CS 33

Memory Hierarchy II

What's Inside A Disk Drive?

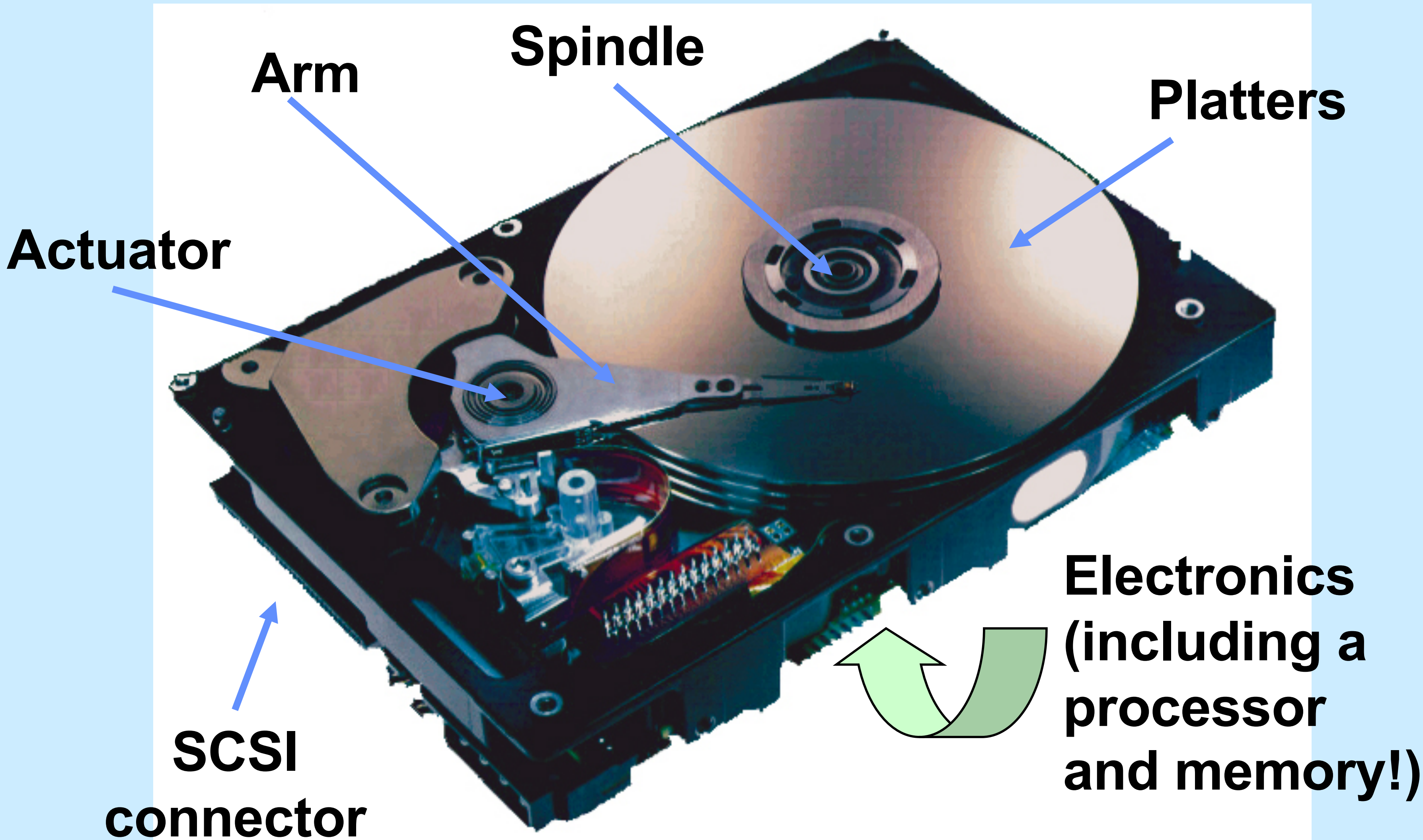
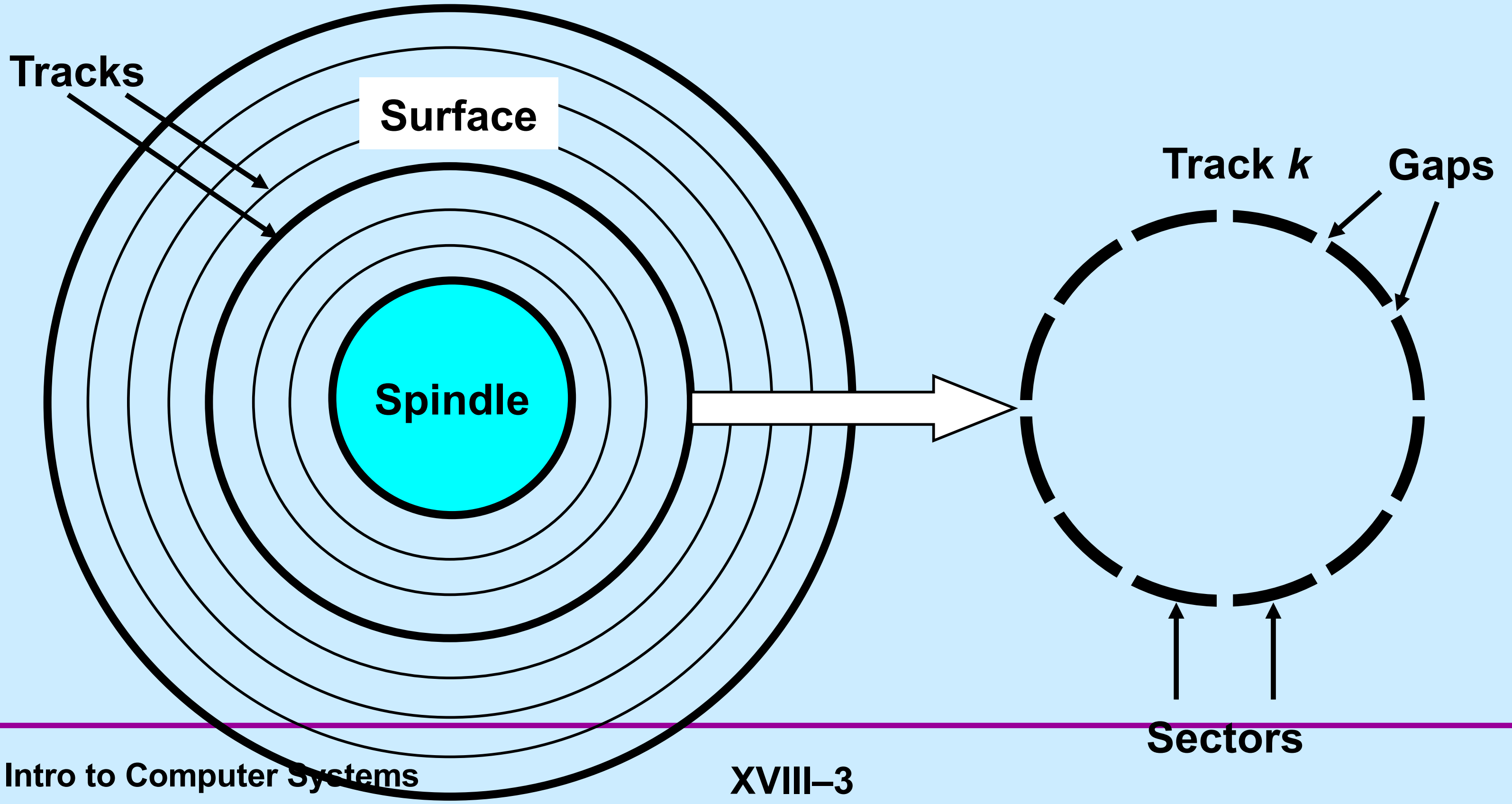


