Structure: Top View of Single Platter

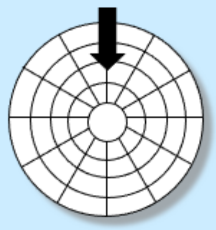


Surface organized into tracks

Tracks divided into sectors

Supplied by CMU.

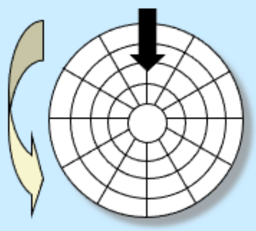
Disk Access



Head in position above a track

Supplied by CMU.

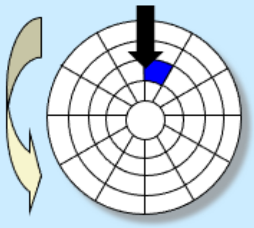
Disk Access



Rotation is counter-clockwise

Supplied by CMU.

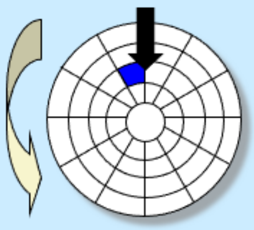
Disk Access – Read



About to read blue sector

Supplied by CMU.

Disk Access – Read

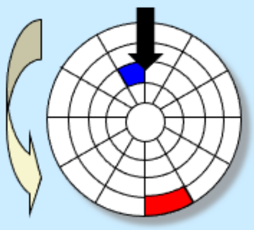


After **BLUE** read

After reading blue sector

Supplied by CMU.

Disk Access – Read

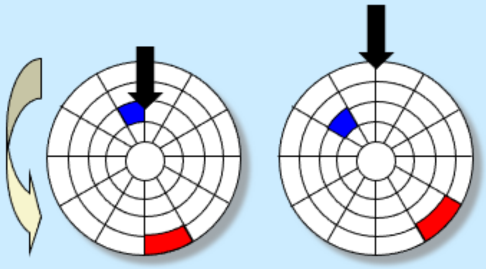


After BLUE read

Red request scheduled next

Supplied by CMU.

