photo by unsplash.com user @purzlbaum

COMP201

Computer Systems & Programming

Lecture #28 – Buffer Overflow Attacks, The Memory Hierarchy

KOÇ UNIVERSITY

Aykut Erdem // Koç University // Fall 2020

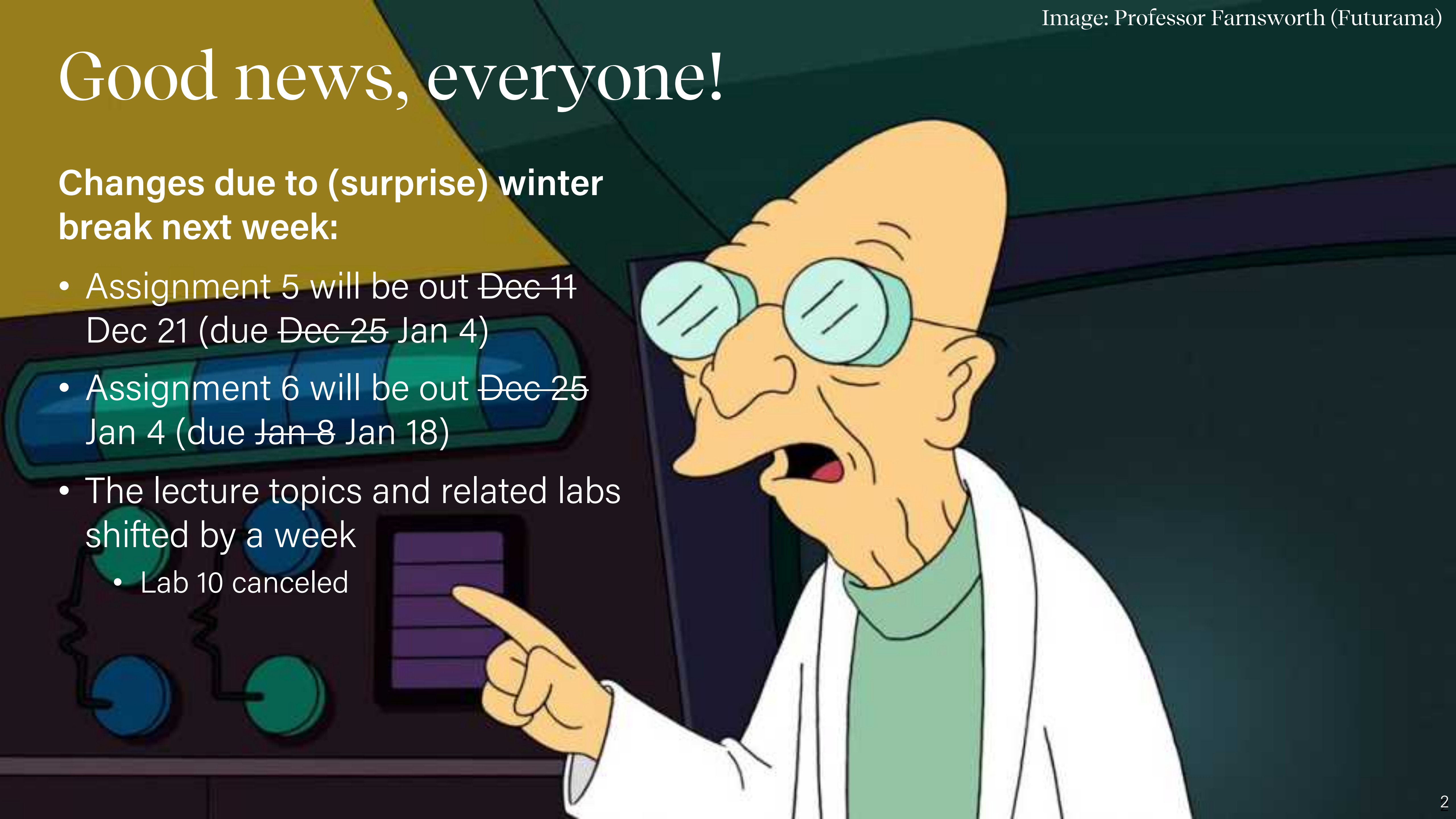


Image: Professor Farnsworth (Futurama)

Good news, everyone!

Changes due to (surprise) winter break next week:

- Assignment 5 will be out ~~Dec 11~~ Dec 21 (due ~~Dec 25~~ Jan 4)
- Assignment 6 will be out ~~Dec 25~~ Jan 4 (due ~~Jan 8~~ Jan 18)
- The lecture topics and related labs shifted by a week
  - Lab 10 canceled

Recap

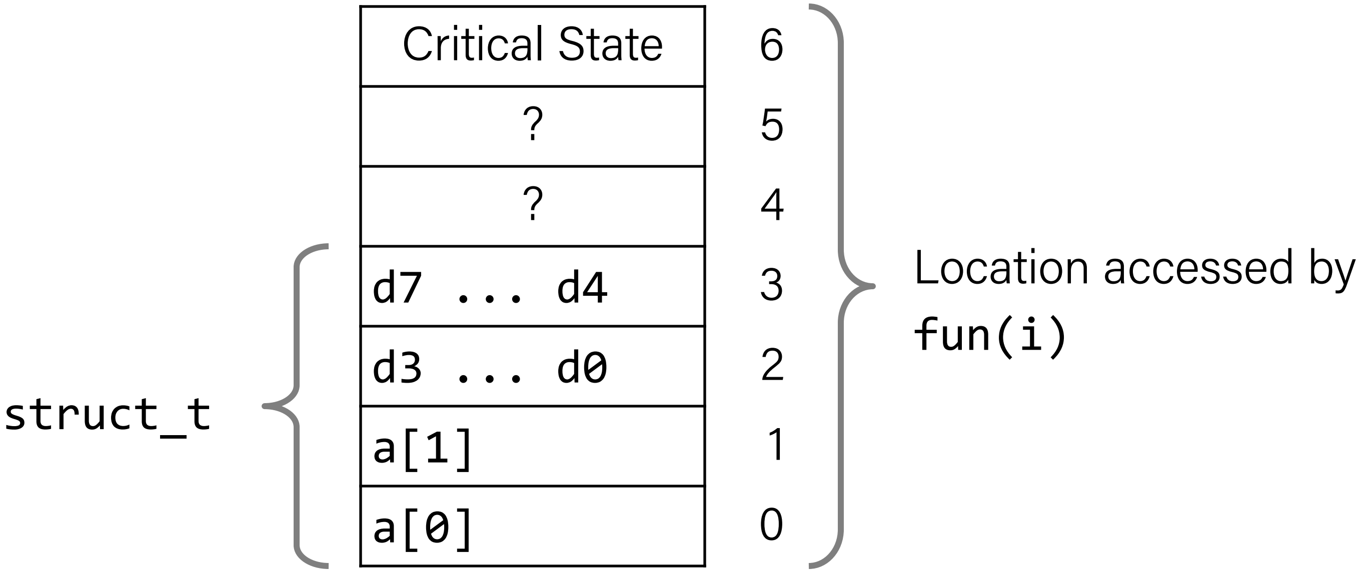
- Structures and Alignment
- Floating Point
- Memory Layout
- Buffer Overflow

Recap: Memory Referencing Bug Example

```
typedef struct {
  int a[2];
  double d;
} struct_t;
```

```
fun(0) → 3.14
fun(1) → 3.14
fun(2) → 3.1399998664856
fun(3) → 2.00000061035156
fun(4) → 3.14
fun(6) → Segmentation fault
```

Explanation:



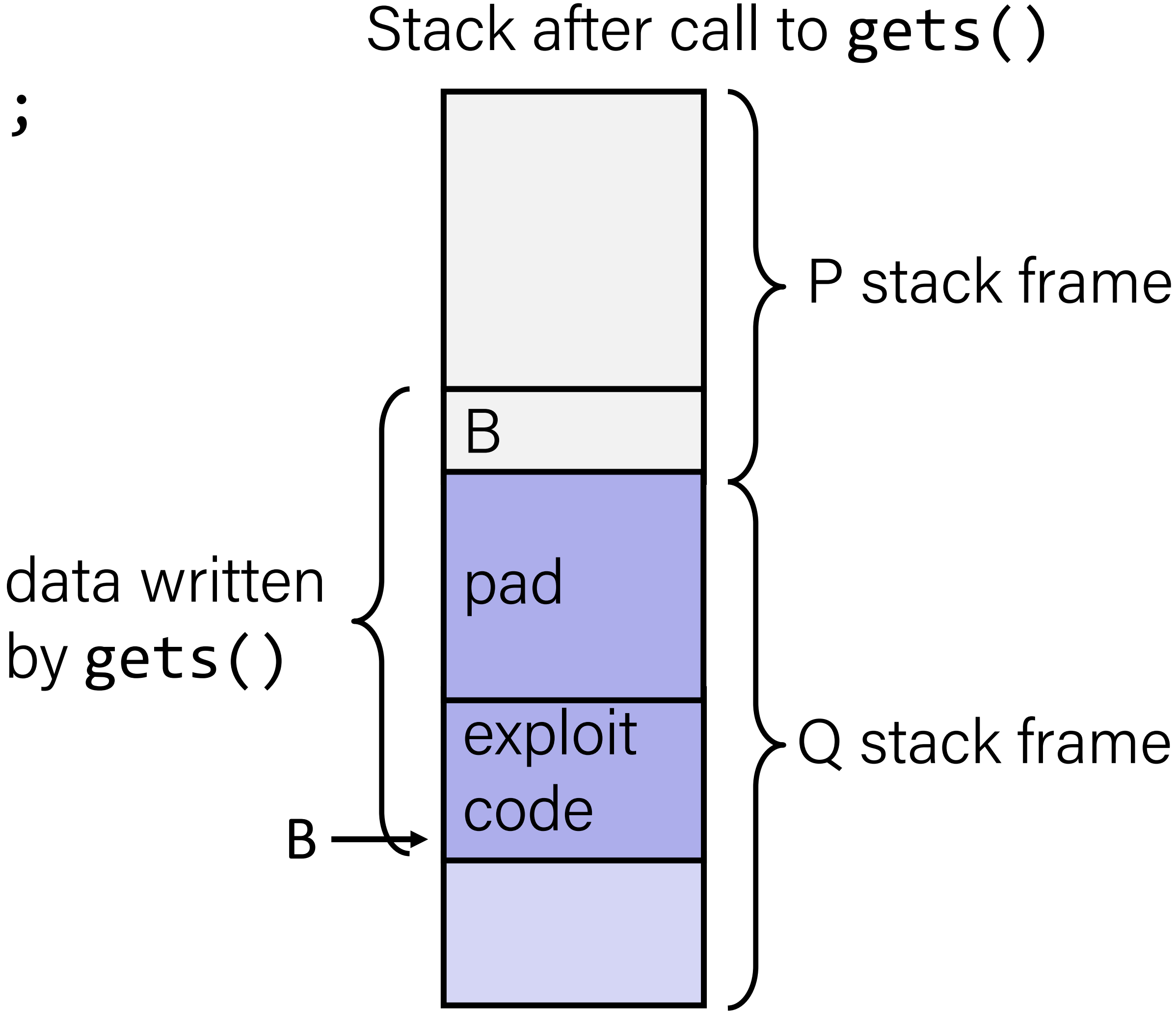
Recap: Code Injection Attacks

```
void P(){
  Q();
  ...
}
```

return address A

```
int Q() {
  char buf[64];
  gets(buf);
  ...
  return ...;
}
```

- Input string contains byte representation of executable code
- Overwrite return address A with address of buffer B
- When Q executes `ret`, will jump to exploit code



Plan for Today

- Buffer overflow attacks and what to do about them
- Storage technologies and trends
- Locality of reference
- Caching in the memory hierarchy

Disclaimer: Slides for this lecture were borrowed from

—Randal E. Bryant and David R. O'Hallaroni's CMU 15-213 class

Lecture Plan

- Buffer overflow attacks and what to do about them
- Storage technologies and trends

Exploits Based on Buffer Overflows

- **Buffer overflow bugs can allow remote machines to execute arbitrary code on victim machines**
- Distressingly common in real programs
  - Programmers keep making the same mistakes ☹️
  - Recent measures make these attacks much more difficult
- Examples across the decades
  - Original “Internet worm” (1988)
  - “IM wars” (1999)
  - Twilight hack on Wii (2000s)
  - ... and many, many more
- You will learn some of the tricks in Assignment 5
  - Hopefully to convince you to never leave such holes in your programs!!

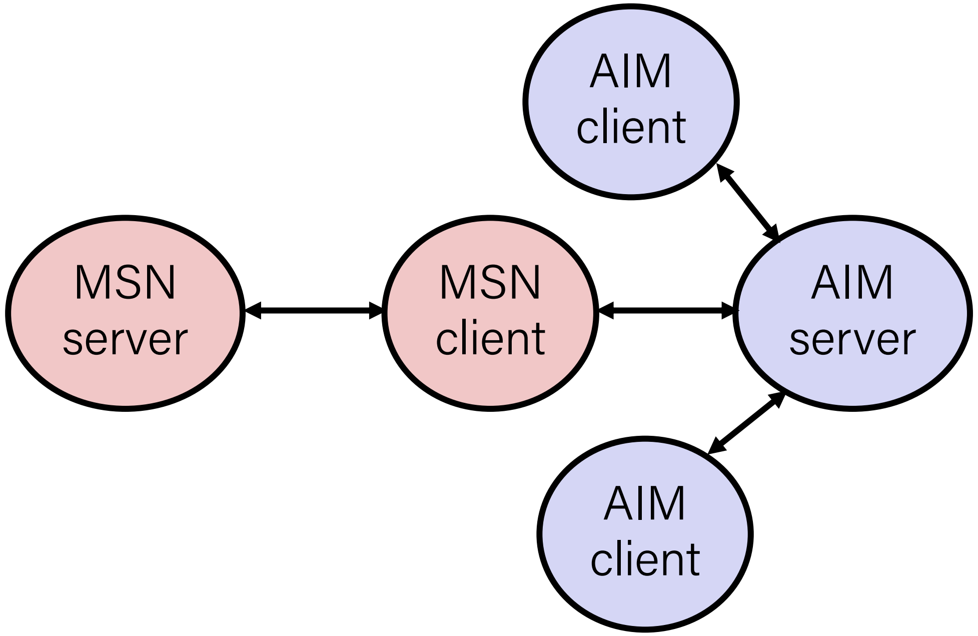
Example: the original Internet worm (1988)

- Exploited a few vulnerabilities to spread
  - Early versions of the finger server (fingerd) used `gets()` to read the argument sent by the client:
    - `finger droh@linuxpool.ku.edu.tr`
  - Worm attacked fingerd server by sending phony argument:
    - `finger “exploit-code  padding  new-return-address”`
    - exploit code: executed a root shell on the victim machine with a direct TCP connection to the attacker.
- Once on a machine, scanned for other machines to attack
  - invaded ~6000 computers in hours (10% of the Internet 🙂)
    - see June 1989 article in Comm. of the ACM
  - the young author of the worm was prosecuted…
  - and CERT was formed… homed at CMU

Example 2: IM War

July 1999:

- Microsoft launches MSN Messenger (instant messaging system).
- Messenger clients can access popular AOL Instant Messaging Service (AIM) servers



IM War (cont.)