Image courtesy of Seagate Technology

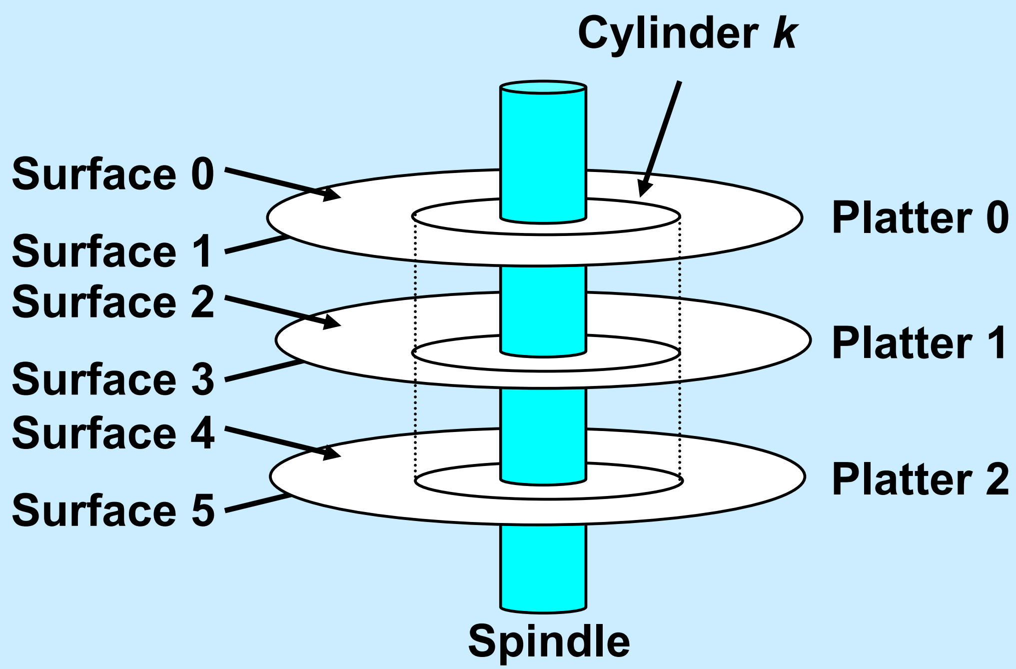
Disk Geometry

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



Disk Geometry (Multiple-Platter View)

- Aligned tracks form a cylinder



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

Computing Disk Capacity

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

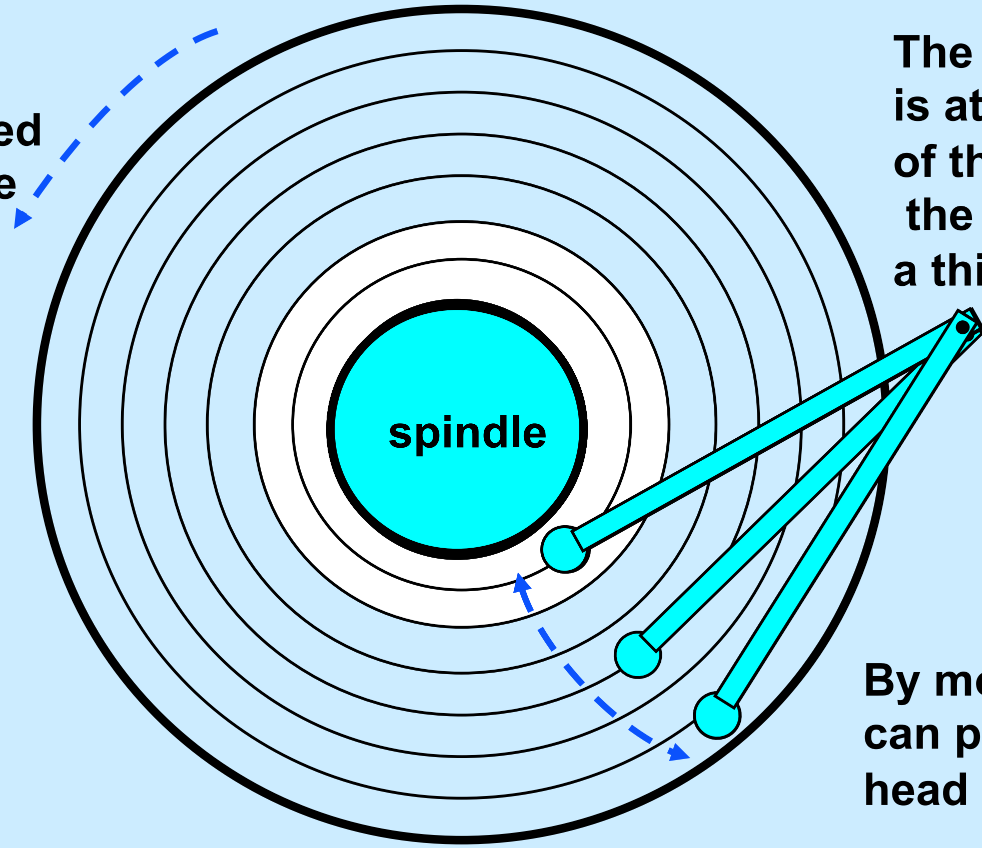
Example:

- 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

Disk Operation (Single-Platter View)

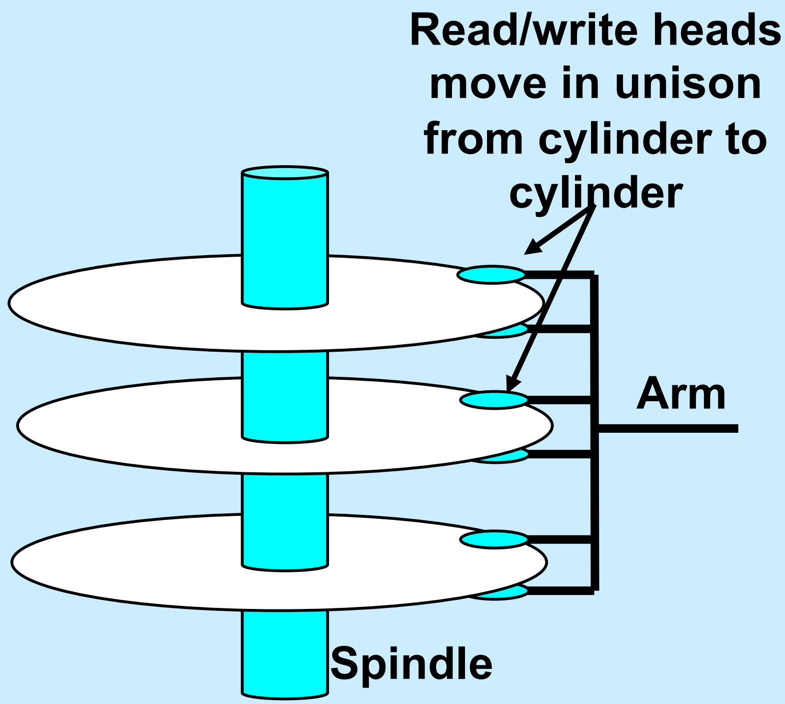
The disk surface spins at a fixed rotational rate