Disk Access – Seek

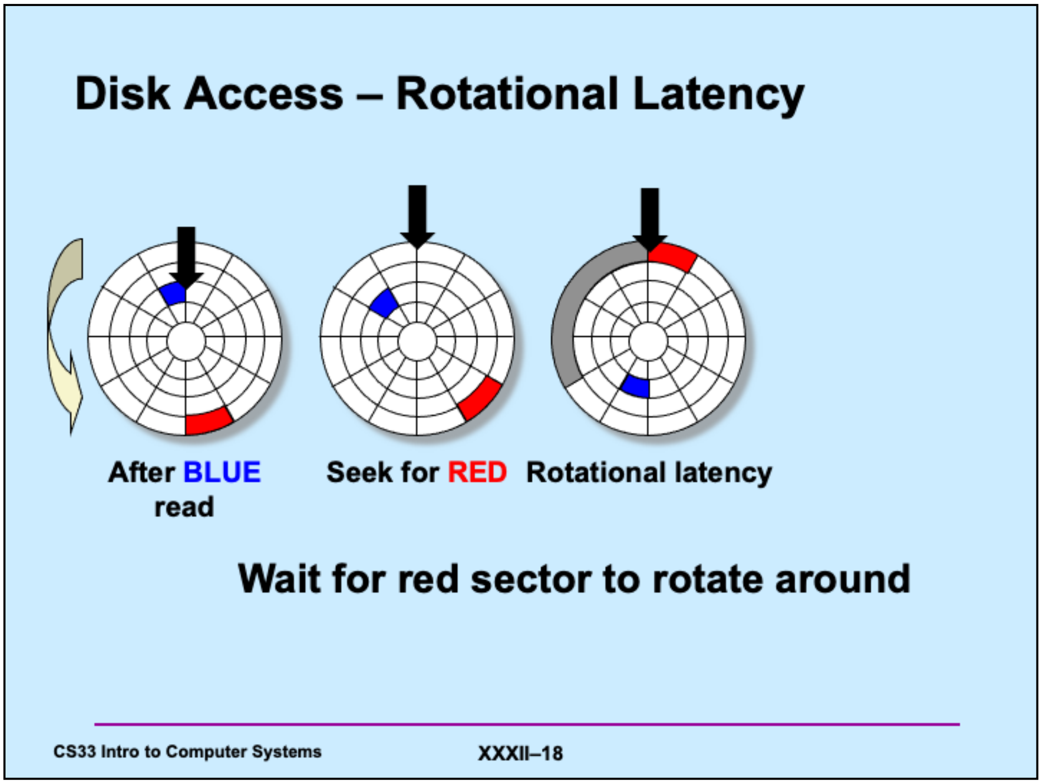


After **BLUE** read

Seek for **RED**

Seek to red's track

Supplied by CMU.



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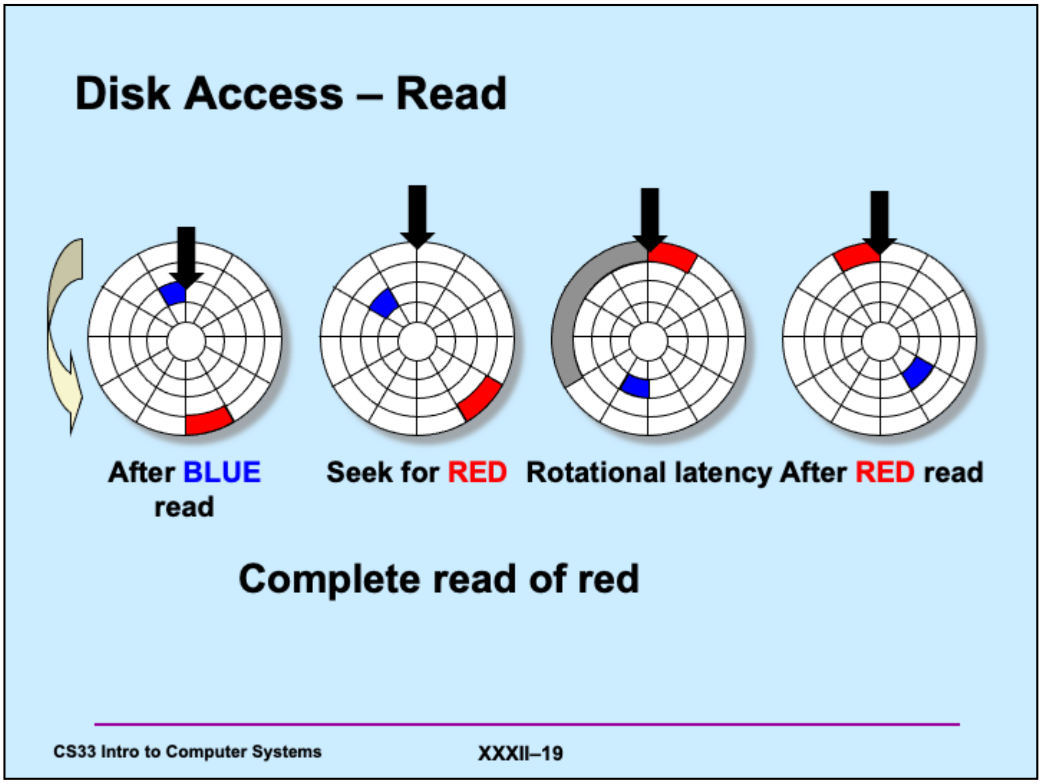

