Systems and Networking I

Applied Computer Science and Artificial Intelligence

2025-2026

SAPIENZA
UNIVERSITÀ DI ROMA

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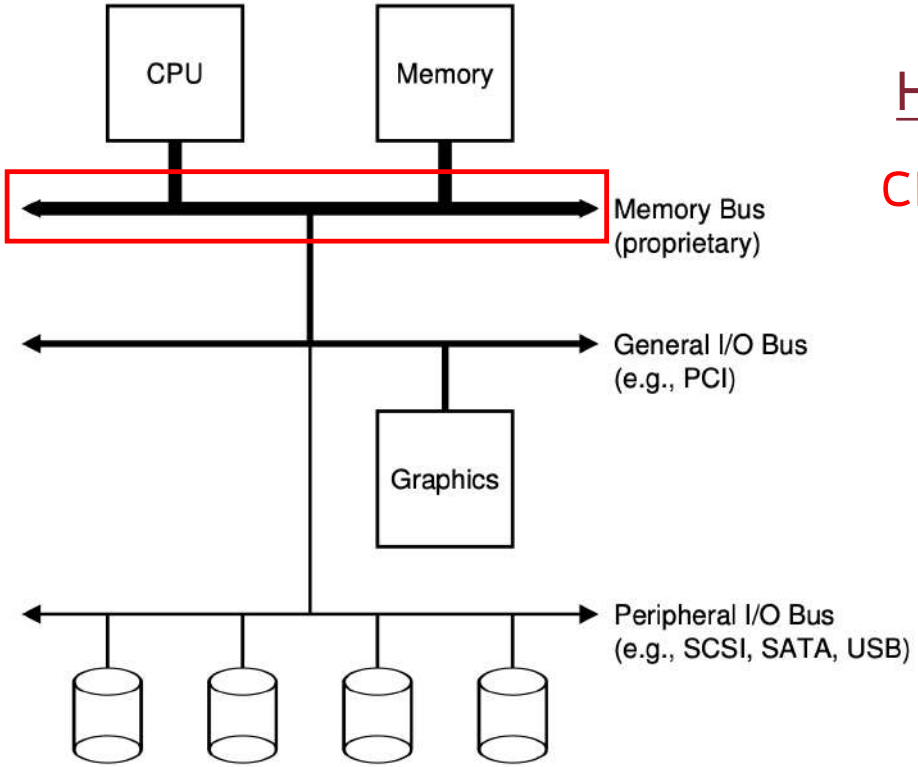
A Quick Recap on I/O

Remember the Basic System Architecture



Hierarchy of Communication Buses

CPU-Memory high-speed bus

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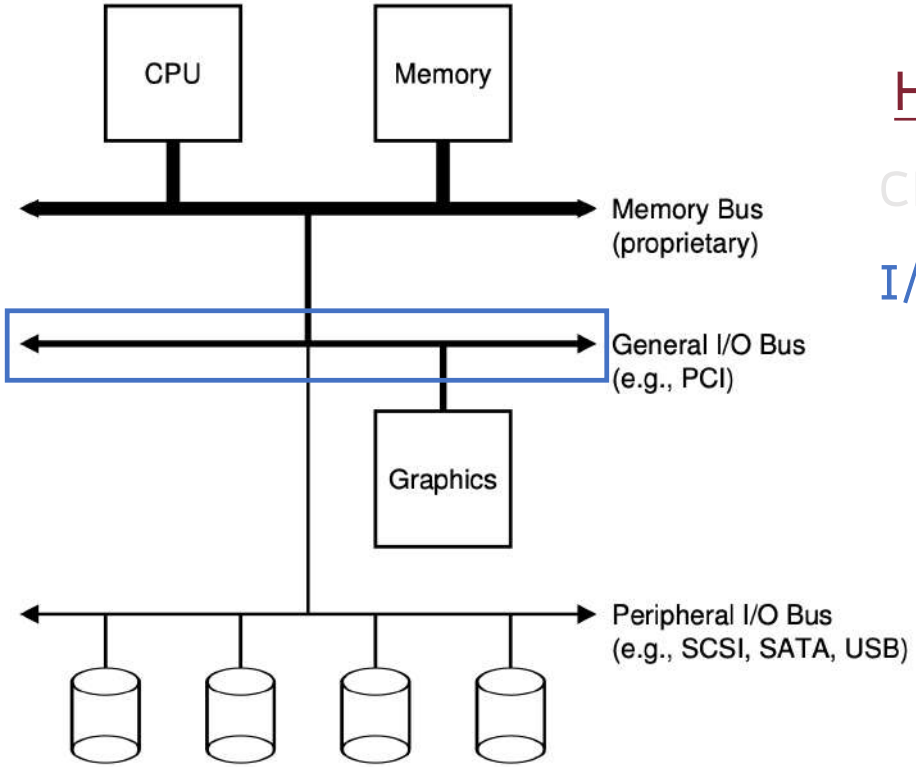