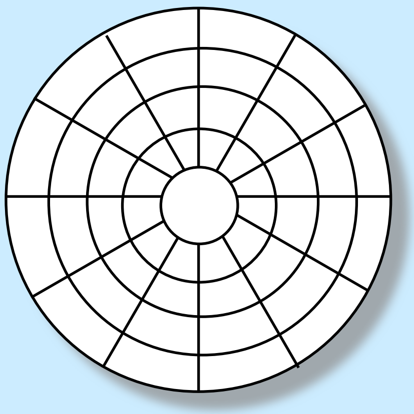
The read/write *head* is attached to the end of the *arm* and flies over the disk surface on a thin cushion of air

By moving radially, the arm can position the read/write head over any track

Disk Operation (Multi-Platter View)



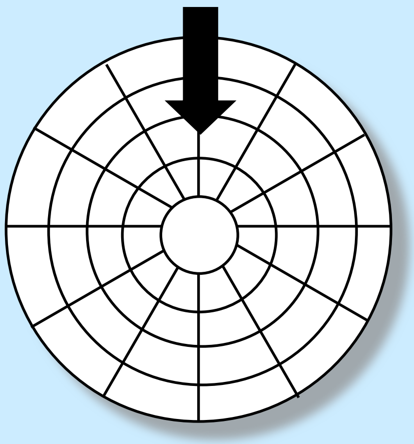
Disk Structure: Top View of Single Platter