August 1999:

- Mysteriously, Messenger clients can no longer access AIM servers
- Microsoft and AOL begin the IM war:
  - AOL changes server to disallow Messenger clients
  - Microsoft makes changes to clients to defeat AOL changes
  - At least 13 such skirmishes
- What was really happening?
  - AOL had discovered a buffer overflow bug in their own AIM clients
  - They exploited it to detect and block Microsoft: the exploit code returned a 4-byte signature (the bytes at some location in the AIM client) to server
  - When Microsoft changed code to match signature, AOL changed signature location

```
Date: Wed, 11 Aug 1999 11:30:57 -0700 (PDT)
From: Phil Bucking <philbucking@yahoo.com>
Subject: AOL exploiting buffer overrun bug in their own software!
To: rms@pharlap.com

Mr. Smith,

I am writing you because I have discovered something that I think you
might find interesting because you are an Internet security expert with
experience in this area. I have also tried to contact AOL but received
no response.

I am a developer who has been working on a revolutionary new instant
messaging client that should be released later this year.
...
It appears that the AIM client has a buffer overrun bug. By itself
this might not be the end of the world, as MS surely has had its share.
But AOL is now *exploiting their own buffer overrun bug* to help in
its efforts to block MS Instant Messenger.
....
Since you have significant credibility with the press I hope that you
can use this information to help inform people that behind AOL's
friendly exterior they are nefariously compromising peoples' security.

Sincerely,
Phil Bucking
Founder, Bucking Consulting
philbucking@yahoo.com
```

It was later determined that this email originated from within Microsoft!

Aside: Worms and Viruses

- **Worm:** A program that
  - Can run by itself
  - Can propagate a fully working version of itself to other computers
- **Virus:** Code that
  - Adds itself to other programs
  - Does not run independently
- Both are (usually) designed to spread among computers and to wreak havoc

OK, what to do about buffer overflow attacks

- Avoid overflow vulnerabilities
- Employ system-level protections
- Have compiler use “stack canaries”

1. Avoid Overflow Vulnerabilities in Code (!)

```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    fgets(buf, 4, stdin);
    puts(buf);
}
```

For example, use library routines that limit string lengths

- `fgets` instead of `gets`
- `strncpy` instead of `strcpy`
- Don't use `scanf` with `%s` conversion specification
  - Use `fgets` to read the string
  - Or use `%ns` where `n` is a suitable integer

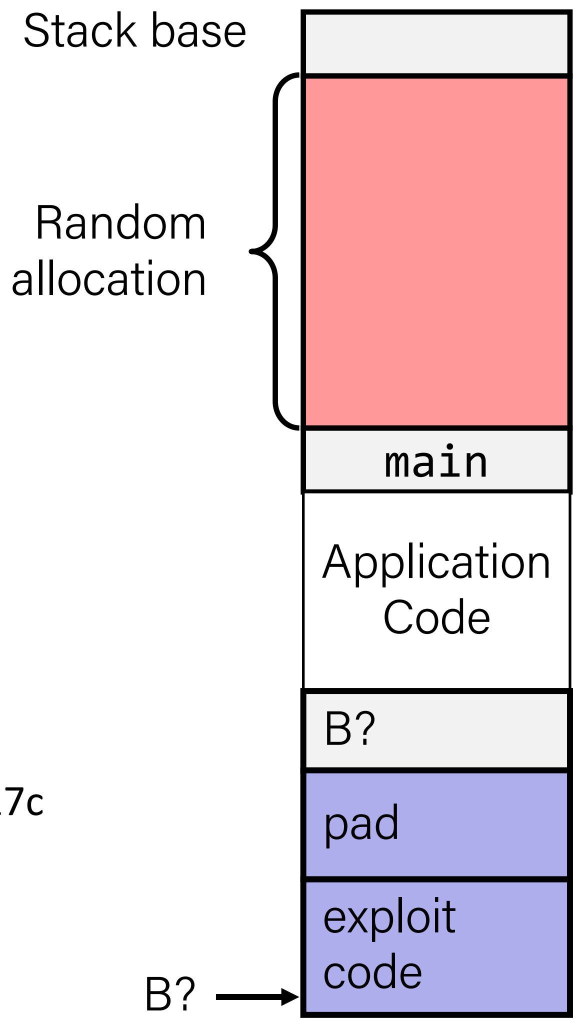
2. System-Level Protections can help

Randomized stack offsets

- At start of program, allocate random amount of space on stack
- Shifts stack addresses for entire program
- Makes it difficult for hacker to predict beginning of inserted code
- E.g.: 5 executions of memory allocation code

local	0x7ffe4d3be87c	0x7fff75a4f9fc	0x7ffeadb7c80c	0x7ffeaea2fdac	0x7ffcd452017c

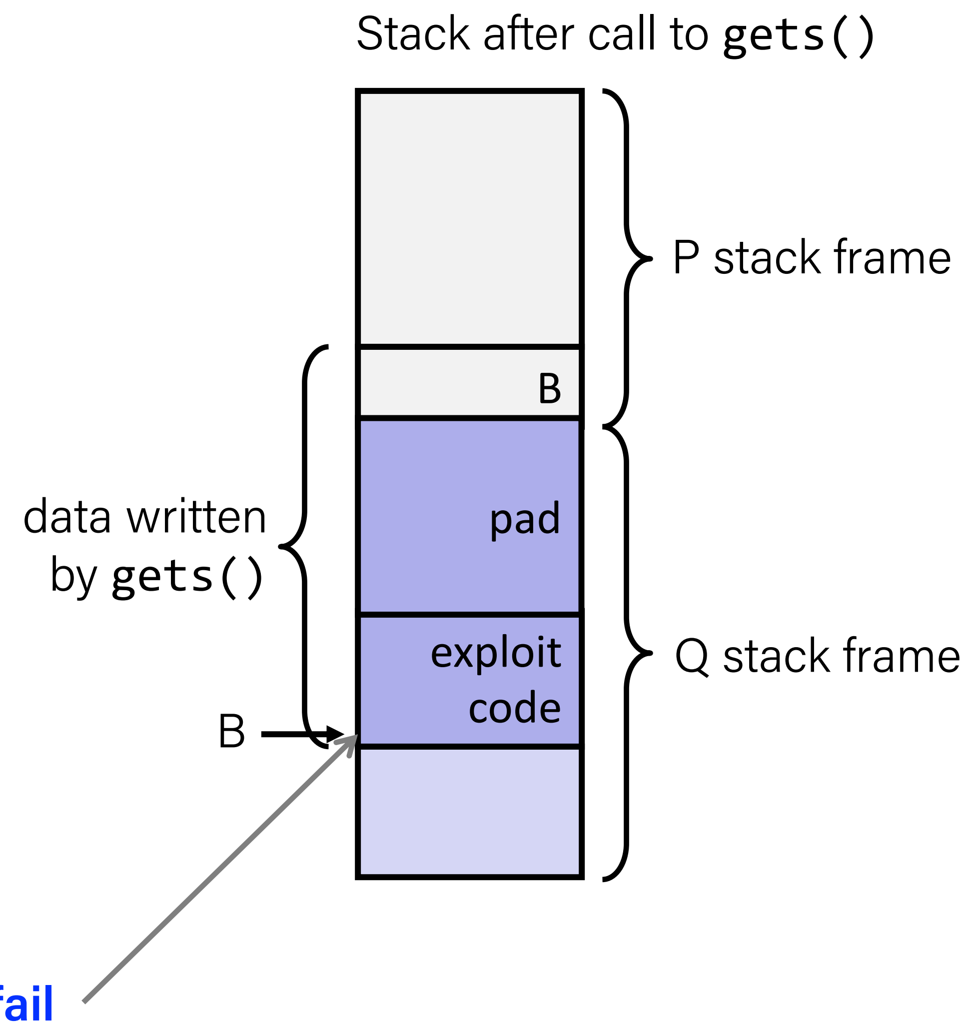
  - Stack repositioned each time program executes



2. System-Level Protections can help

Nonexecutable code segments

- In traditional x86, can mark region of memory as either “read-only” or “writeable”
  - ~~Can execute anything readable~~
- X86-64 added explicit “execute” permission
- Stack marked as non-executable



Any attempt to execute this code will fail

3. Stack Canaries can help

Idea:

- Place special value (“canary”) on stack just beyond buffer
- Check for corruption before exiting function

GCC Implementation

- `-fstack-protector`
- Now the default (disabled earlier)

```
unix>./bufdemo-sp
Type a string:
0123456
0123456
```

```
unix>./bufdemo-sp
Type a string:
01234567
*** stack smashing detected ***
```

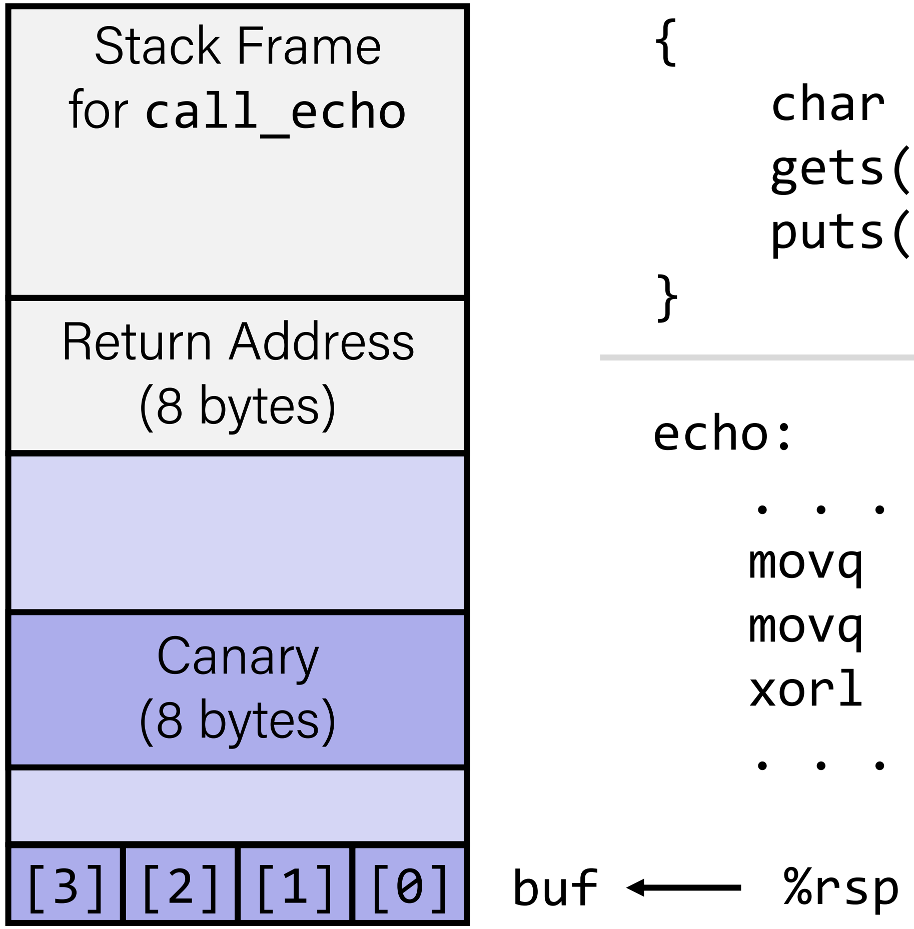
Protected Buffer Disassembly

```
echo:

  40072f: sub    $0x18,%rsp
  400733: mov    %fs:0x28,%rax
  40073c: mov    %rax,0x8(%rsp)
  400741: xor    %eax,%eax
  400743: mov    %rsp,%rdi
  400746: callq  4006e0 <gets>
  40074b: mov    %rsp,%rdi
  40074e: callq  400570 <puts@plt>
  400753: mov    0x8(%rsp),%rax
  400758: xor    %fs:0x28,%rax
  400761: je     400768 <echo+0x39>
  400763: callq  400580 <__stack_chk_fail@plt>
  400768: add    $0x18,%rsp
  40076c: retq
```

Setting Up Canary

Before call to gets

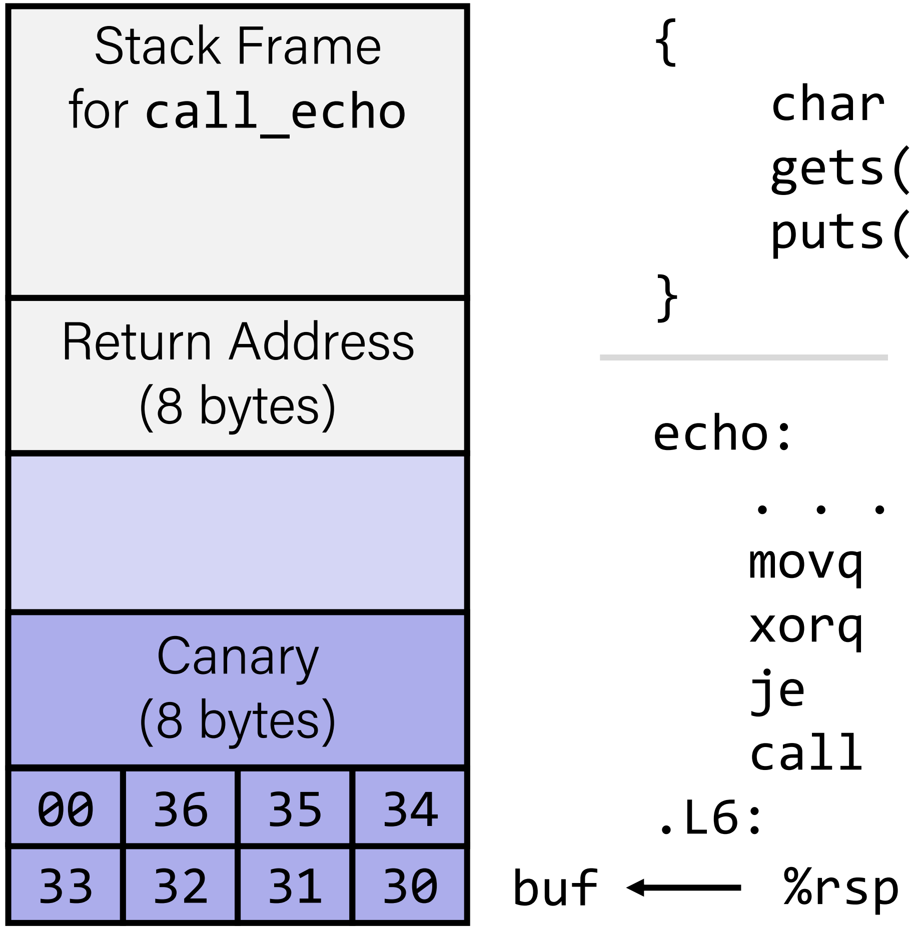



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
    . . .
    movq    %fs:40, %rax  # Get canary
    movq    %rax, 8(%rsp) # Place on stack
    xorl    %eax, %eax    # Erase canary
    . . .
```

Checking Canary

After call to gets