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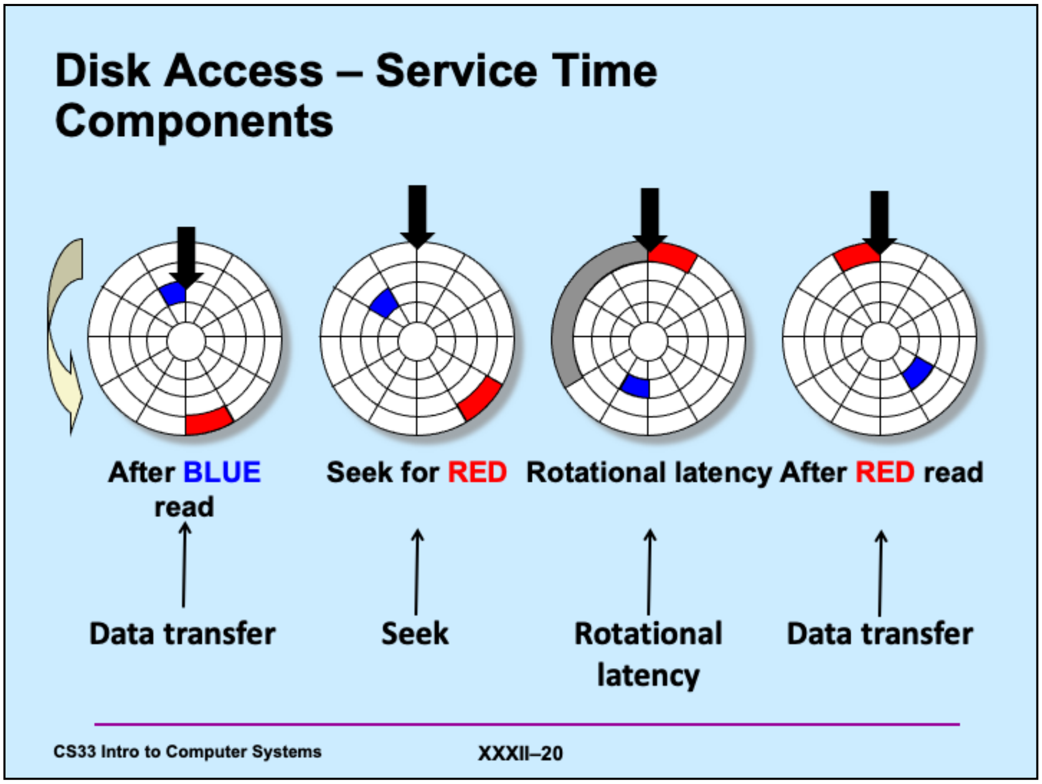


Supplied by CMU.

Disk Access Time

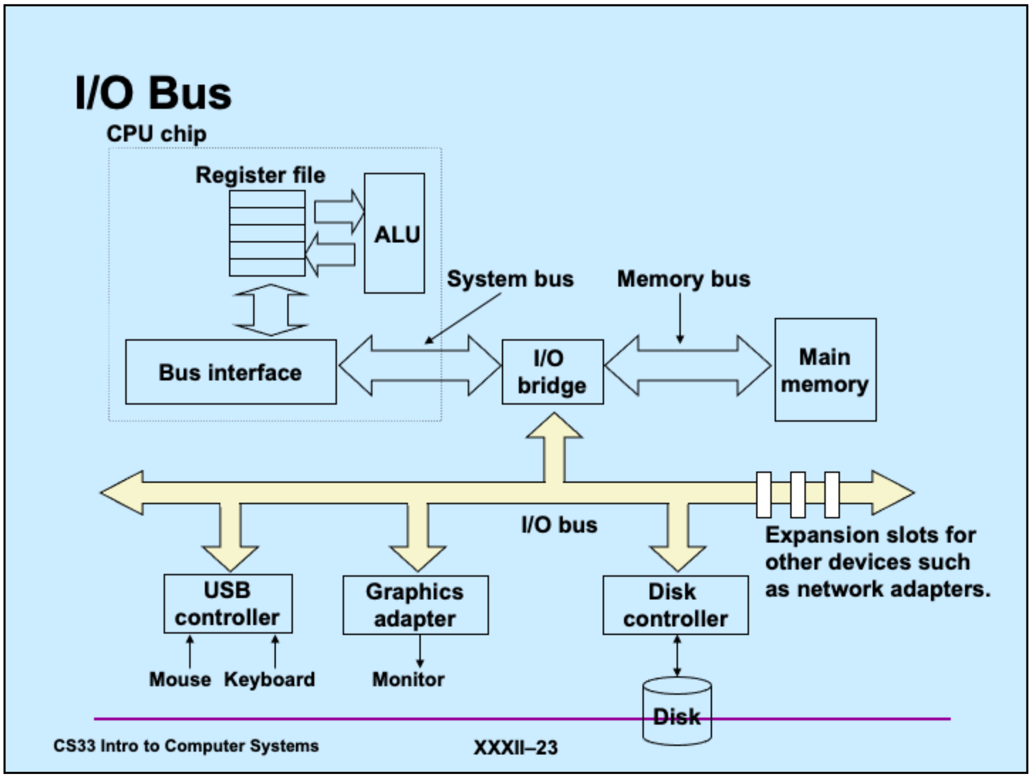
- Average time to access some target sector approximated by :
  - Taccess = Tavg seek + Tavg rotation + Tavg transfer
- **Seek time** (Tavg seek)
  - time to position heads over cylinder containing target sector
  - typical Tavg seek is 3–9 ms
- **Rotational latency** (Tavg rotation)
  - time waiting 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.