Surface organized into tracks

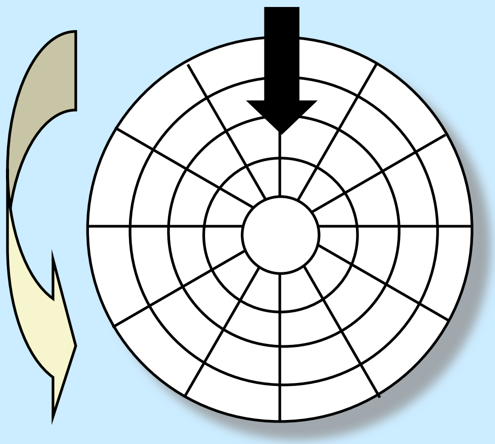
Tracks divided into sectors

Disk Access



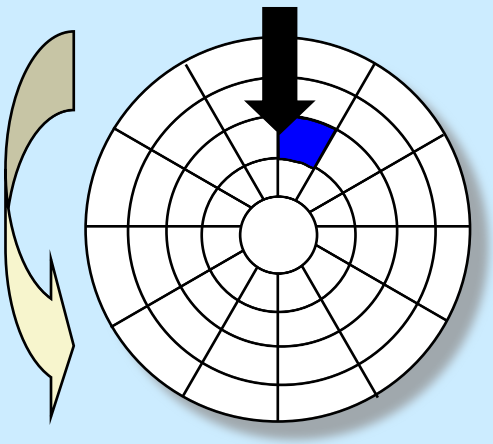
Head in position above a track

Disk Access



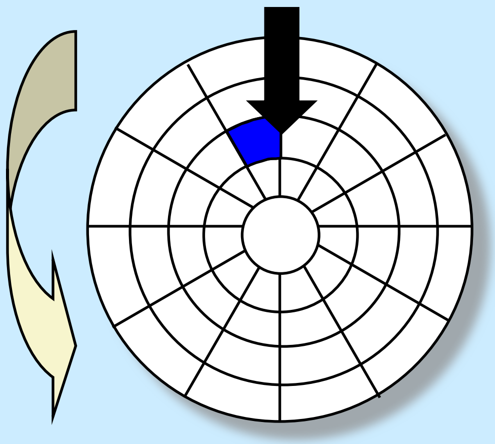
Rotation is counter-clockwise

Disk Access – Read



About to read blue sector

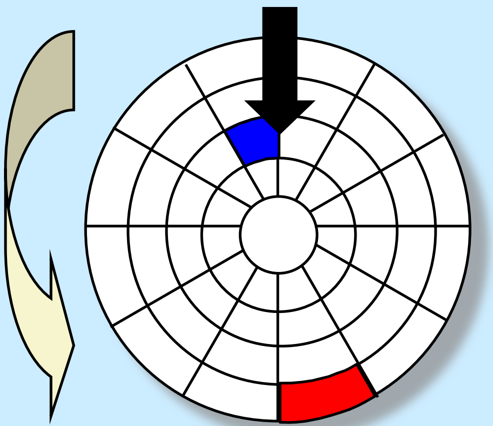
Disk Access – Read



After BLUE
read

After reading blue sector

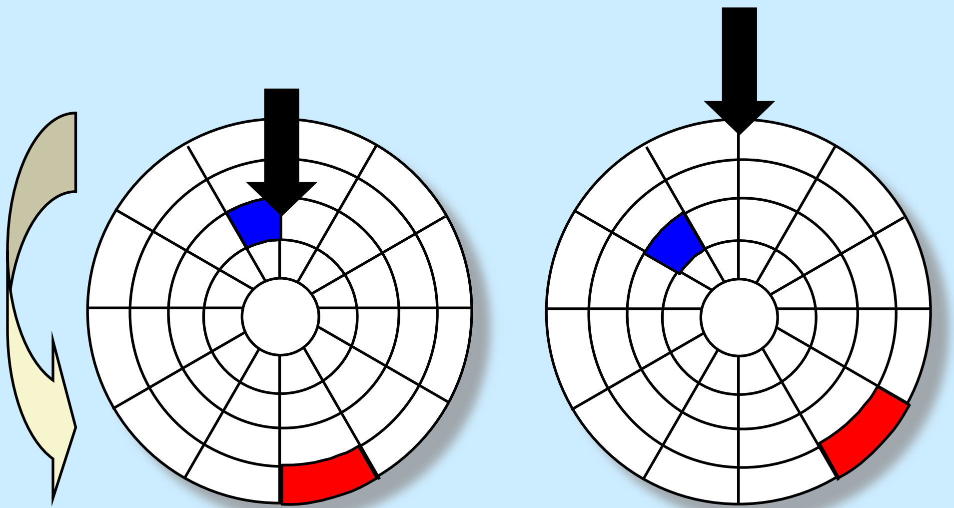
Disk Access – Read



After **BLUE** read

Red request scheduled next

Disk Access – Seek

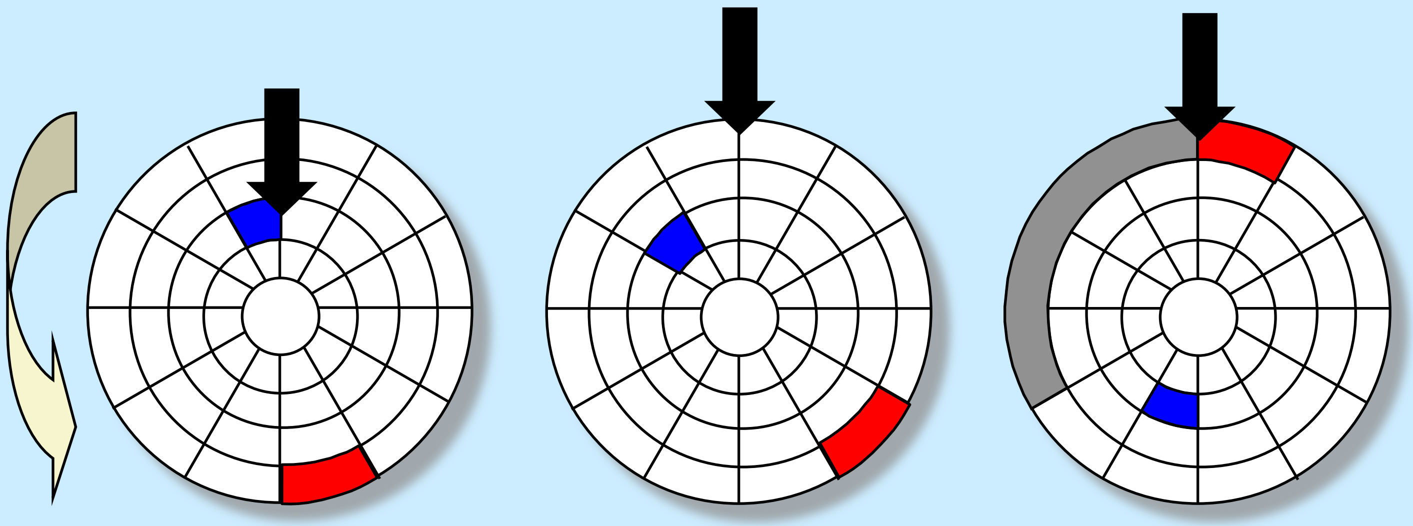


After **BLUE** read

Seek for **RED**

Seek to red's track

Disk Access – Rotational Latency



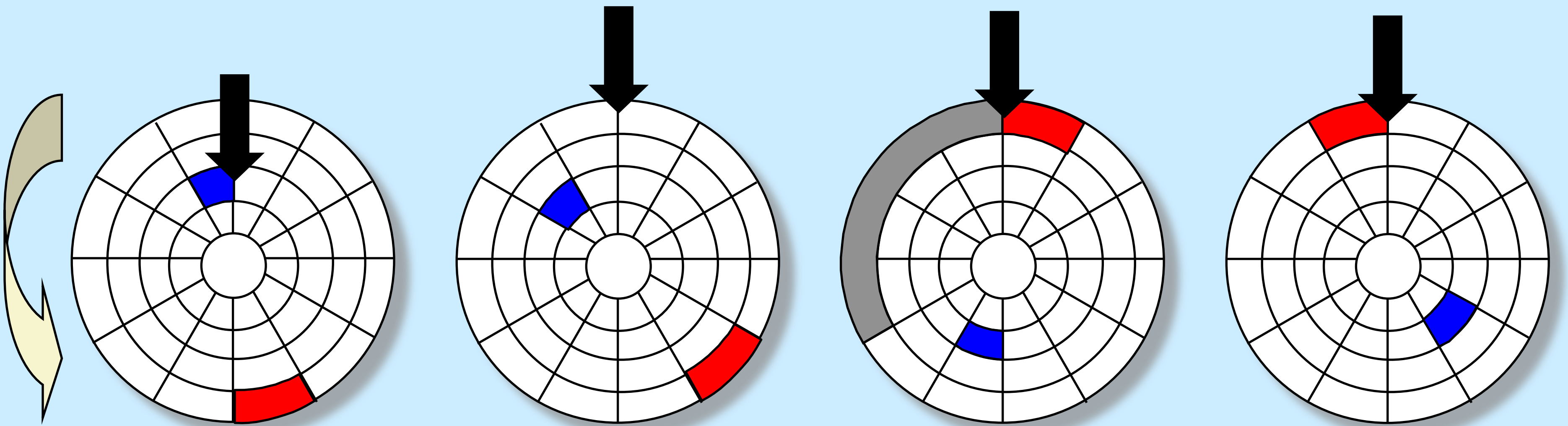
After **BLUE** read

Seek for **RED**

Rotational latency

Wait for red sector to rotate around

Disk Access – Read



After **BLUE** read

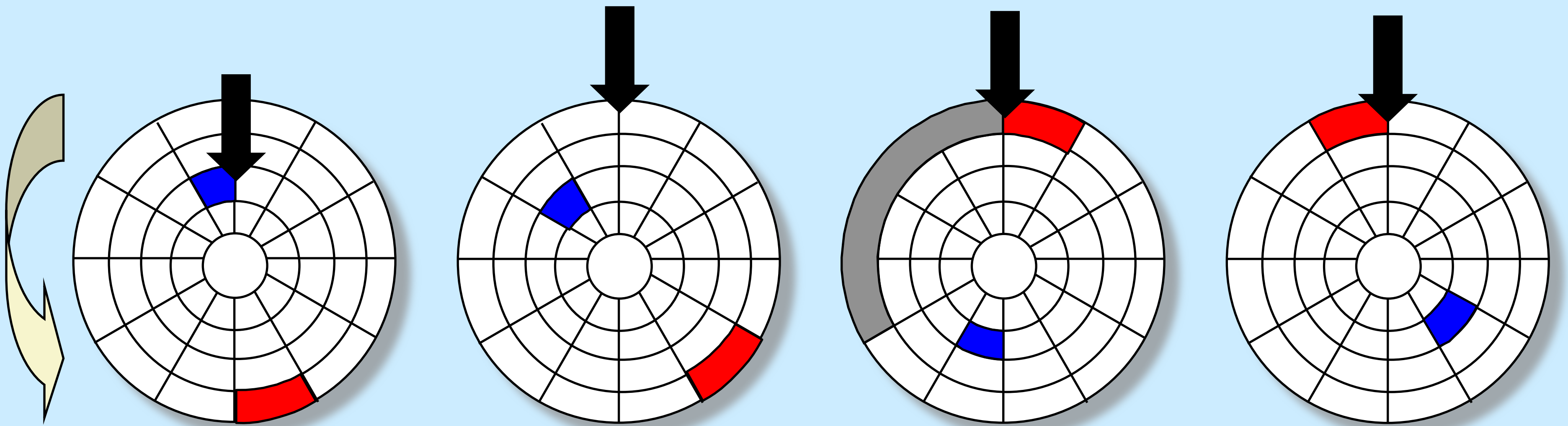