```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

Input: `0123456`

```
echo:
    . . .
    movq    8(%rsp), %rax     # Retrieve from stack
    xorq    %fs:40, %rax      # Compare to canary
    je      .L6               # If same, OK
    call    __stack_chk_fail  # FAIL
.L6:        . . .
```

Demo: Stack Canaries

`bufdemo.c`

Return-Oriented Programming Attacks

- Challenge (for hackers)
  - Stack randomization makes it hard to predict buffer location
  - Marking stack nonexecutable makes it hard to insert binary code
- Alternative Strategy
  - Use existing code
    - E.g., library code from stdlib
  - String together fragments to achieve overall desired outcome
  - *Does not overcome stack canaries*
- Construct program from gadgets
  - Sequence of instructions ending in `ret`
    - Encoded by single byte `0xc3`
  - Code positions fixed from run to run
  - Code is executable

Gadget Example #1

```
long ab_plus_c
  (long a, long b, long c) {
   return a*b + c;
}
```

```
00000000004004d0 <ab_plus_c>:
  4004d0:  48 0f af fe  imul %rsi,%rdi
  4004d4:  48 8d 04 17  lea (%rdi,%rdx,1),%rax
  4004d8:  c3           retq
```

rax ← rdi + rdx

Gadget address = `0x4004d4`

- Use tail end of existing functions

Gadget Example #2

```
void setval(unsigned *p) {
    *p = 3347663060u;
}
```

Encodes `movq %rax, %rdi`

```
<setval>:
  4004d9:  c7 07 d4 48 89 c7  movl  $0xc78948d4,(%rdi)
  4004df:  c3                 retq
```

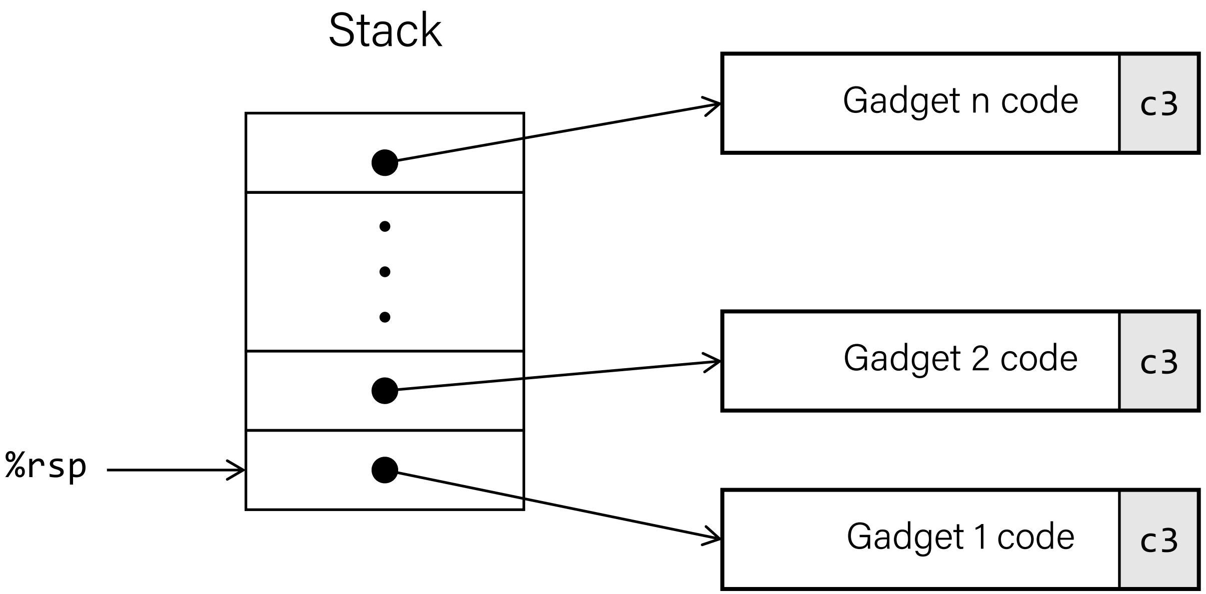
rdi ← rax

Gadget address = `0x4004dc`

- Repurpose byte codes

ROP Execution

- Trigger with `ret` instruction
  - Will start executing Gadget 1
- Final `ret` in each gadget will start next one



COMP201 Topic 7: How does the memory system is organized as a hierarchy of different storage devices with unique capacities?

Lecture Plan

- Buffer overflow attacks and what to do about them
- Storage technologies and trends

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.

- RAM comes in two varieties:
  - SRAM (Static RAM)
  - DRAM (Dynamic RAM)

SRAM vs DRAM Summary

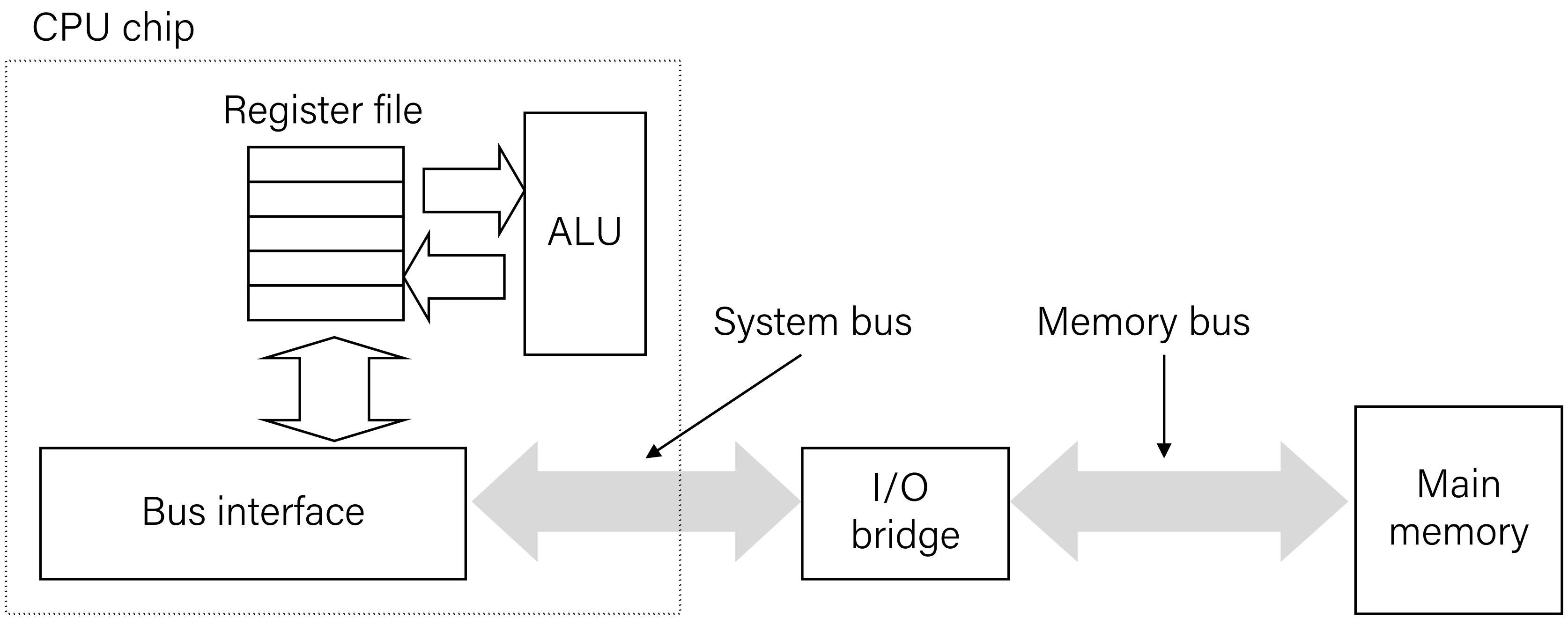
	Trans. per bit	Access time	Needs refresh?	Need EDC?	Cost	Applications
SRAM	4 or 6	1X	No	Maybe	100X	Cache memories
DRAM	1	10X	Yes	Yes	1X	Main memories, frame buffers

Nonvolatile Memories

- **DRAM and SRAM are volatile memories**
  - Lose information if powered off.
- **Nonvolatile memories retain value even if powered off**
  - Read-only memory (**ROM**): programmed during production
  - Programmable ROM (**PROM**): can be programmed once
  - Eraseable PROM (**EPROM**): can be bulk erased (UV, X-Ray)
  - Electrically eraseable PROM (**EEPROM**): electronic erase capability
  - Flash memory: EEPROMs. with partial (block-level) erase capability
    - Wears out after about 100,000 erasings
- **Uses for Nonvolatile Memories**
  - Firmware programs stored in a ROM (BIOS, controllers for disks, network cards, graphics accelerators, security subsystems,...)
  - Solid state disks (replace rotating disks in thumb drives, smart phones, mp3 players, tablets, laptops,...)
  - Disk caches

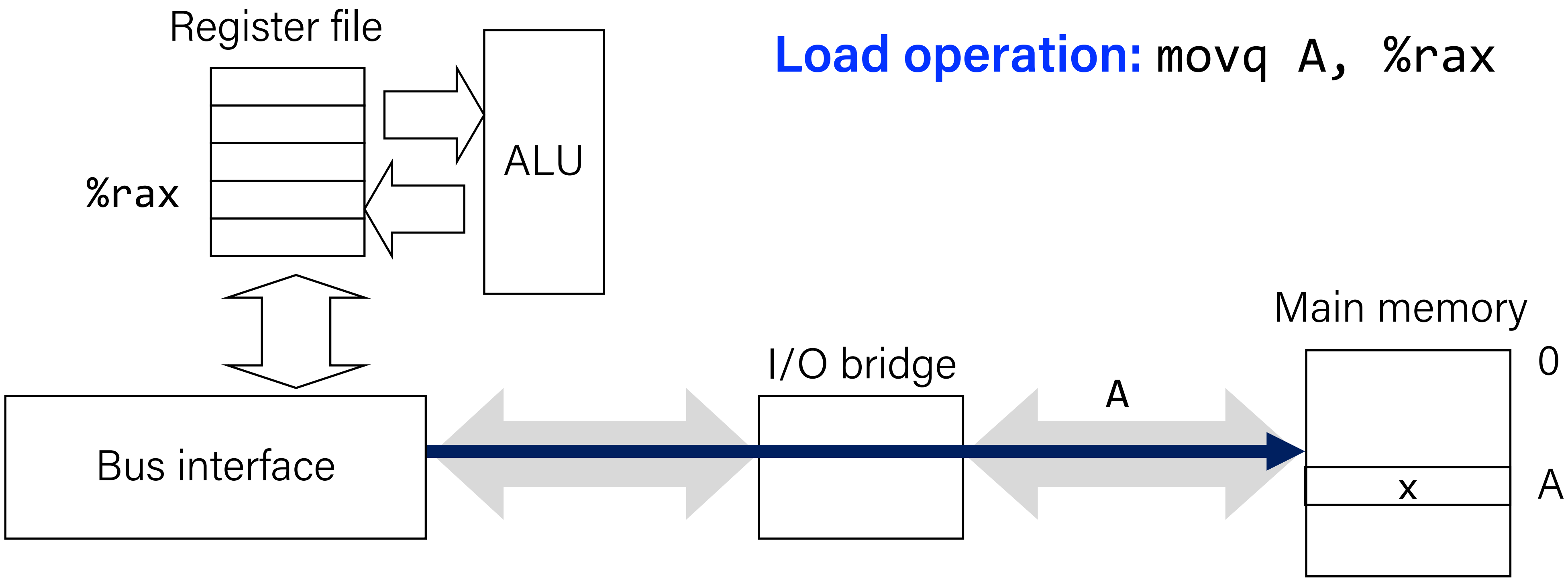
Traditional Bus Structure Connecting CPU and Memory

- A bus is a collection of parallel wires that carry address, data, and control signals.
- Buses are typically shared by multiple devices.