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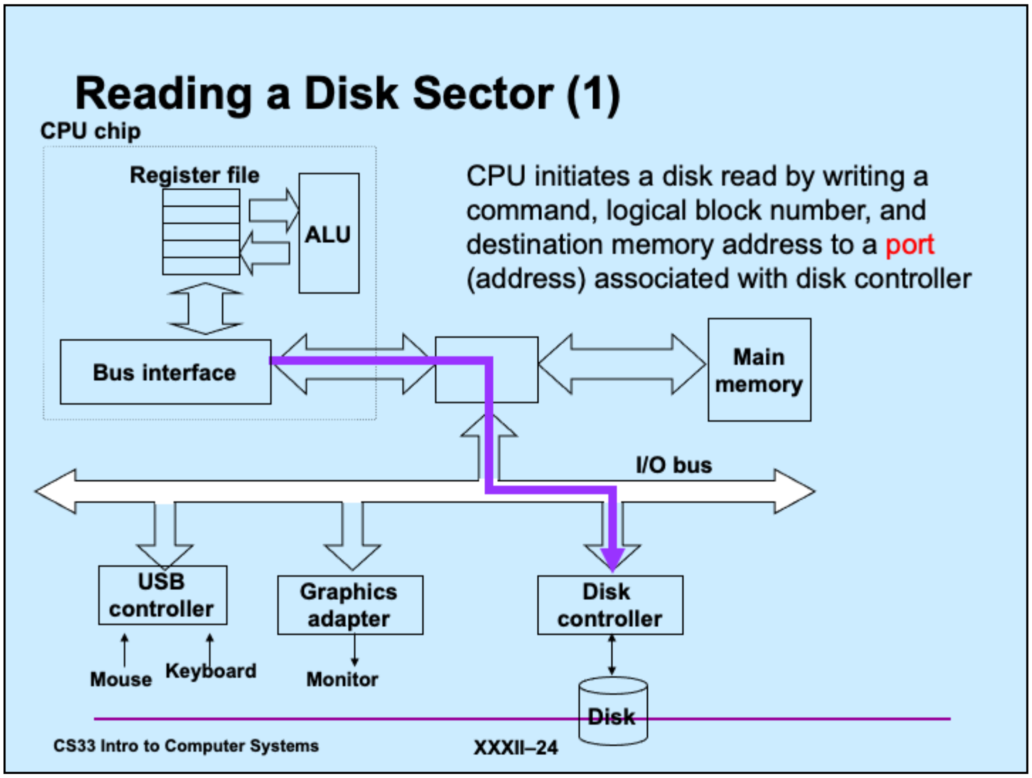