Seek for **RED**

Rotational latency

After **RED** read

Complete read of red

Disk Access – Service Time Components



After **BLUE** read | Seek for **RED** | Rotational latency | After **RED** read

Data transfer | Seek | Rotational latency | Data transfer

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

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

Quiz 1

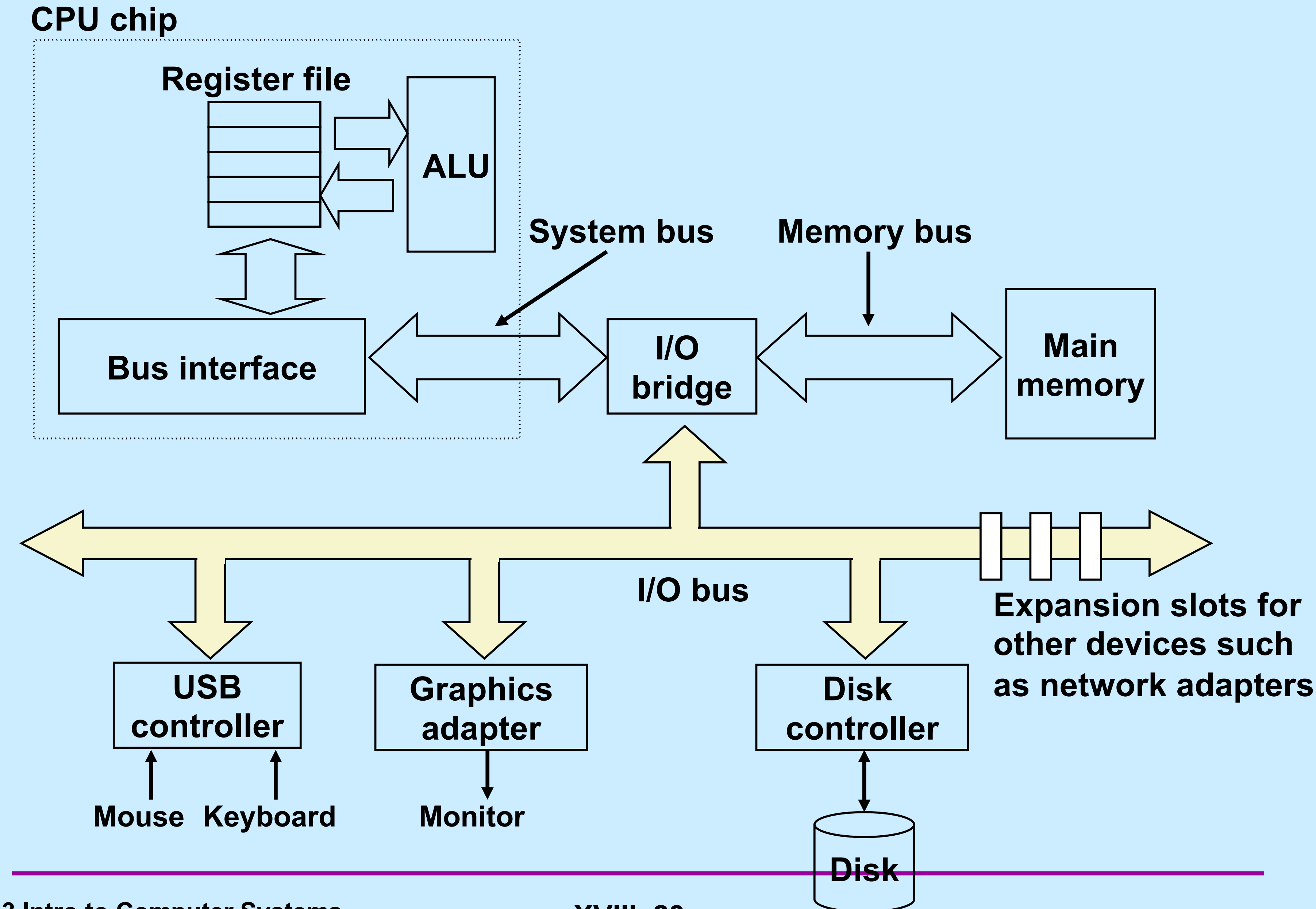
Assuming a 5-inch diameter disk spinning at 10,000 RPM, what is the approximate speed at which the outermost track is moving?

a) faster than a speeding bullet (i.e., supersonic)
b) roughly the speed of a pretty fast car (150 mph)
c) roughly the speed of a pretty slow car (50 mph)
d) roughly the speed of a world-class marathoner (13.1 mph)

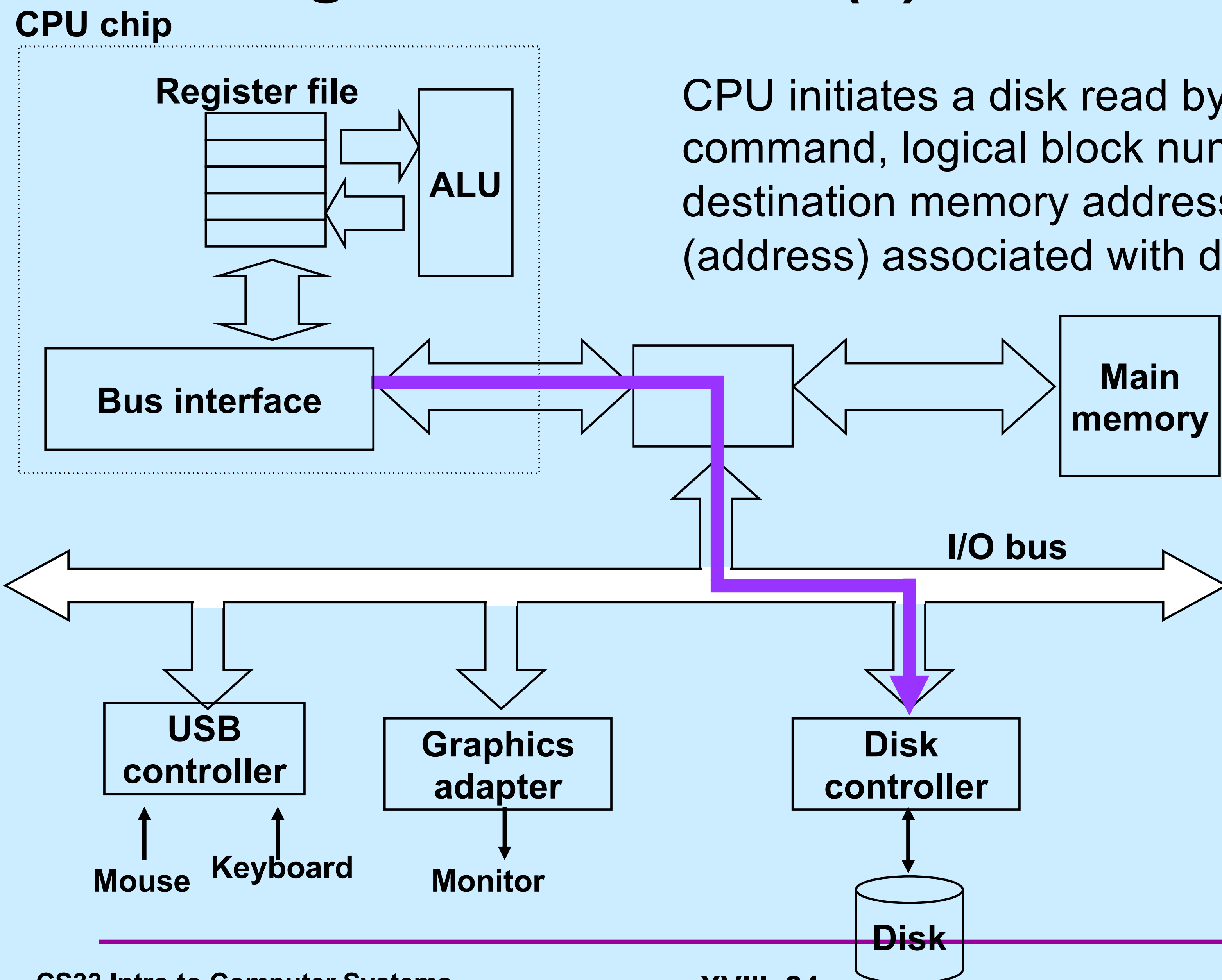
Logical Disk Blocks

- **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”