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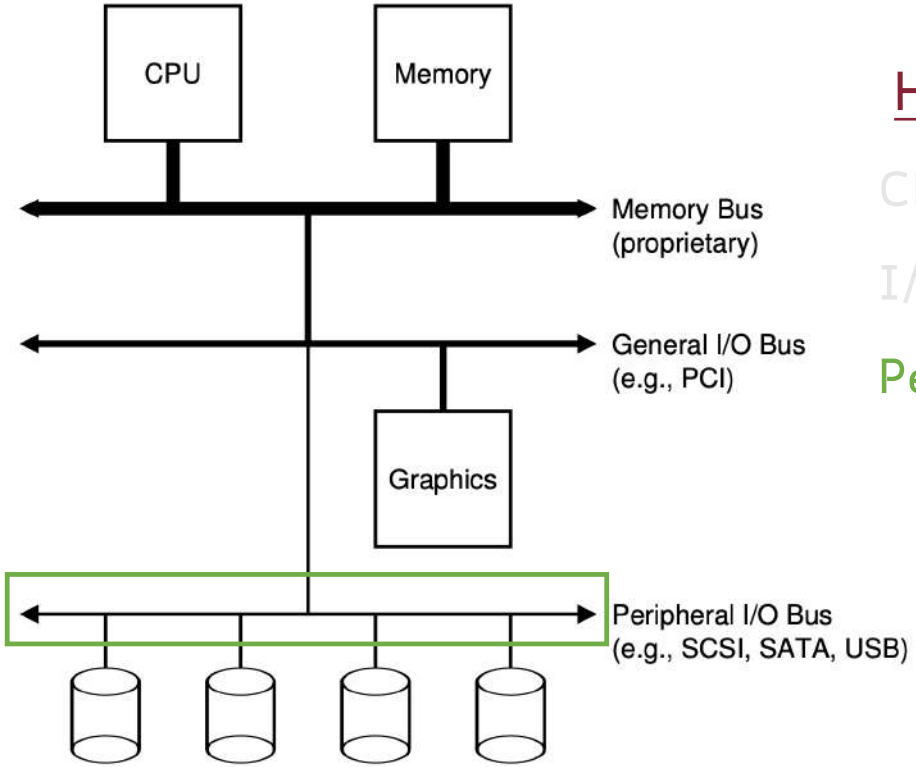