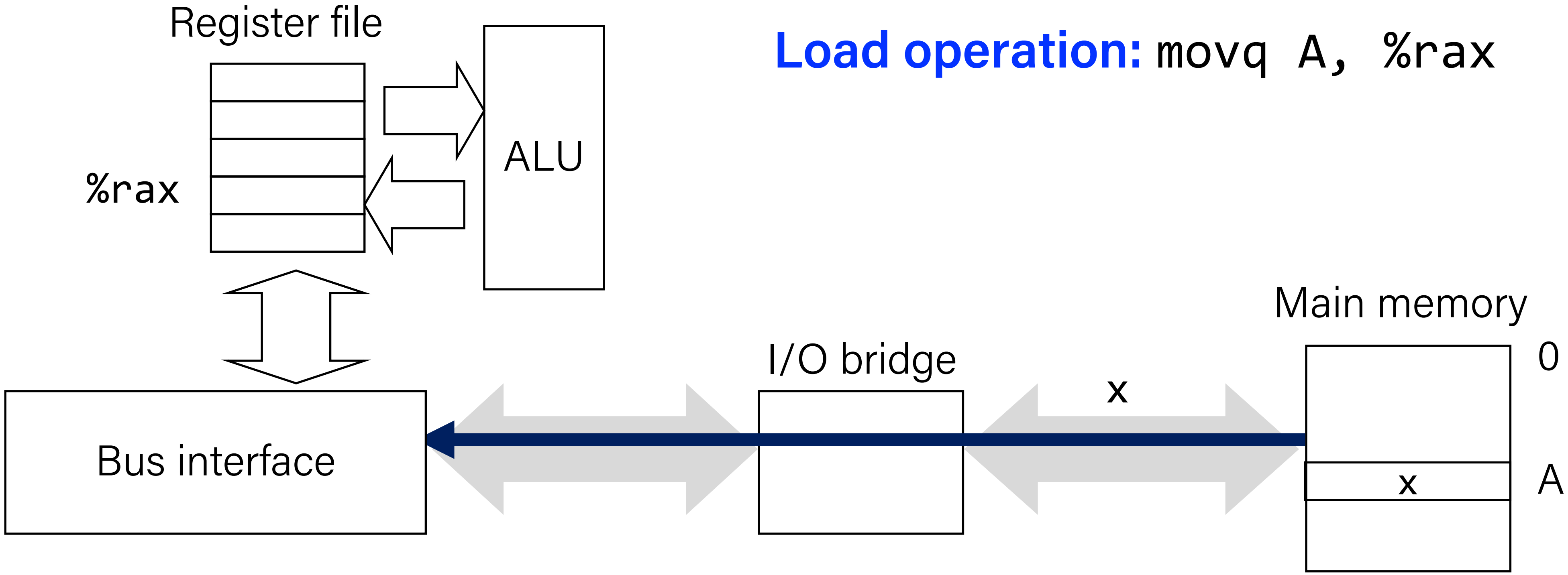
Memory Read Transaction (1)

- CPU places address `A` on the memory bus.



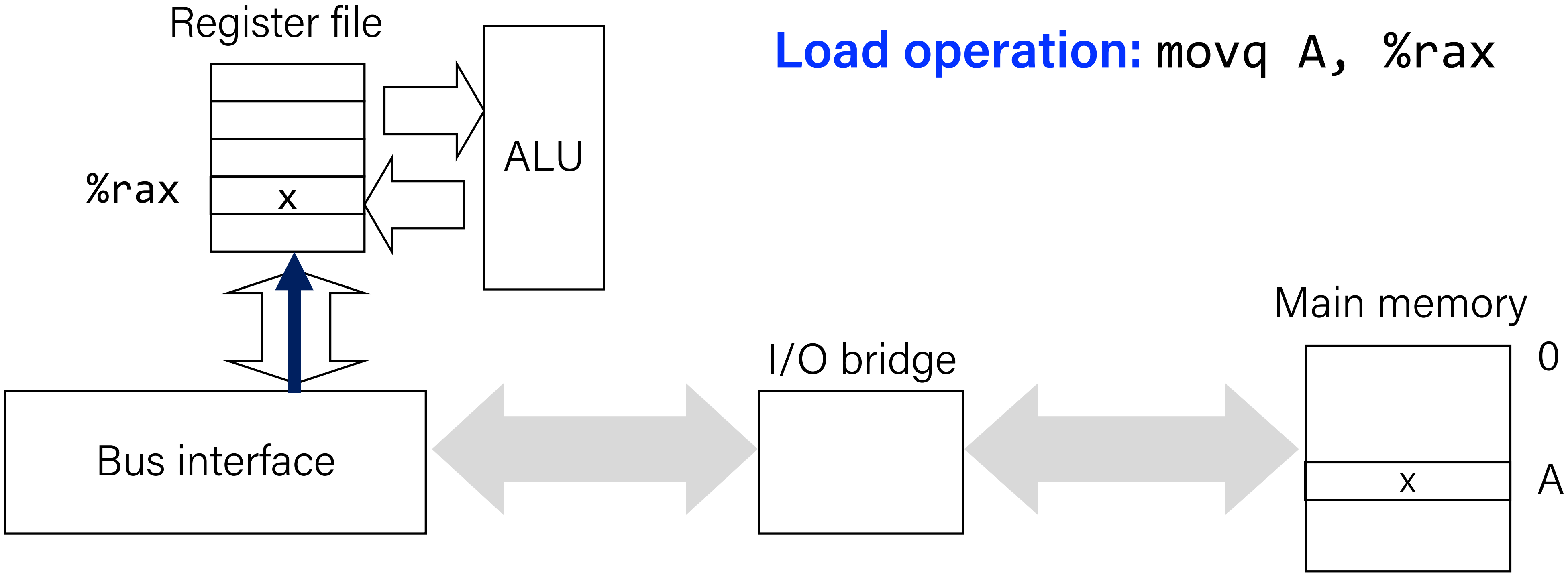
Memory Read Transaction (2)

- Main memory reads `A` from the memory bus, retrieves word `x`, and places it on the bus.



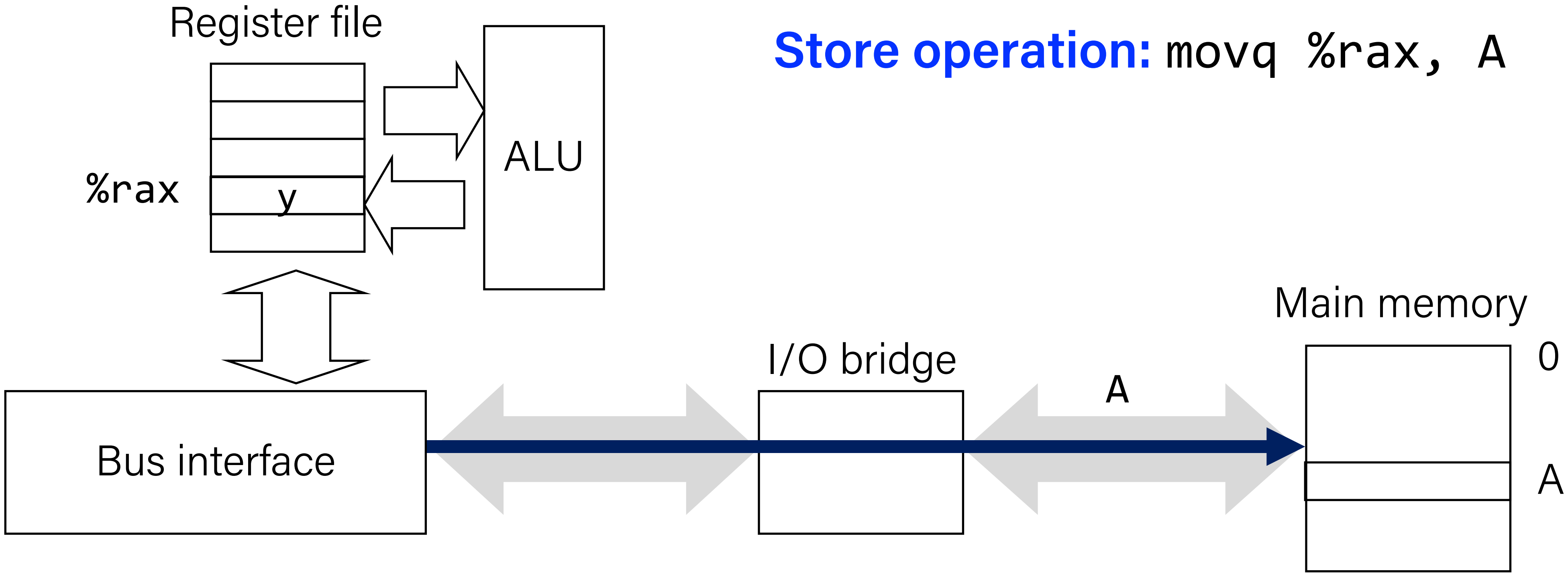
Memory Read Transaction (3)

- CPU read word `x` from the bus and copies it into register `%rax`.



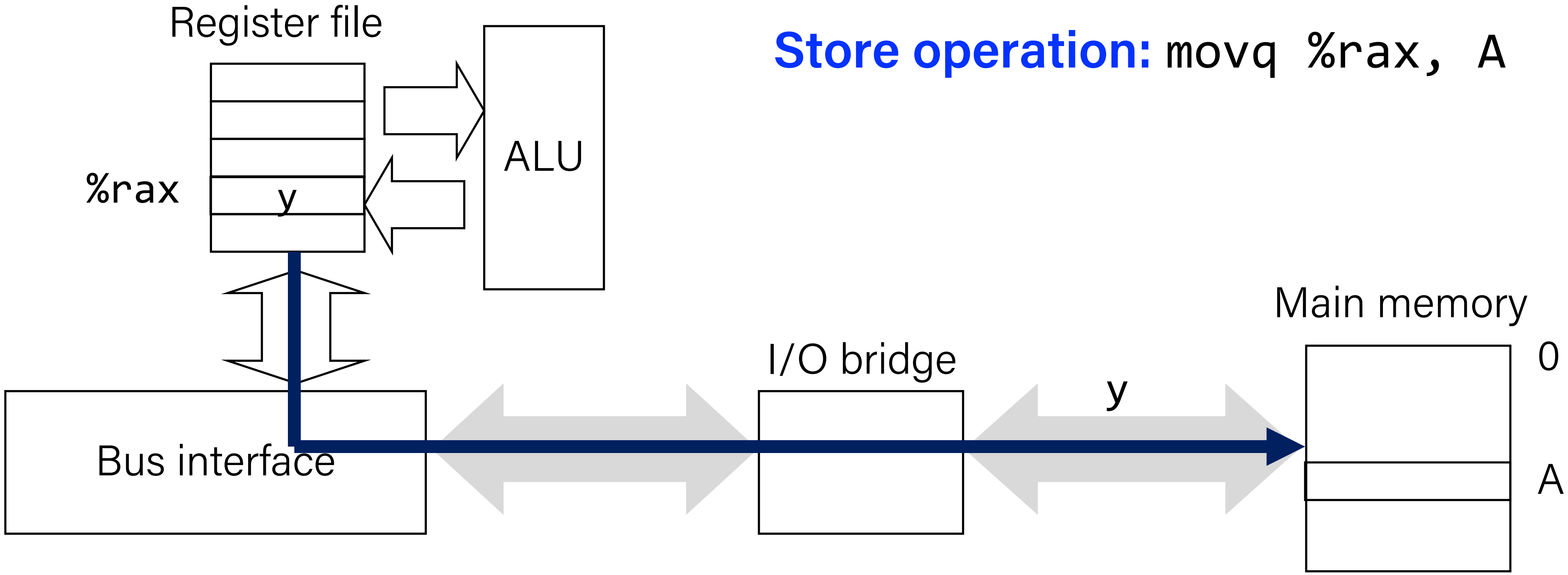
Memory Write Transaction (1)

- CPU places address `A` on bus. Main memory reads it and waits for the corresponding data word to arrive.



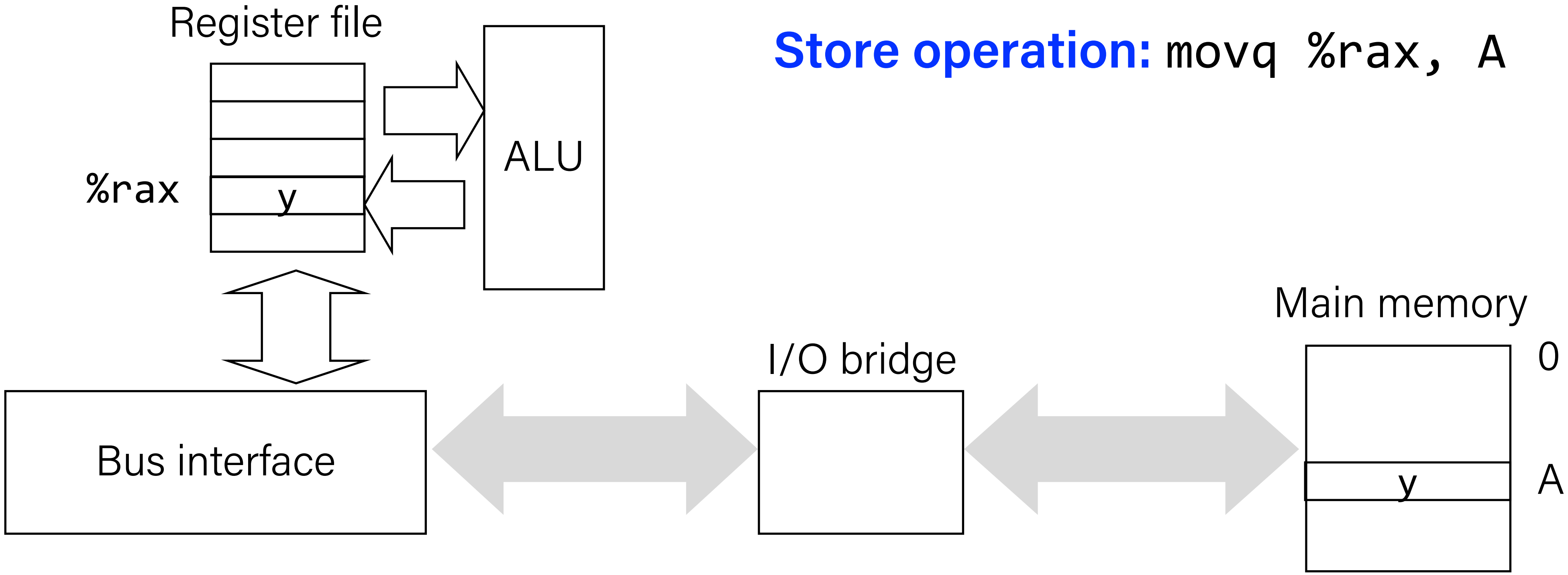
Memory Write Transaction (2)

- CPU places data word y on the bus.



Memory Write Transaction (3)

- Main memory reads data word `y` from the bus and stores it at address `A`.



What's Inside A Disk Drive?