I/O Bus


CPU chip
Register file
ALU
Bus interface
System bus
Memory bus
I/O
bridge
Main
memory
I/O bus
Expansion slots for
other devices such
as network adapters.
USB
controller
Graphics
adapter
Disk
controller
Mouse
Keyboard
Monitor
Disk

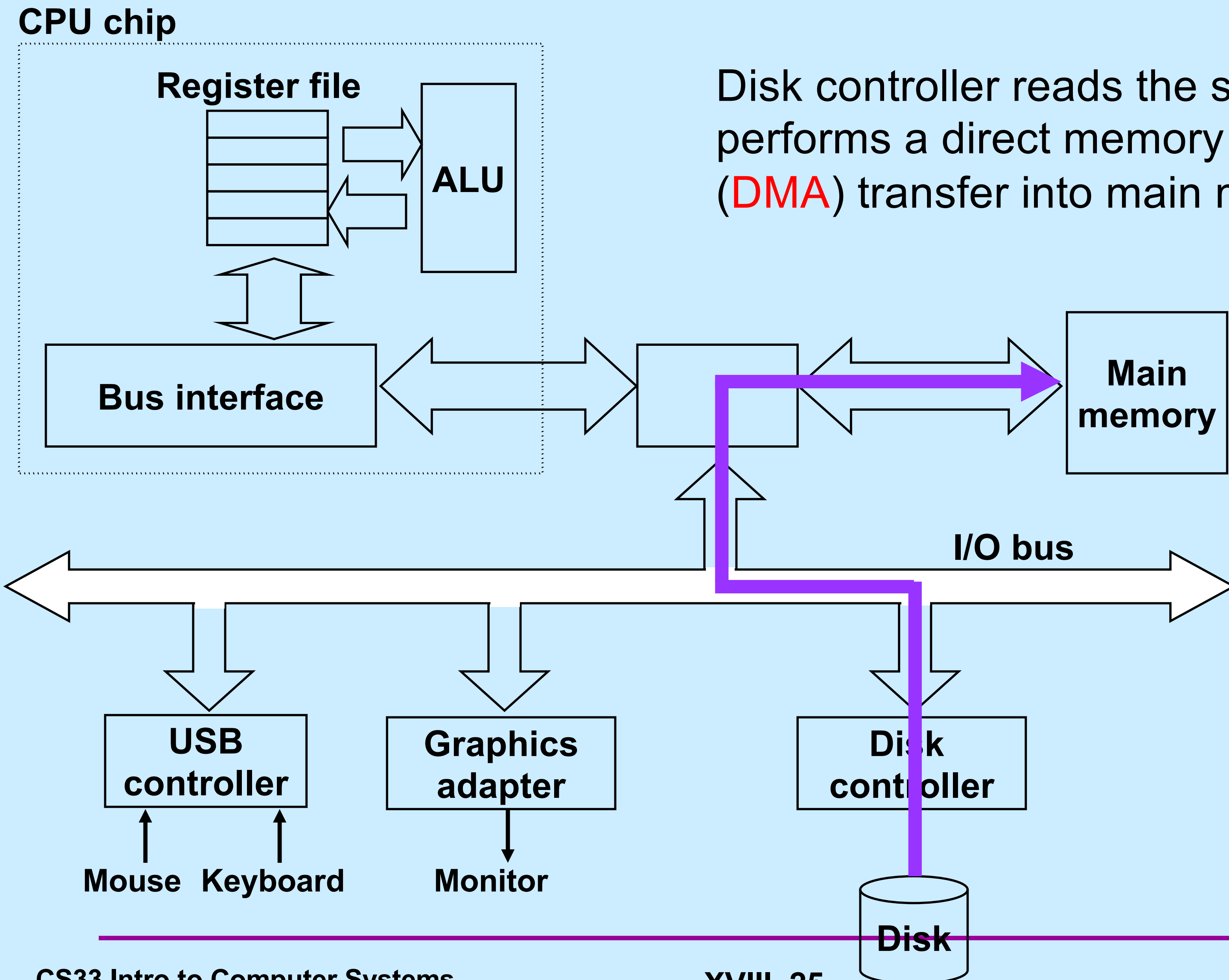
Reading a Disk Sector (1)



CPU initiates a disk read by writing a command, logical block number, and destination memory address to a port (address) associated with disk controller

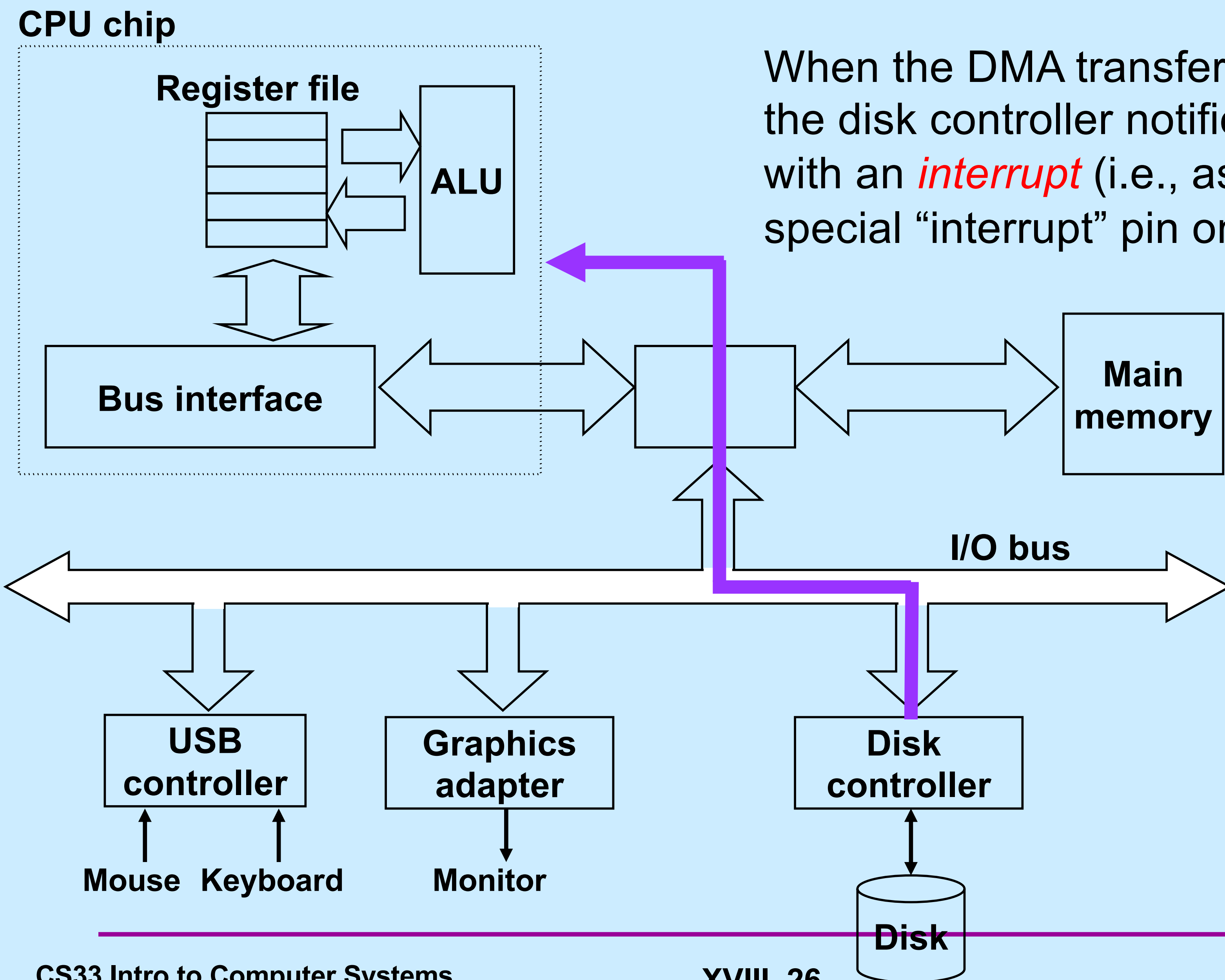
Reading a Disk Sector (2)