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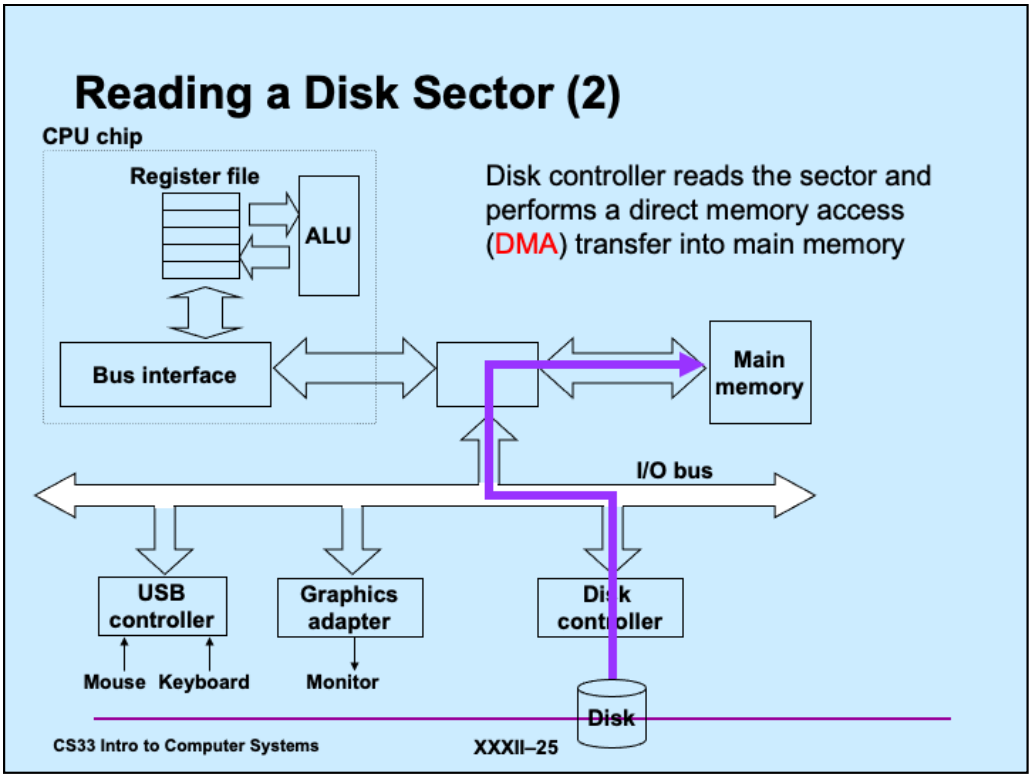

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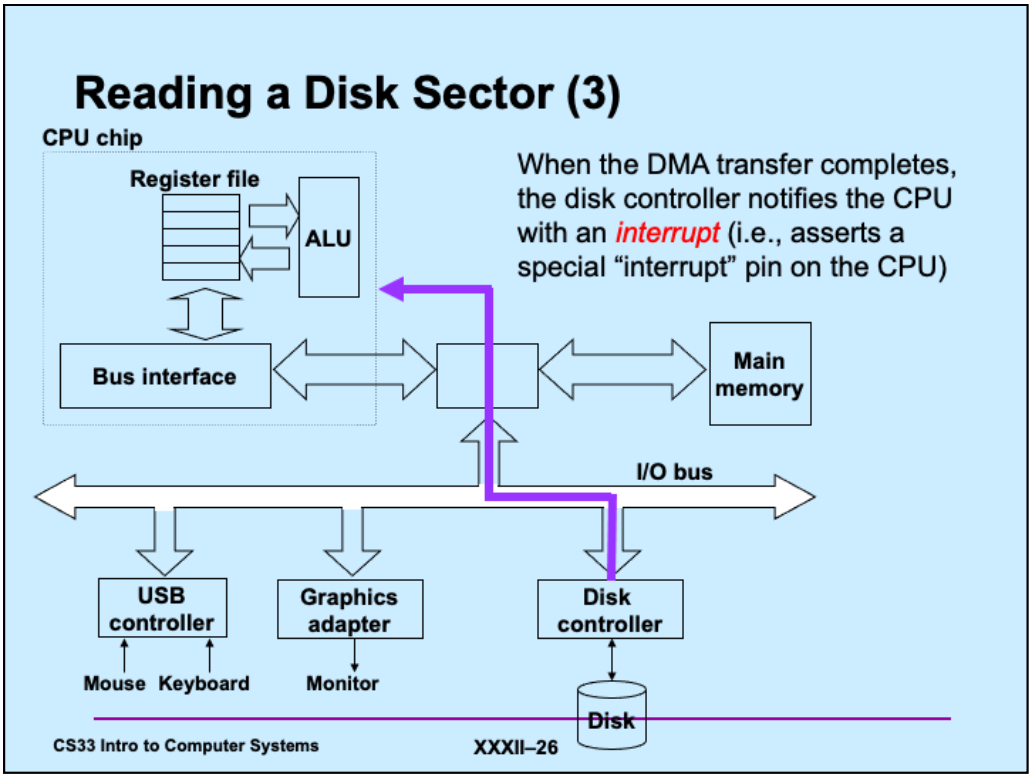