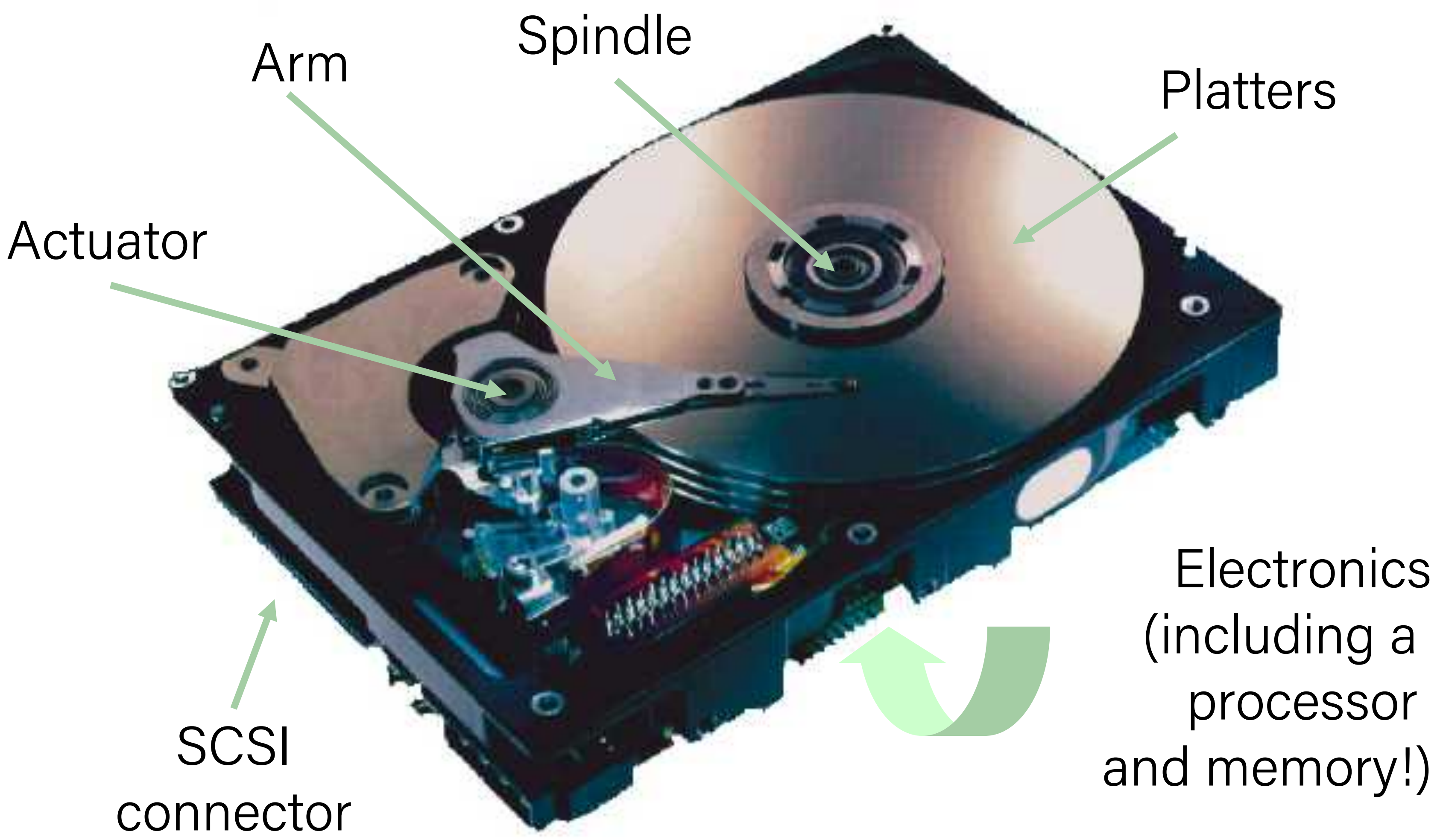
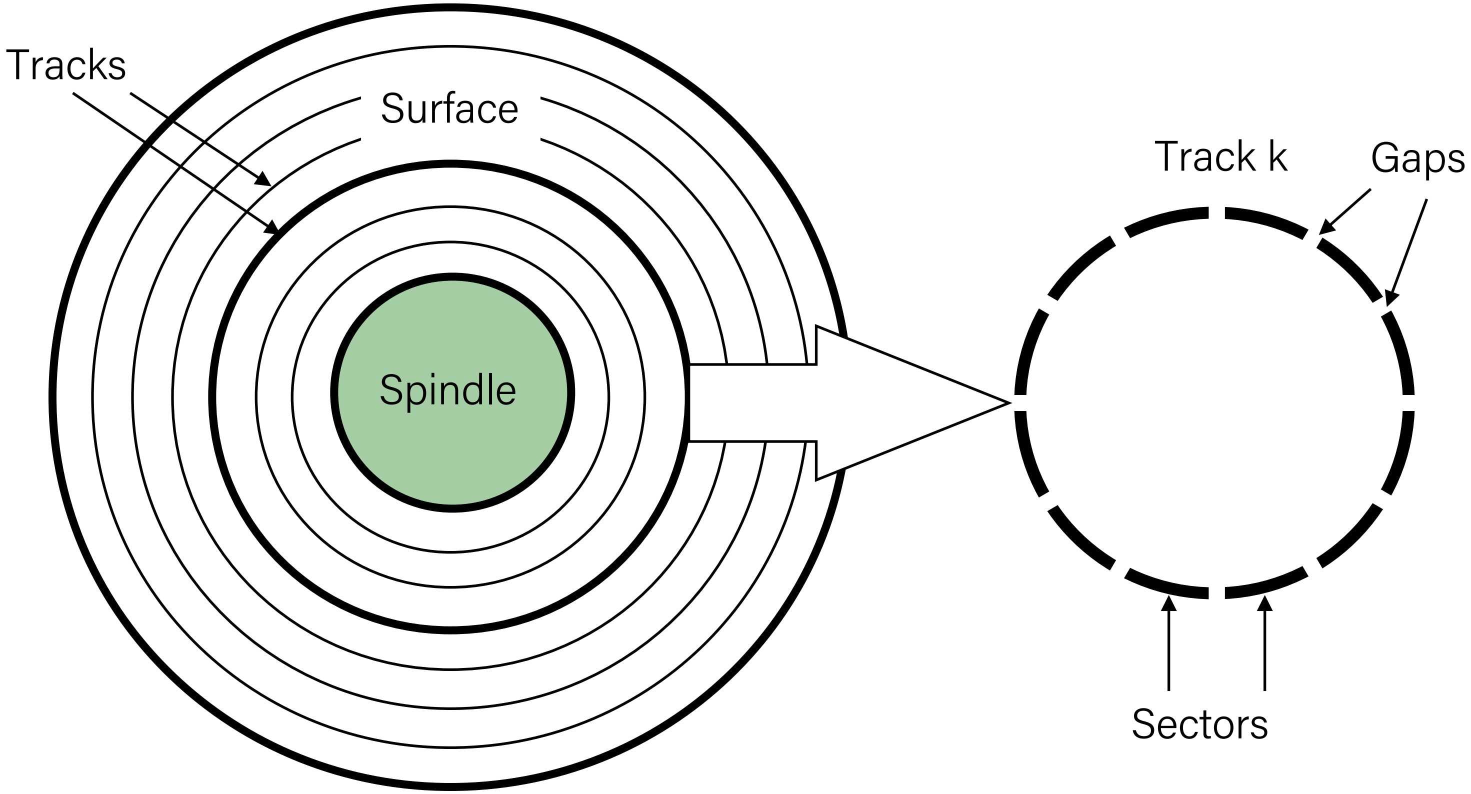


Image courtesy of Seagate Technology

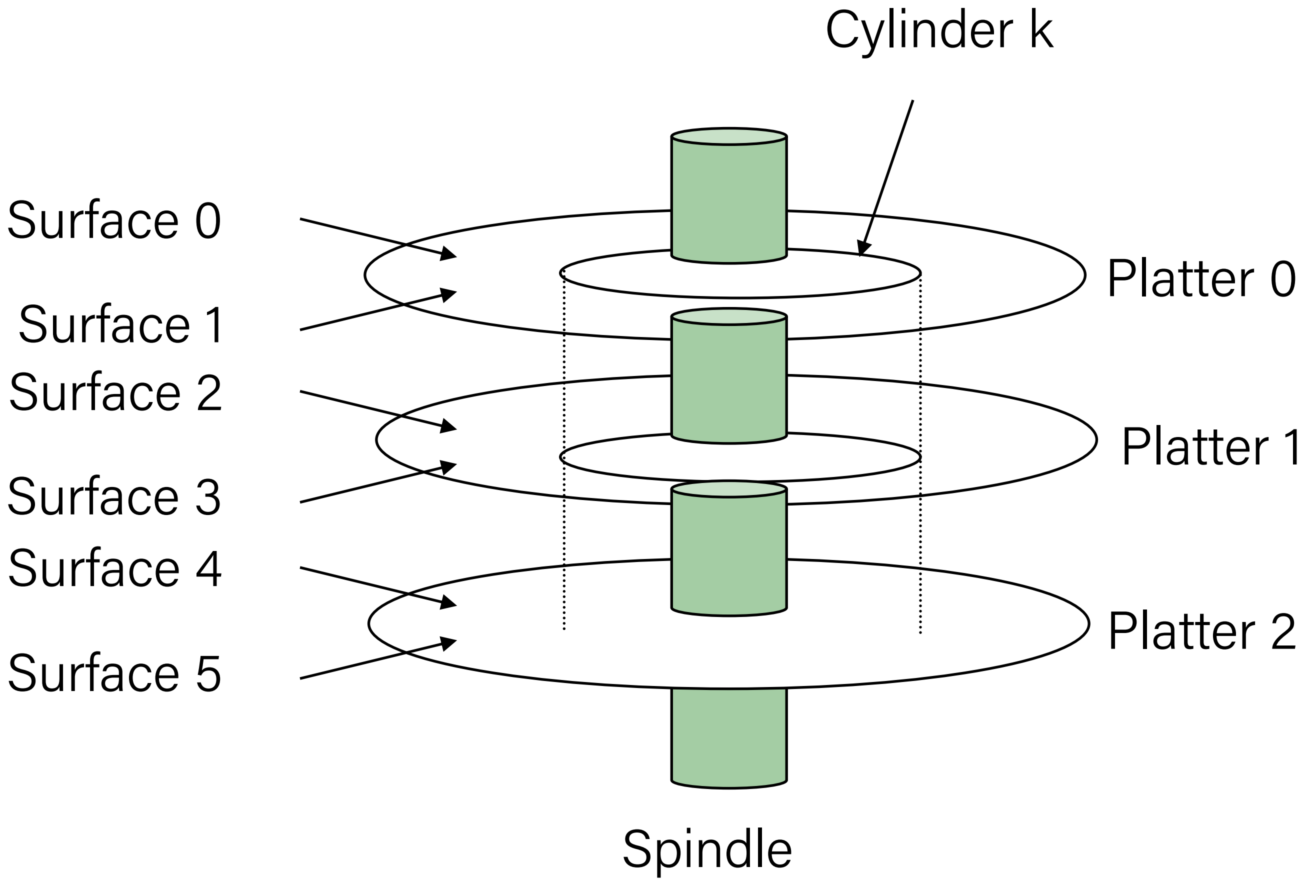
Disk Geometry

- 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 (Muliple-Platter View)

- Aligned tracks form a cylinder.



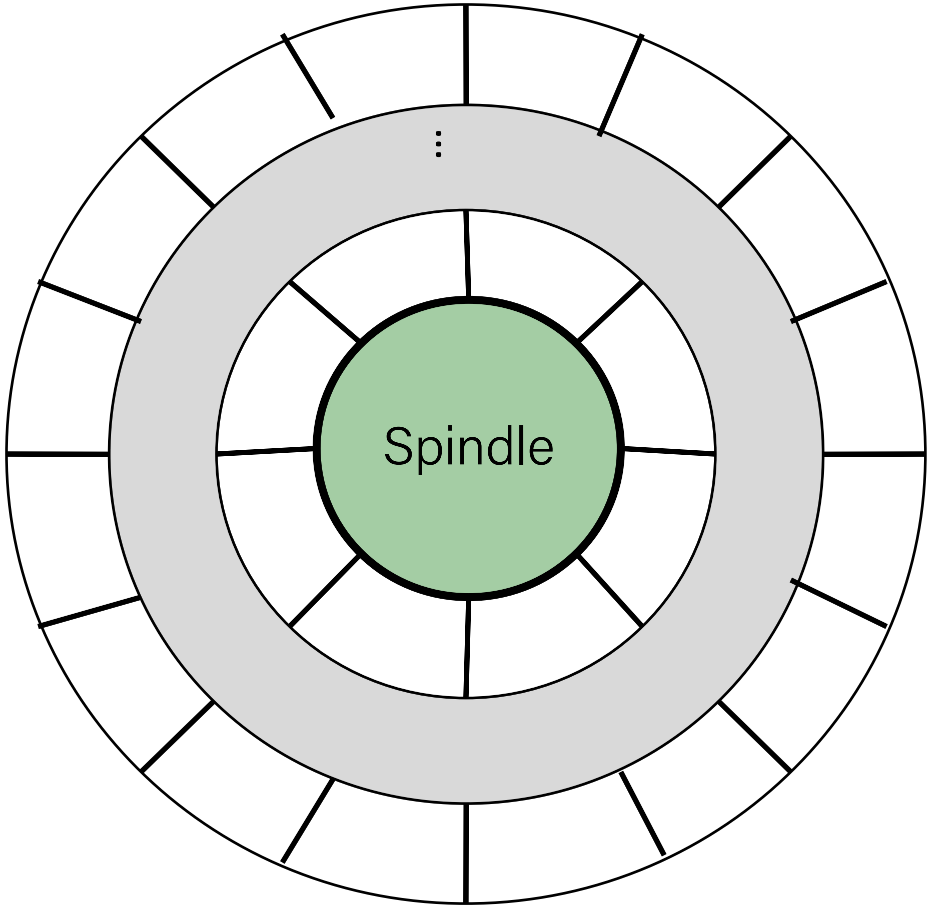
Disk Capacity

- **Capacity**: maximum number of bits that can be stored.
  - Vendors express capacity in units of gigabytes (GB), where 1 GB = 109 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/in2): product of recording and track density.

Recording zones

- 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, outer zones have more sectors/track than inner zones.
  - So we use average number of sectors/track when computing capacity.