Disk controller reads the sector and performs a direct memory access (DMA) transfer into main memory

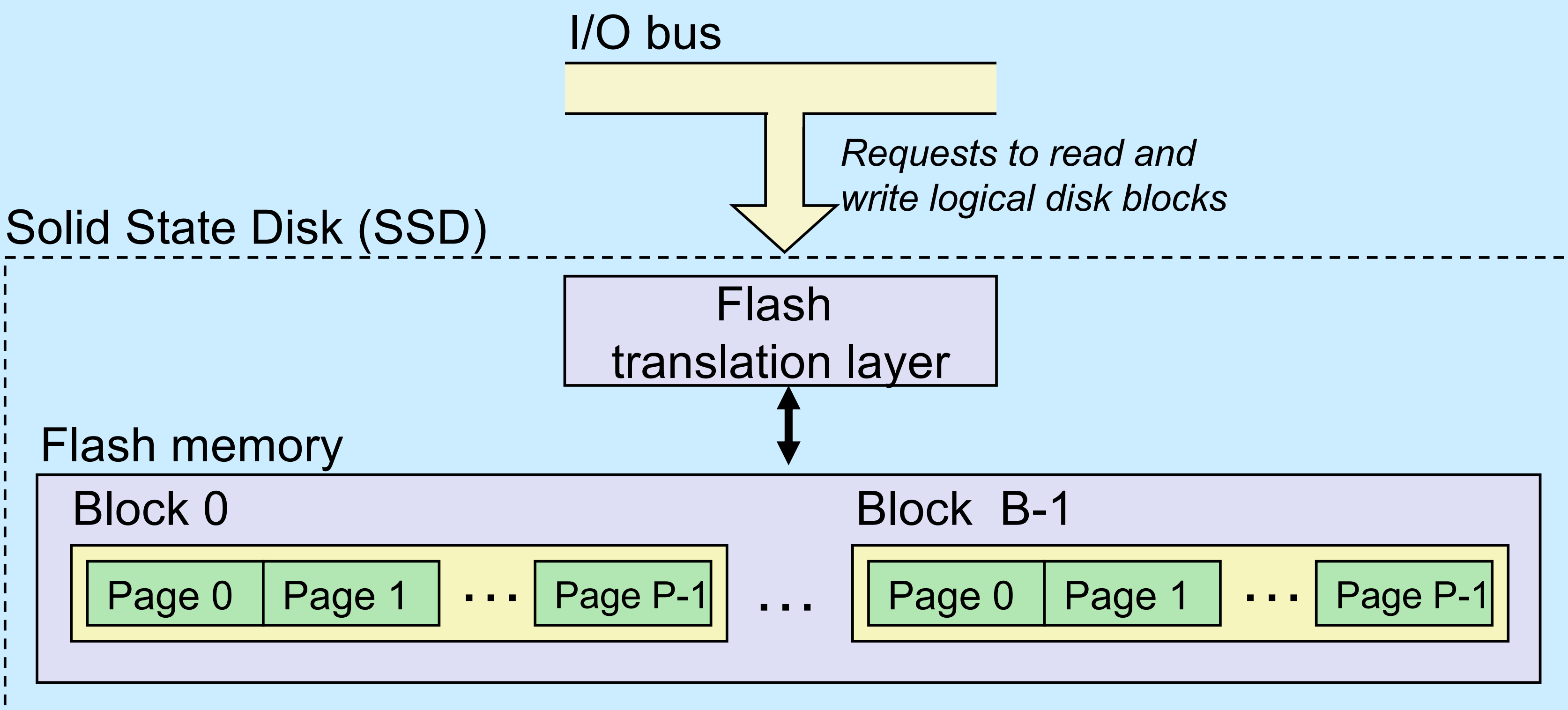


Reading a Disk Sector (3)

When the DMA transfer completes, the disk controller notifies the CPU with an *interrupt* (i.e., asserts a special “interrupt” pin on the CPU)



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**

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

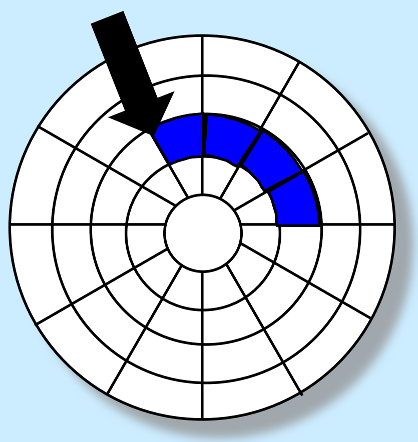
- **Why are random writes so slow?**
  - erasing a block is slow (around 1 ms)
  - modifying a page triggers a copy of all useful pages in the block
    - » find a used block (new block) and erase it
    - » write the page into the new block
    - » copy other pages from old block to the new block

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

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

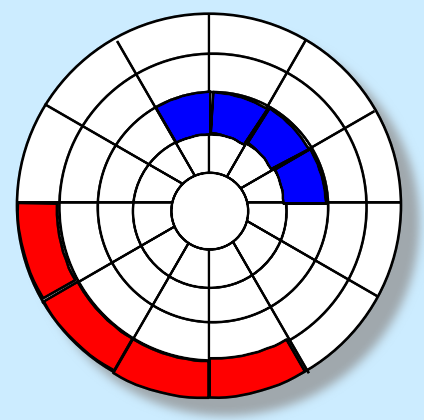
We have two files on the same (rotating) disk. The first file's data resides in consecutive sectors on one track, the second in consecutive sectors on another track. It takes a total of *t* seconds to read all of the first file then all of the second file.