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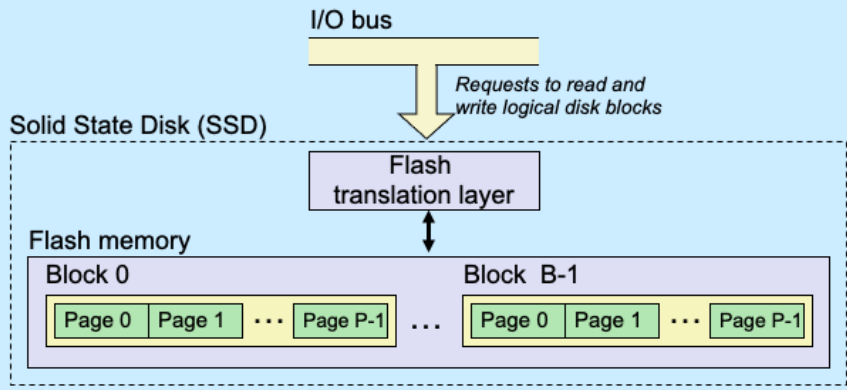
Solid-State Disks (SSDs)



- **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

Supplied by CMU.

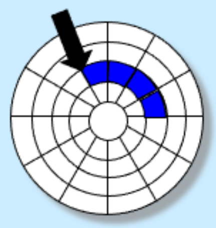
SSD Tradeoffs vs Rotating Disks

- **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

Supplied by CMU.

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 1

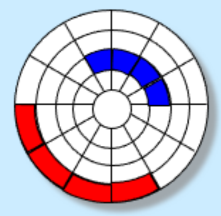
We have two files on the same (rotating) disk. The first file's data resides in consecutive sectors on one track, the second in consecutive sectors on another track. It takes a total of *t* seconds to read all of the first file then all of the second file.

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) a lot less time

b) around the same amount of time

c) a lot more time



Quiz 2

We have two files on the same solid-state disk. Each file's data resides in consecutive blocks. 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 block of the first, then a block of the second, then the first, then the second, etc. Compared to reading them sequentially, this will take

a) a lot less time

b) around the same amount of time

c) a lot more time

Storage Trends

SRAM

Metric	1985	1990	1995	2000	2005	2010	2015	*2015:1985*
$/MB	2,900	320	256	100	75	60	25	116
access (ns)	150	35	15	3	2	1.5	1.3	115

DRAM

Metric	1985	1990	1995	2000	2005	2010	2015	*2015:1985*
$/MB	880	100	30	1	0.1	0.06	0.02	44,000
access (ns)	200	100	70	60	50	40	20	10
typical size (MB)	0.256	4	16	64	2,000	8,000	16,000	62,500

Disk

Metric	1985	1990	1995	2000	2005	2010	2015	*2015:1985*
$/GB	100,000	8,000	300	10	5	.3	0. 03	3,333,333
access (ms)	75	28	10	8	5	3	3	25
typical size (GB)	.01	.16	1	20	160	1,500	3,000	300,000

CS33 Intro to Computer Systems XXXII–33

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Current (2020) prices for SRAM vary a fair amount. As of 11/22, it can be had for around $3/MB.

Current DRAM prices are around $.00075/MB.