Computing Disk Capacity

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

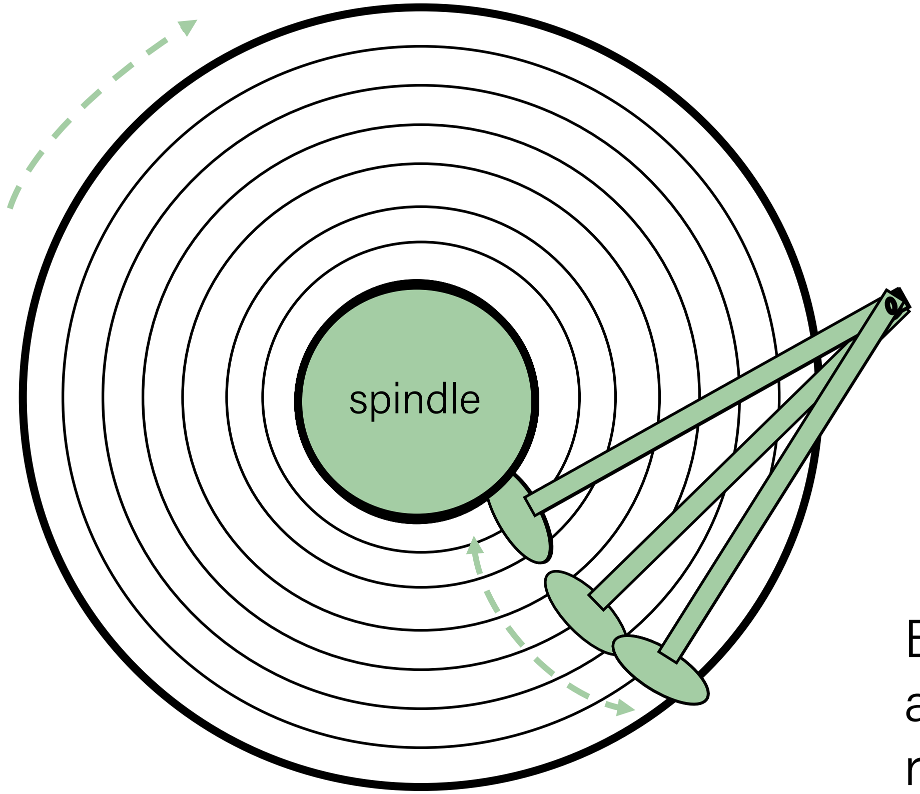
Example:

- 512 bytes/sector
- 300 sectors/track (on average)
- 20,000 tracks/surface
- 2 surfaces/platter
- 5 platters/disk

Capacity = 512 × 300 × 20000 × 2 × 5
= 30,720,000,000
= 30.72 GB

Disk Operation (Single-Platter View)

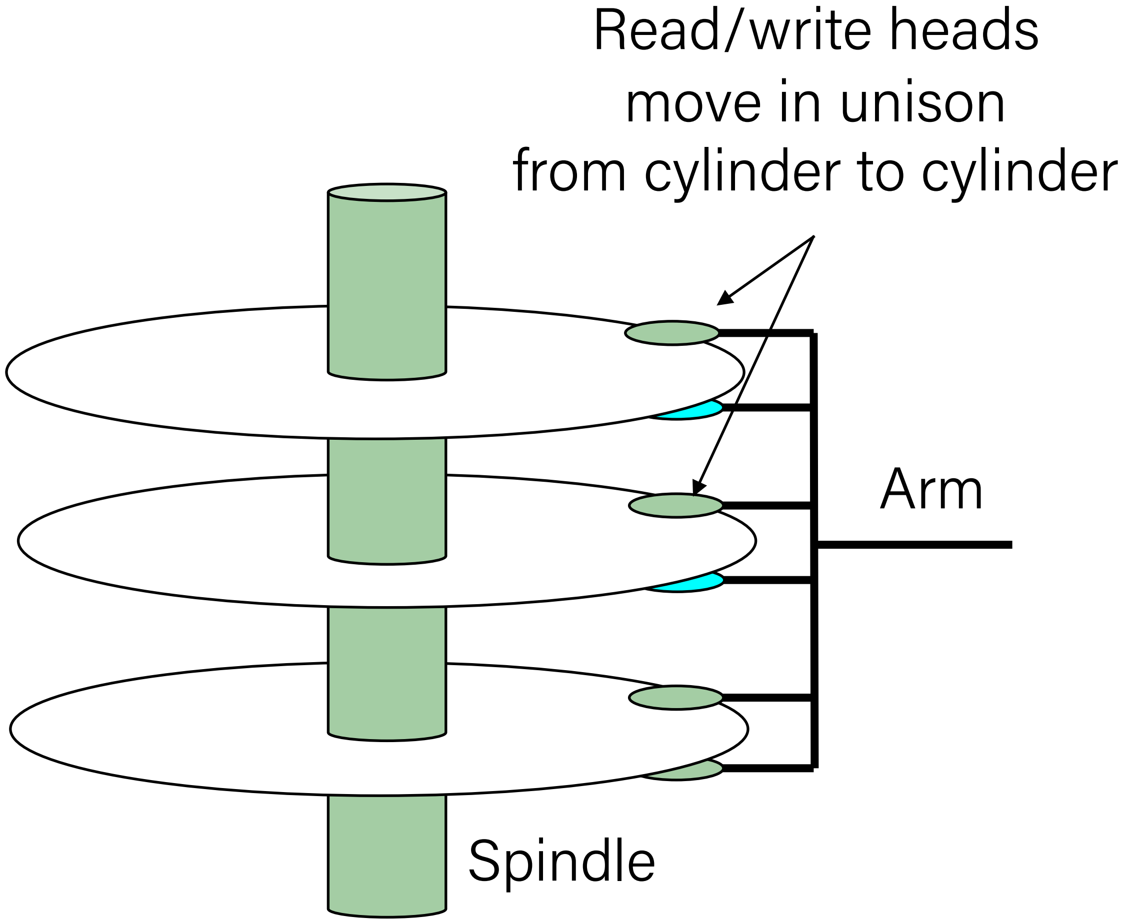
The disk surface spins at a fixed rotational rate



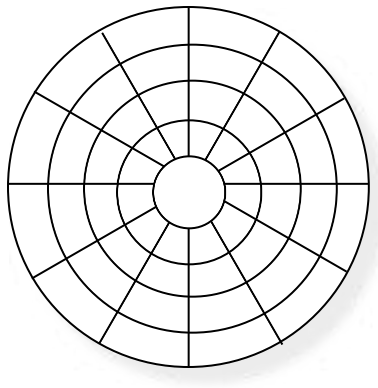
The read/write head is attached to the end of the arm and flies over the disk surface on a thin cushion of air.

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

Disk Operation (Multi-Platter View)



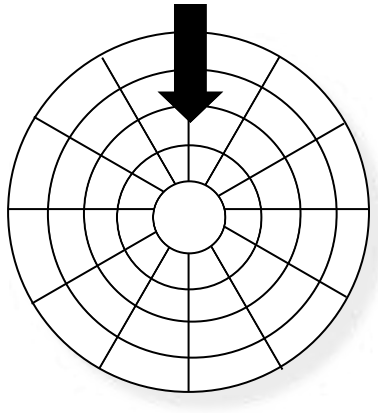
Disk Structure - top view of single platter