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

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) less time

b) about the same amount of time

c) 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

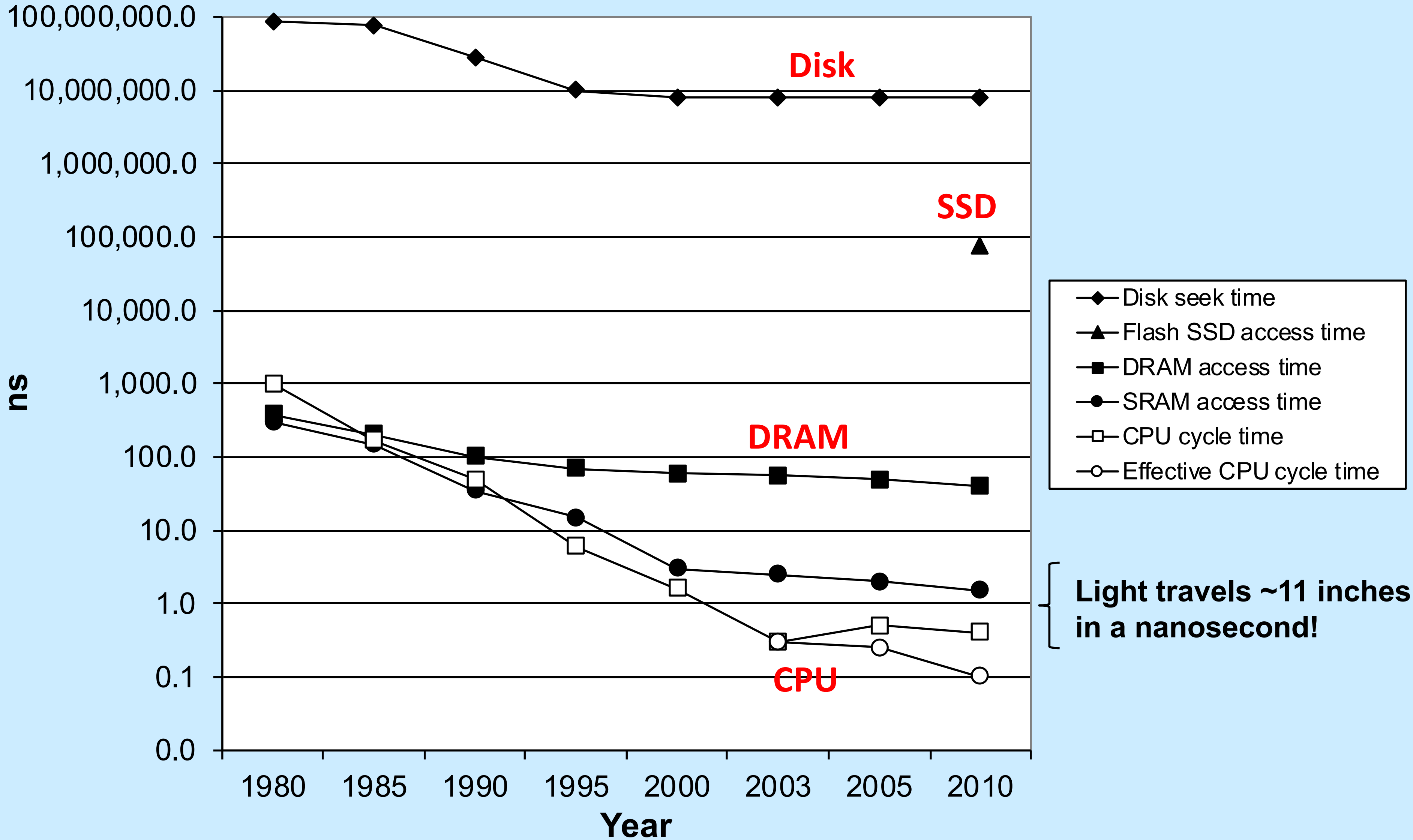
CPU Clock Rates

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

The CPU-Memory Gap

The gap widens between DRAM, disk, and CPU speeds

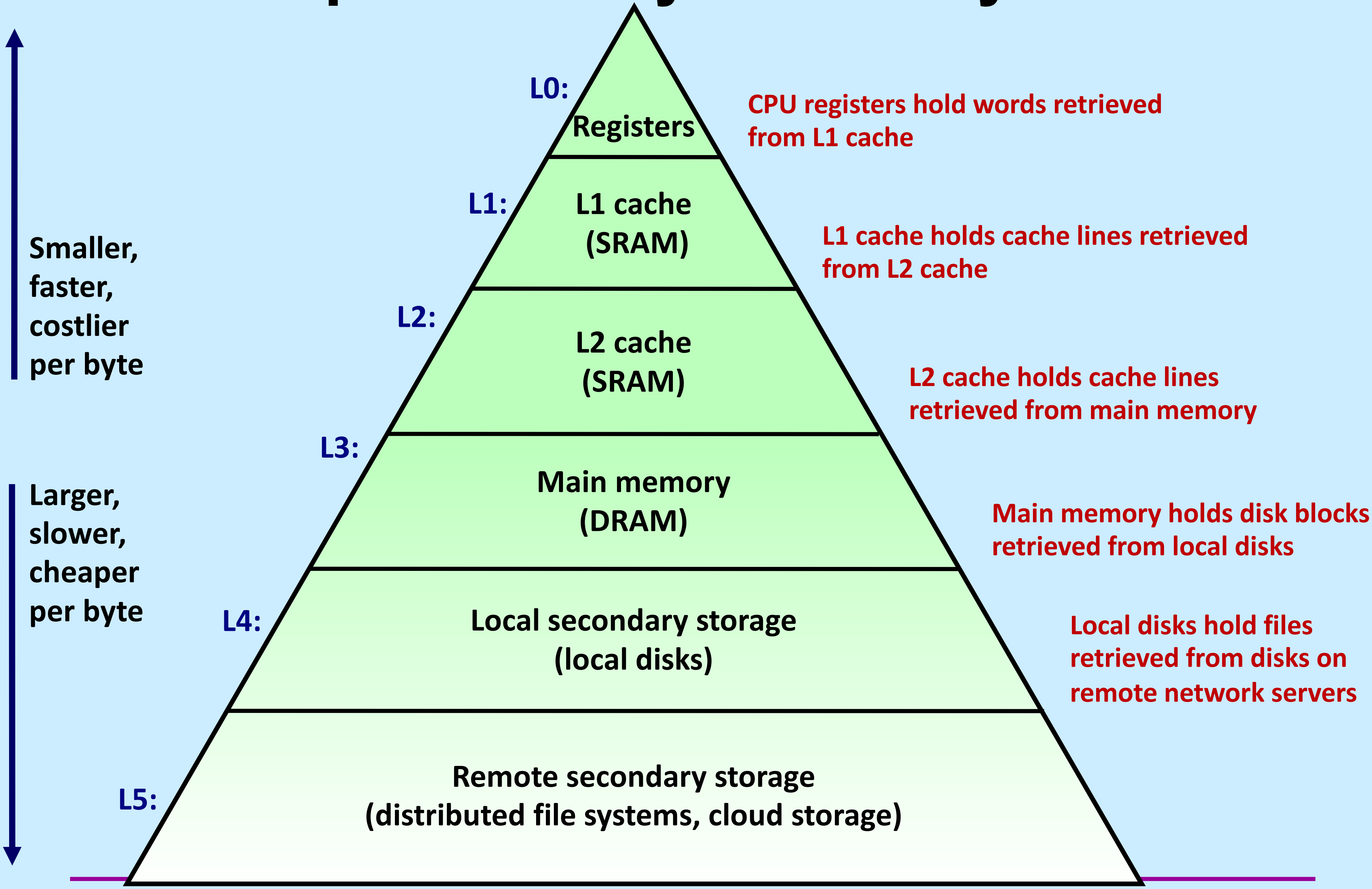


Light travels ~11 inches in a nanosecond!

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

An Example Memory Hierarchy



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

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 strings/performance 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