CPU Clock Rates

Inflection point in computer history
when designers hit the "Power Wall"

	1985	1990	1995	2000	2003	2005	2015	*2015:1985*
CPU	286	386	Pentium	P-III	P-4	Core 2	Core i7	---
Clock rate (MHz)	6	20	150	600	3300	2000	3000	500
Cycle time (ns)	166	50	6	1.6	0.3	0.50	0.33	500
Cores	1	1	1	1	1	2	4	4
Effective cycle time (ns)	166	50	6	1.6	0.3	0.25	0.08	2075

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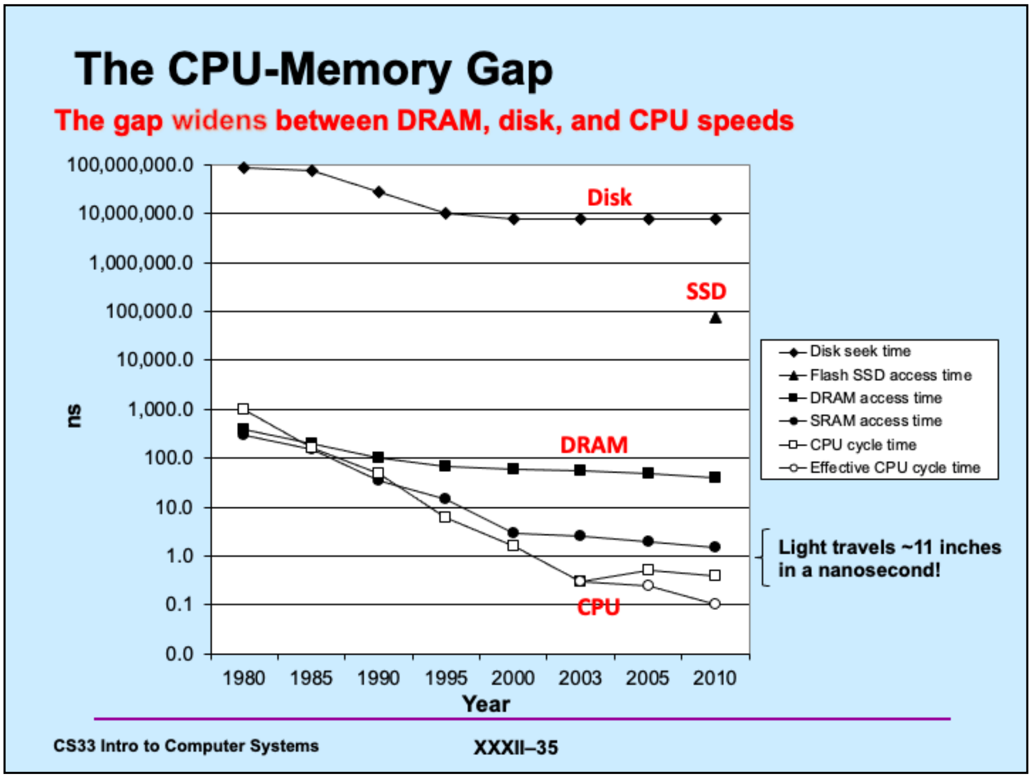