Surface organized into tracks

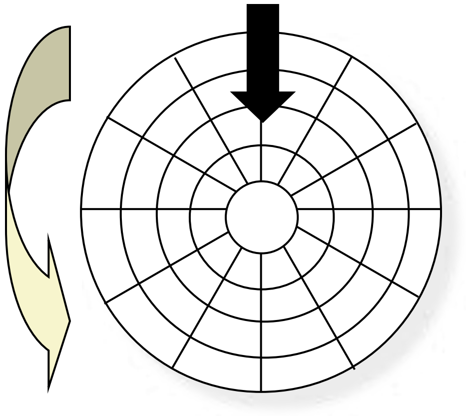
Tracks divided into sectors

Disk Access



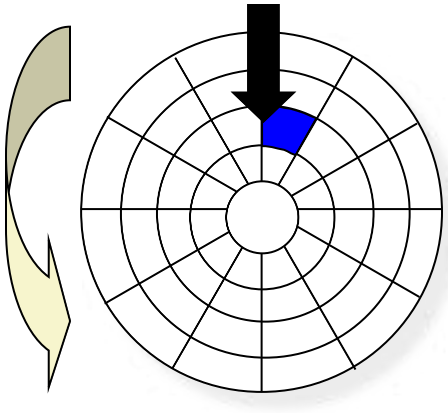
Head in position above a track

Disk Access



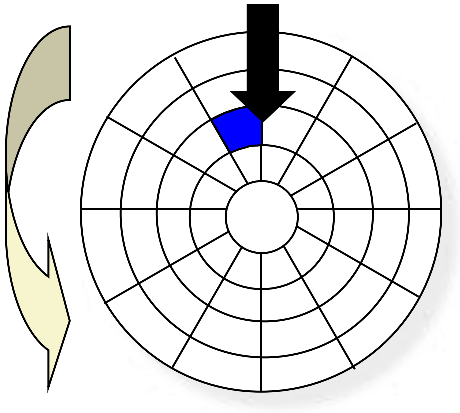
Rotation is counter-clockwise

Disk Access – Read



About to read blue sector

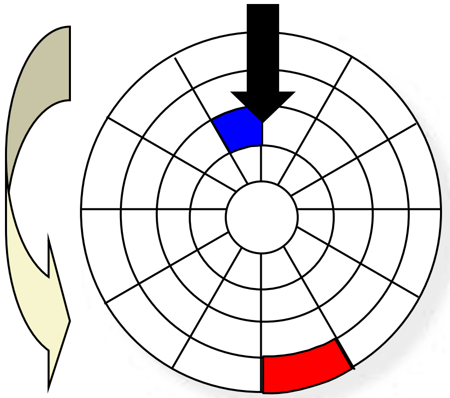
Disk Access – Read



After BLUE read

After reading blue sector

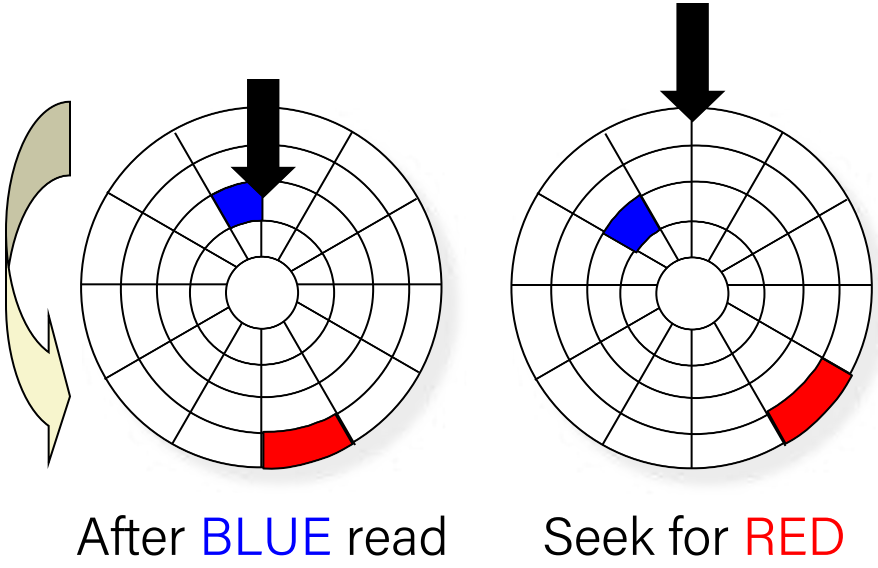
Disk Access – Read



After BLUE read

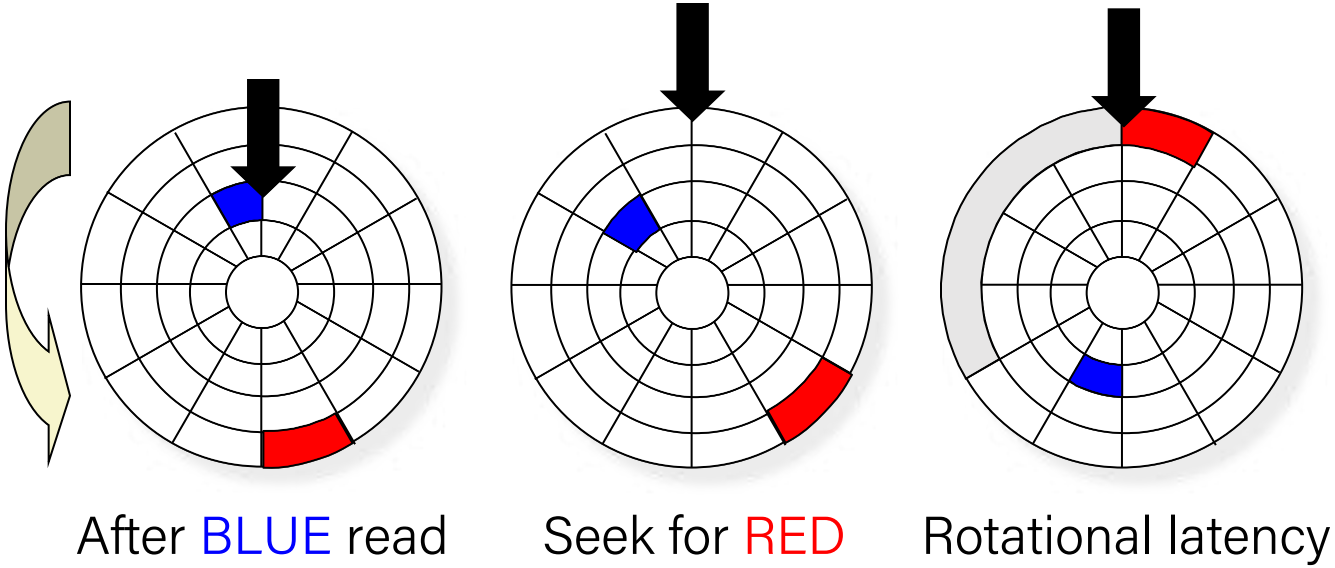
Red request scheduled next

Disk Access – Seek



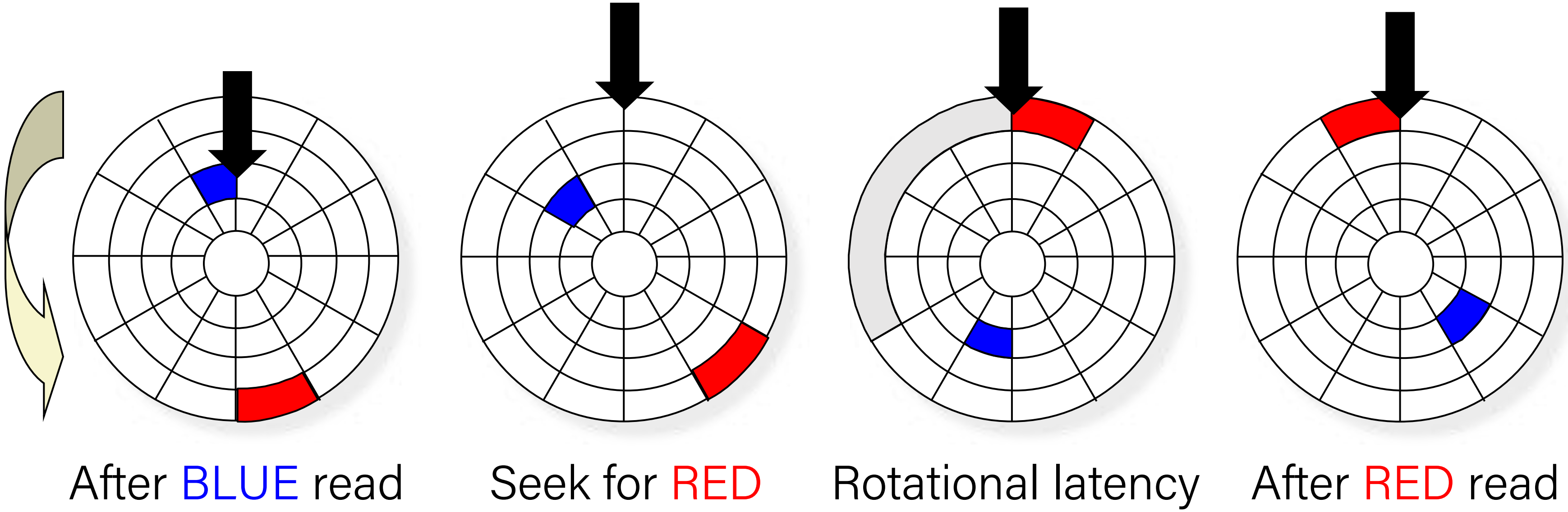
Seek to red's track

Disk Access – Rotational Latency



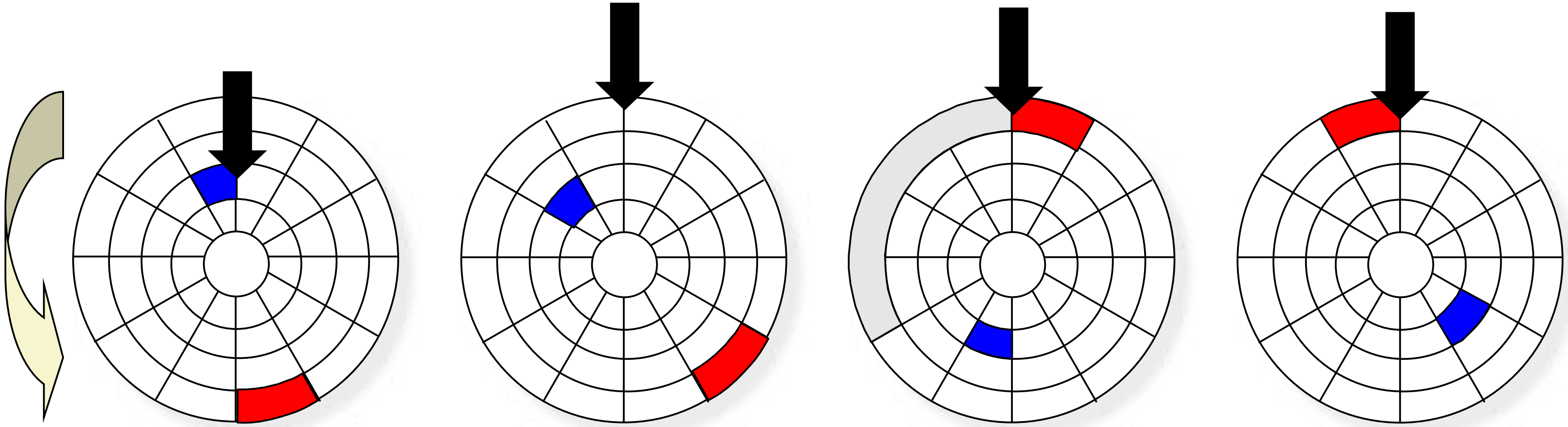
Wait for red sector to rotate around

Disk Access – 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.
  - Tavg rotation = 1/2 × 1/RPMs x 60 sec/1 min
  - Typical Tavg rotation = 7200 RPMs
- Transfer time (Tavg transfer)
  - Time to read the bits in the target sector.
  - Tavg transfer = 1/RPM × 1/(avg # sectors/track) × 60 secs/1 min.

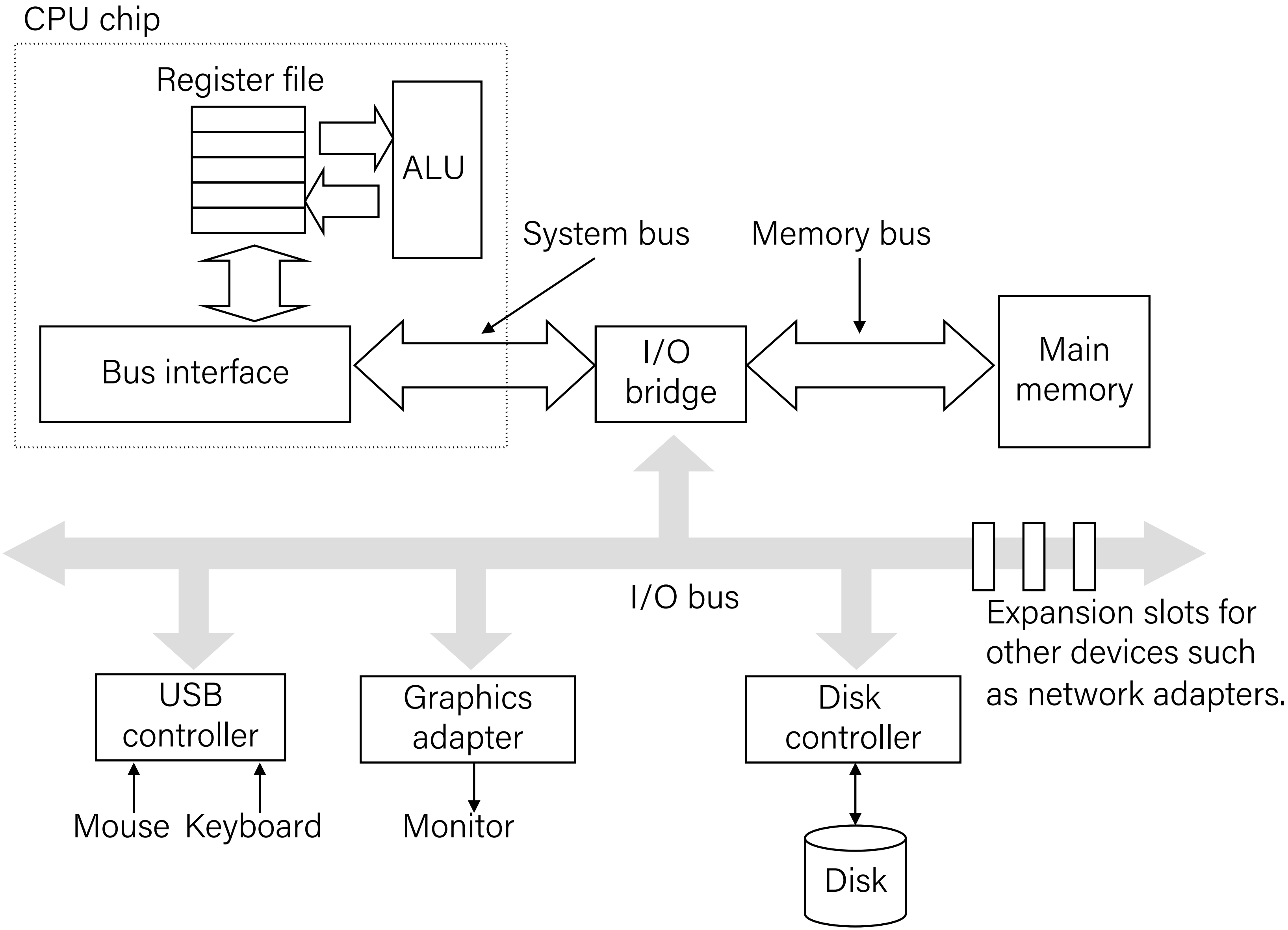
Disk Access Time Example

- Given:
  - Rotational rate = 7,200 RPM
  - Average seek time = 9 ms.
  - Avg # sectors/track = 400.
- Derived:
  - Tavg rotation = 1/2 × (60 secs/7200 RPM) × 1000 ms/sec = 4 ms.
  - Tavg transfer = 60/7200 RPM × 1/400 secs/track × 1000 ms/sec = 0.02 ms
  - Taccess = 9 ms + 4 ms + 0.02 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 then DRAM.

Logical Disk Blocks

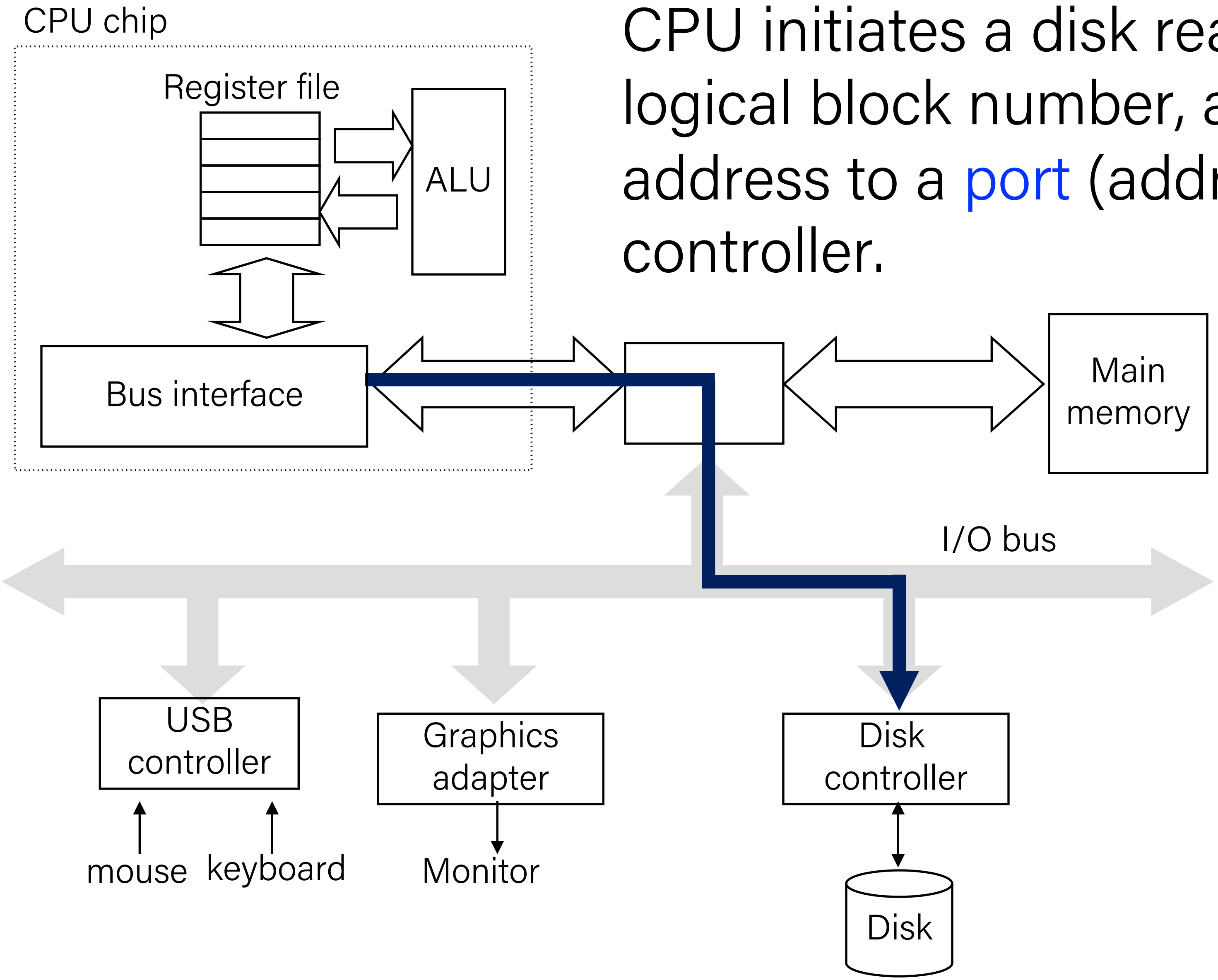
- Modern disks present a simpler abstract view of the complex sector geometry:
  - The set of available sectors is modeled as a sequence of b-sized **logical blocks** (0, 1, 2, …)
- Mapping between logical blocks and actual (physical) sectors
  - Maintained by hardware/firmware device called disk controller.
  - 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
System bus
Memory bus
Bus interface
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