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Memory Hierarchies

- 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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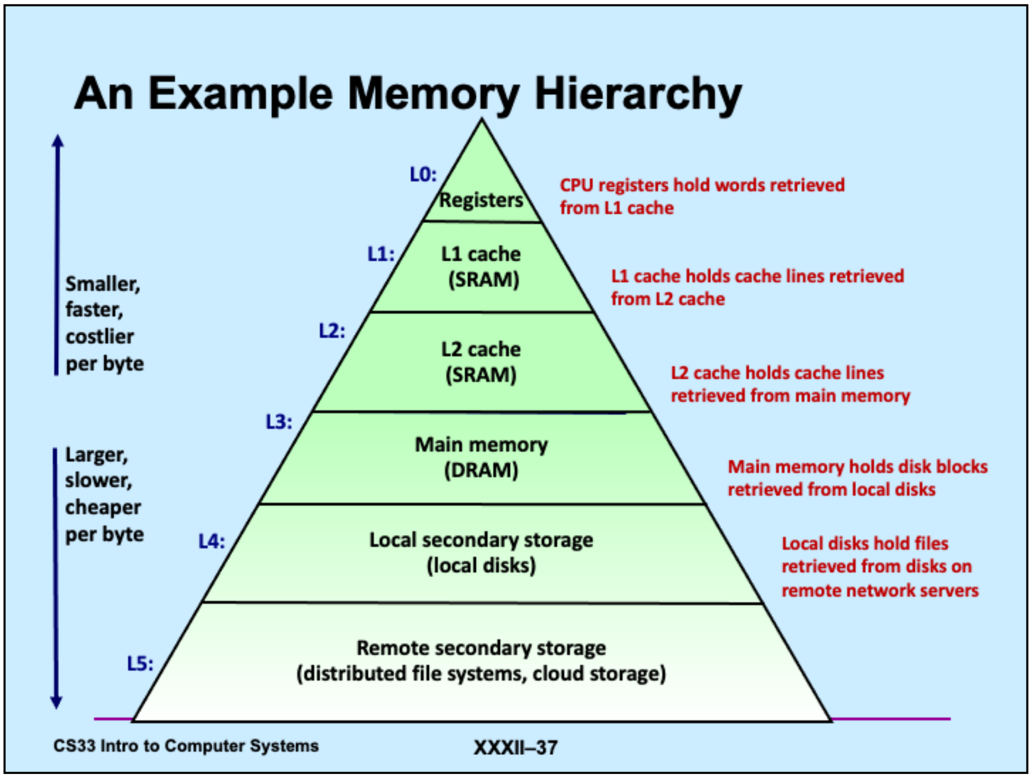

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Putting Things Into Perspective ...

- **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!).

Disks Are Important

- Cheap
  - cost/byte much less than SSDs
- (fairly) Reliable
  - data written to a disk is likely to be there next year
- Sometimes fast
  - data in consecutive sectors on a track can be read quickly
- Sometimes slow
  - data in randomly scattered sectors takes a long time to read

Abstraction to the Rescue

- Programs don't deal with sectors, tracks, and cylinders
- Programs deal with *files*
  - maze.c rather than an ordered collection of sectors
  - OS provides the implementation

Implementation Problems

- Speed
  - use the hierarchy
    - » copy files into RAM, copy back when done
  - optimize layout
    - » put sectors of a file in consecutive locations
  - use parallelism
    - » spread file over multiple disks
    - » read multiple sectors at once

Implementation Problems

- Reliability
  - computer crashes
    - » what you thought was safely written to the file never made it to the disk — it's still in RAM, which is lost
    - » worse yet, some parts made it back to disk, some didn't
      - you don't know which is which
      - on-disk data structures might be totally trashed
  - disk crashes
    - » you had backed it up … yesterday
  - you screw up
    - » you accidentally delete the entire directory containing your malloc solution

Implementation Problems

- **Reliability solutions**
  - computer crashes
    - » transaction-oriented file systems
    - » on-disk data structures always in well defined states
  - disk crashes
    - » files stored redundantly on multiple disks
  - you screw up
    - » file system automatically keeps “snapshots” of previous versions of files

You'll Soon Finish CS 33 …

- You might
  - celebrate

  - take another systems course
    - » 32
    - » 138
    - » 166
    - » 167

  - become a 33 TA

Systems Courses Next Semester

- CS 32 (Intro to Software Engineering)
  - you've mastered low-level systems programming
  - now do things at a higher level
  - learn software-engineering techniques using Java, XML, etc.
- CS 138 (Distributed Systems)
  - you now know how things work on one computer
  - what if you've got lots of computers?
  - some may have crashed, others may have been taken over by your worst (and smartest) enemy
- CS 166 (Computer Systems Security)
  - liked buffer?
  - you'll really like 166
- CS 167/169 (Operating Systems)
  - still mystified about what the OS does?
  - write your own!

The End

Well, not quite …

Database is due on 12/10

No office hours Wednesday through Sunday

A few of us will be monitoring Piazza

Office hours resume next week

Happy coding and happy thanksgiving!