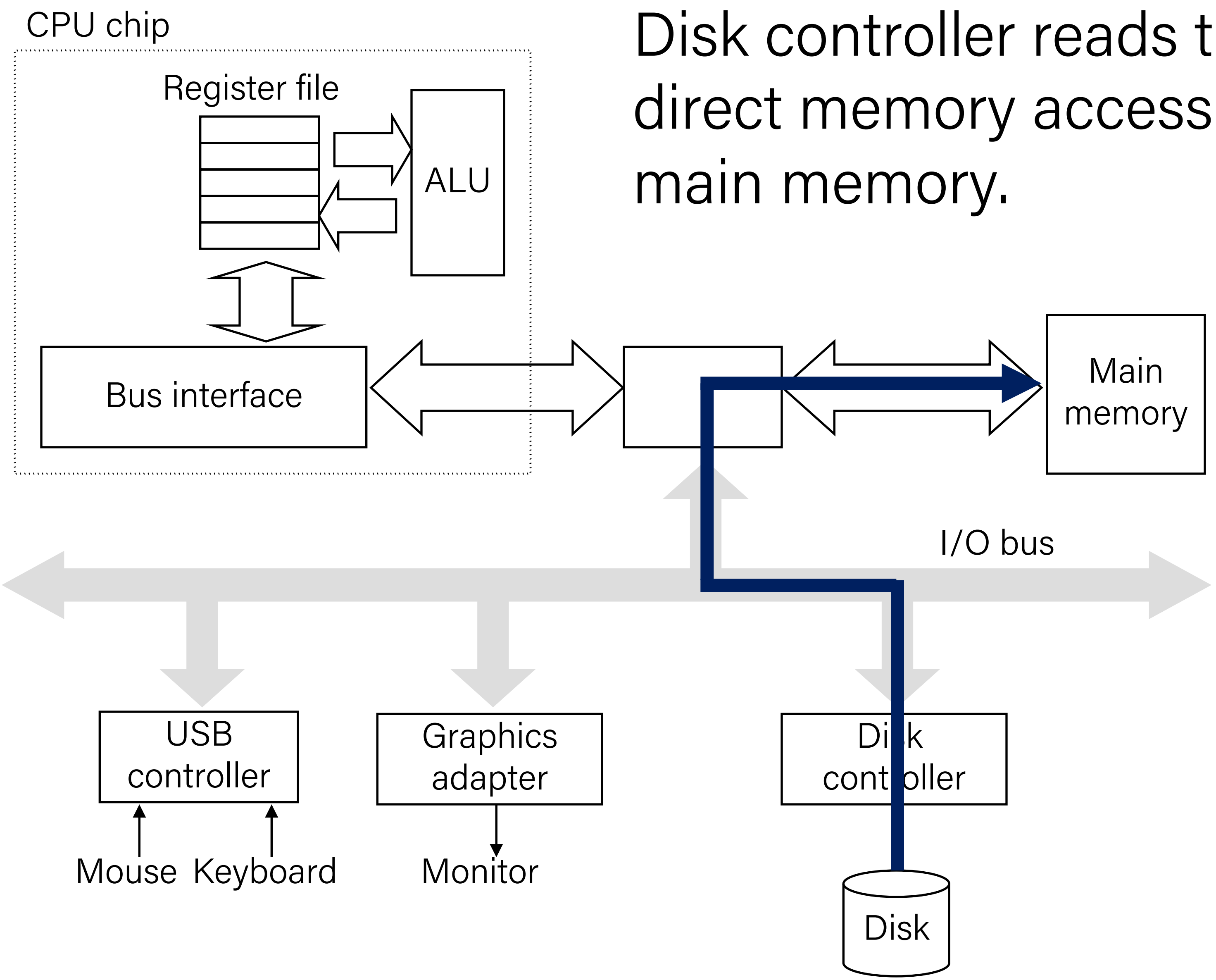
Reading a Disk Sector (1)

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



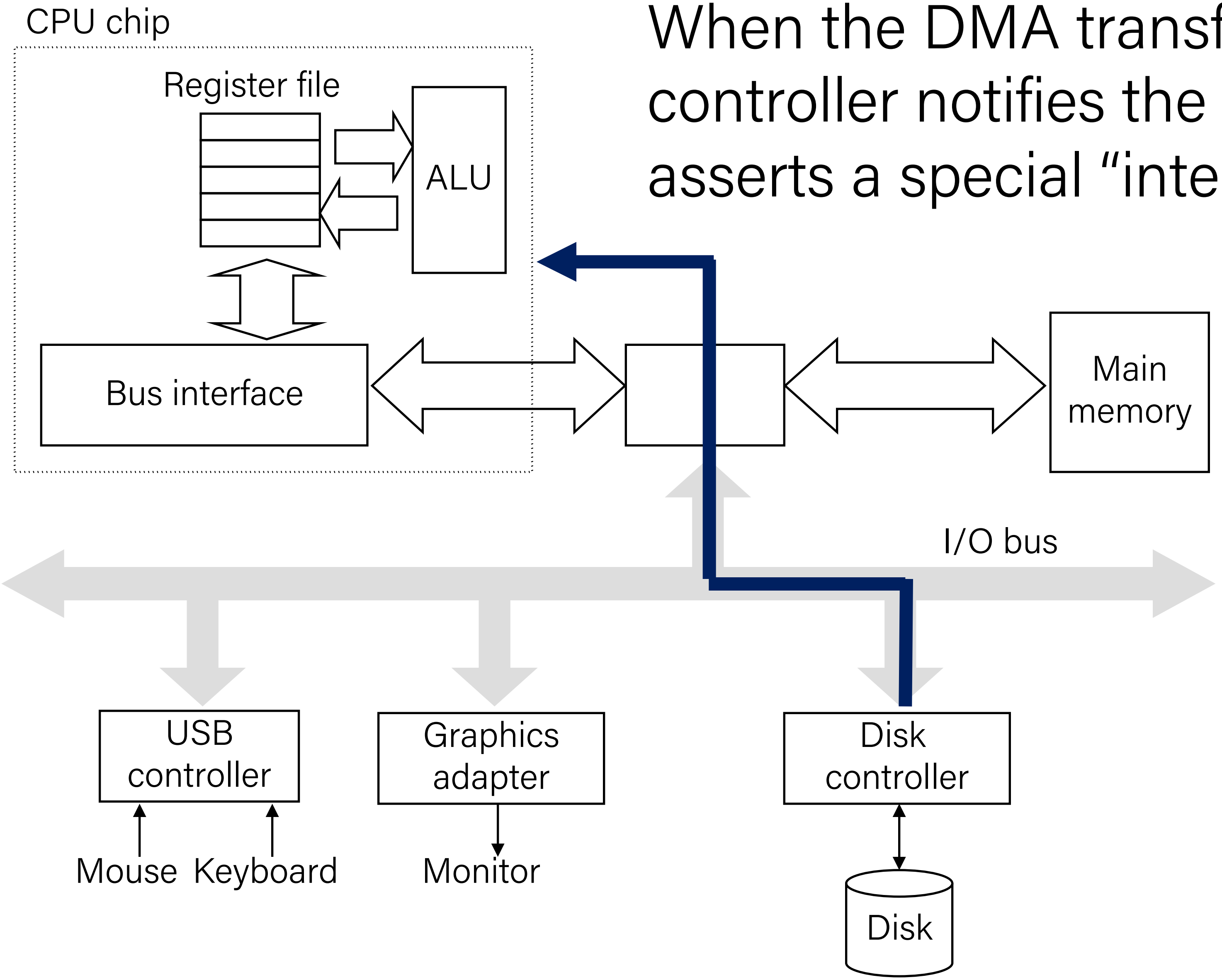
Reading a Disk Sector (2)

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

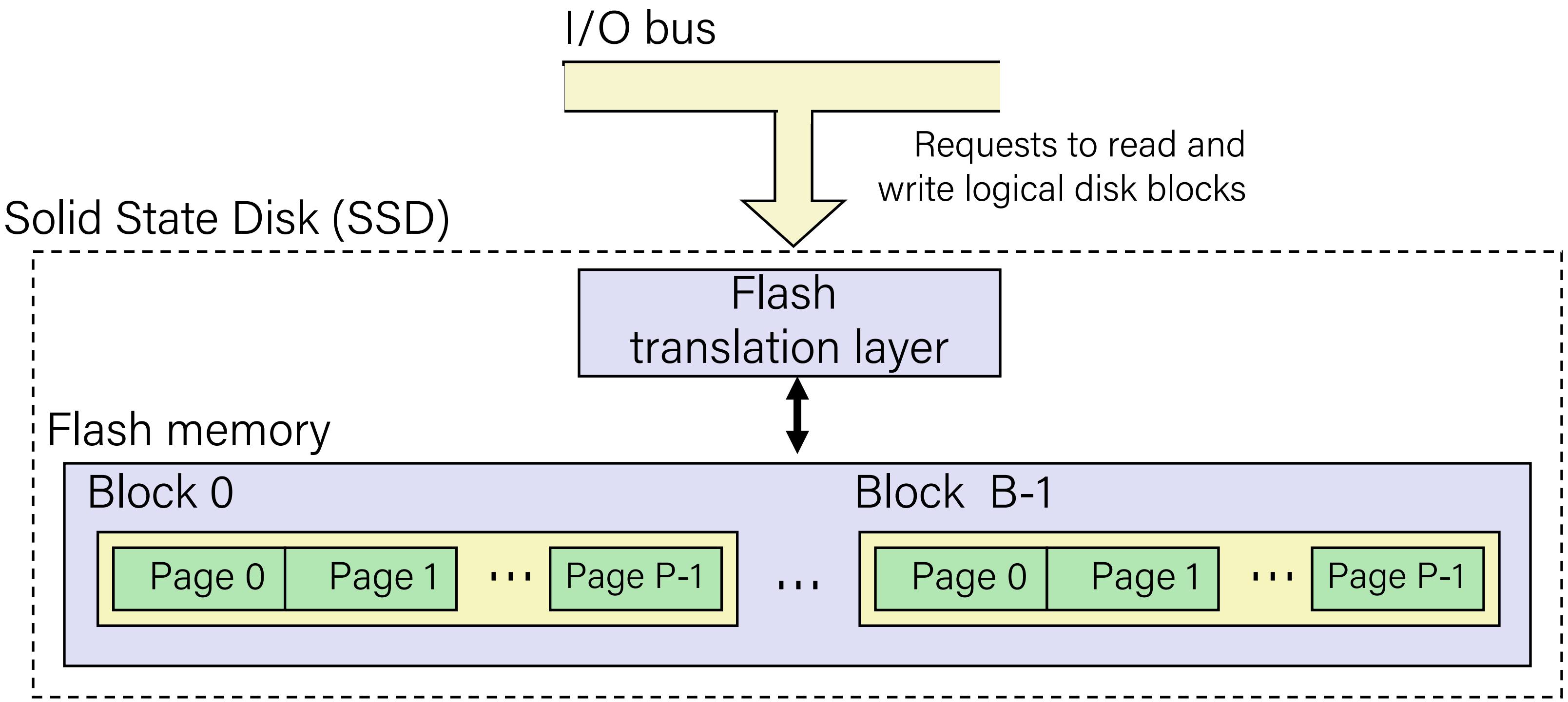


Reading a Disk Sector (3)

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 about 100,000 repeated writes.

SSD Performance Characteristics

Sequential read tput	550 MB/s	Sequential write tput	470 MB/s
Random read tput	365 MB/s	Random write tput	303 MB/s
Avg seq read time	50 us	Avg seq write time	60 us

- Sequential access faster than random access
  - Common theme in the memory hierarchy
- Random writes are somewhat slower
  - Erasing a block takes a long time (~1 ms)
  - Modifying a block page requires all other pages to be copied to new block
  - In earlier SSDs, the read/write gap was much larger.

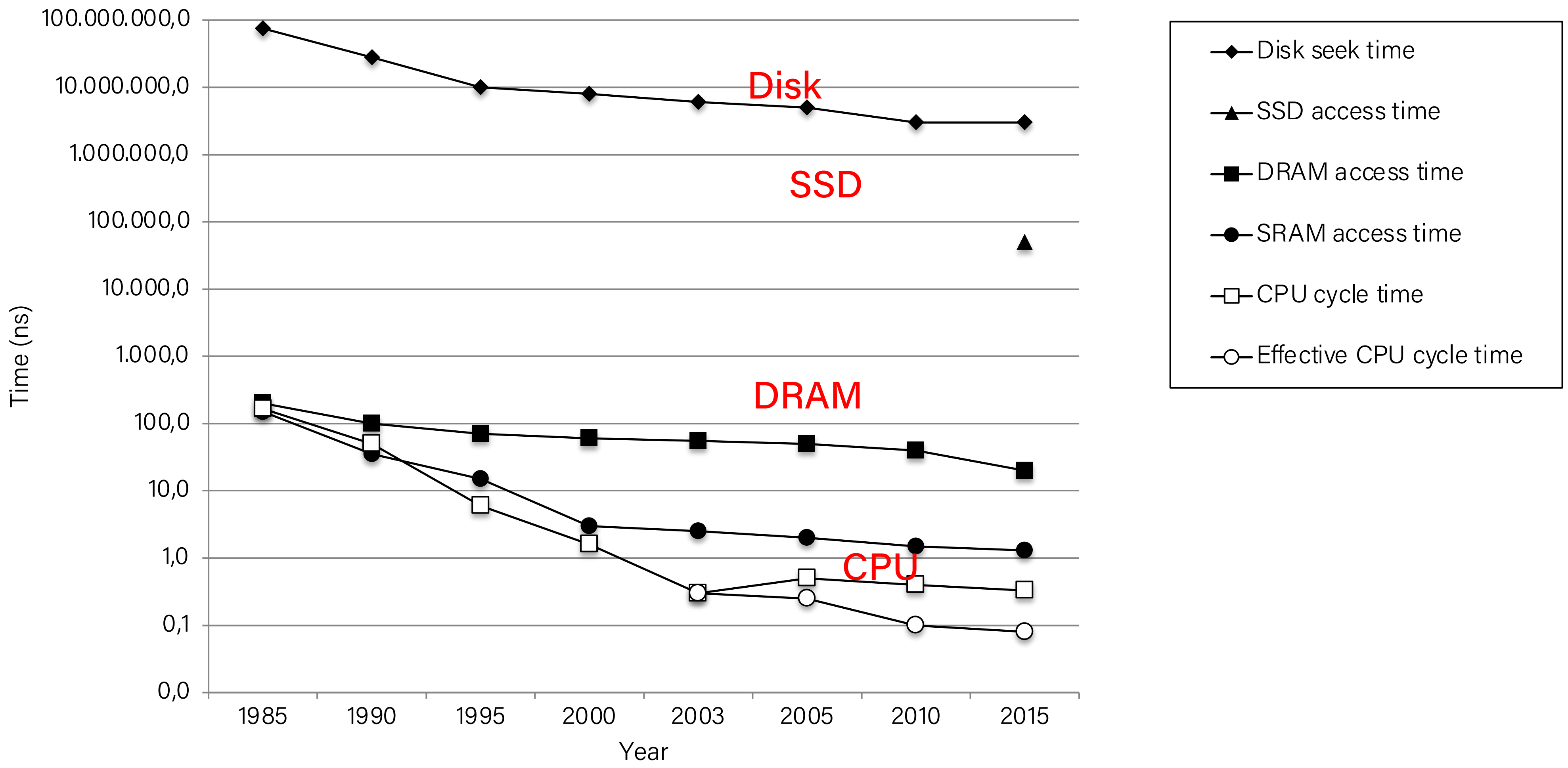
Source: Intel SSD 730 product specification.

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 SSD 730 guarantees 128 petabyte (128 x 1015 bytes) of writes before they wear out
  - In 2015, about 30 times more expensive per byte
- **Applications**
  - MP3 players, smart phones, laptops
  - Beginning to appear in desktops and servers

The CPU-Memory Gap

- The gap widens between DRAM, disk, and CPU speeds.



Locality to the Rescue!

- The key to bridging this CPU-Memory gap is a fundamental property of computer programs known as locality

Recap

- Buffer overflow attacks and what to do about them
- Storage technologies and trends

Next: More on the memory hierarchy