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CPU-Memory high-speed bus

I/O bus

Peripheral bus

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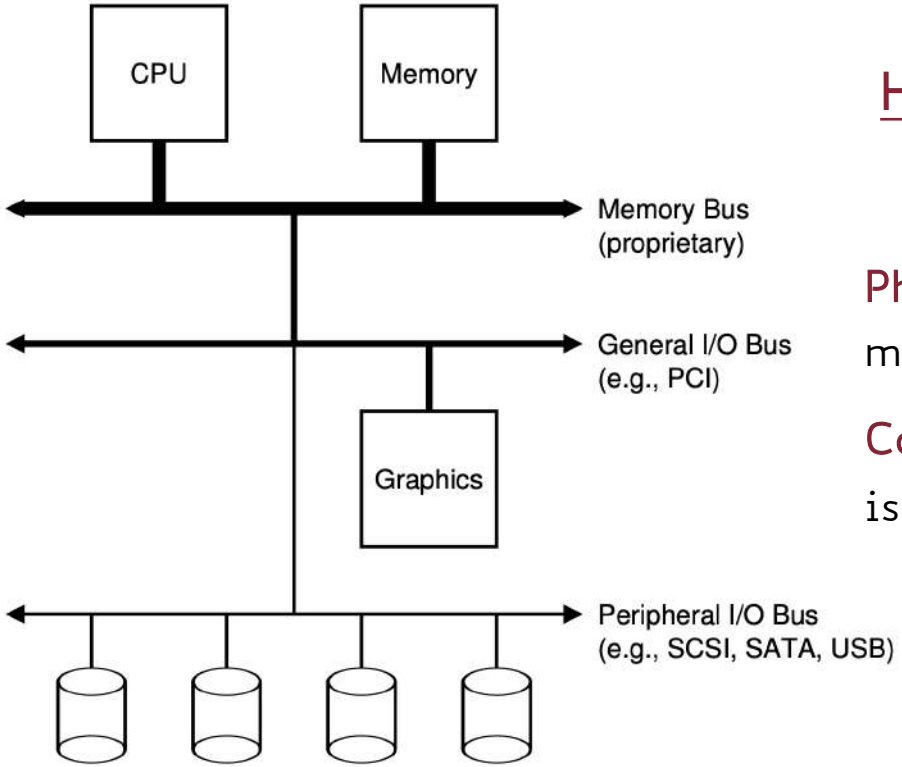


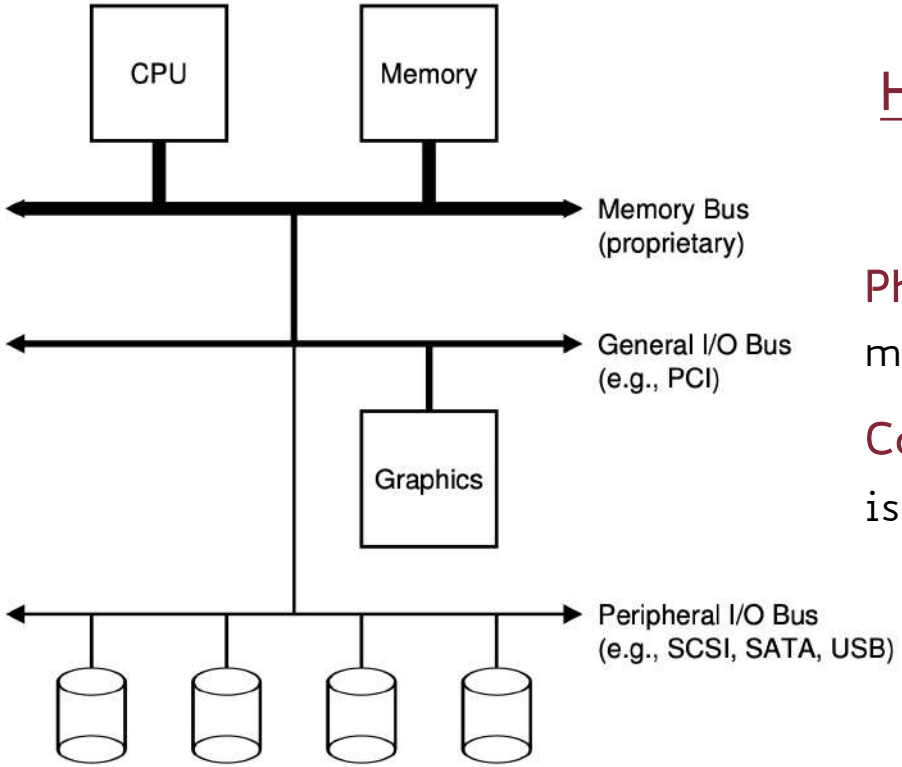
Hierarchy of Communication Buses

Why?

Physics: The faster a bus is, the shorter it must be!

Costs: Engineering a high-performance bus is expensive!

Remember the Basic System Architecture



Hierarchy of Communication Buses

Why?

Physics: The faster a bus is, the shorter it must be!

Costs: Engineering a high-performance bus is expensive!

High-speed I/O devices are closer to the CPU (e.g., graphics card)

Low-speed I/O devices are closer to the CPU (e.g., hard disks)

A Canonical I/O Device: Components

- Each I/O device is made of **2 parts**:
  - the **physical device** itself
  - the **device controller** (chip or set of chips controlling a family of physical devices)

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- Can be categorized as:
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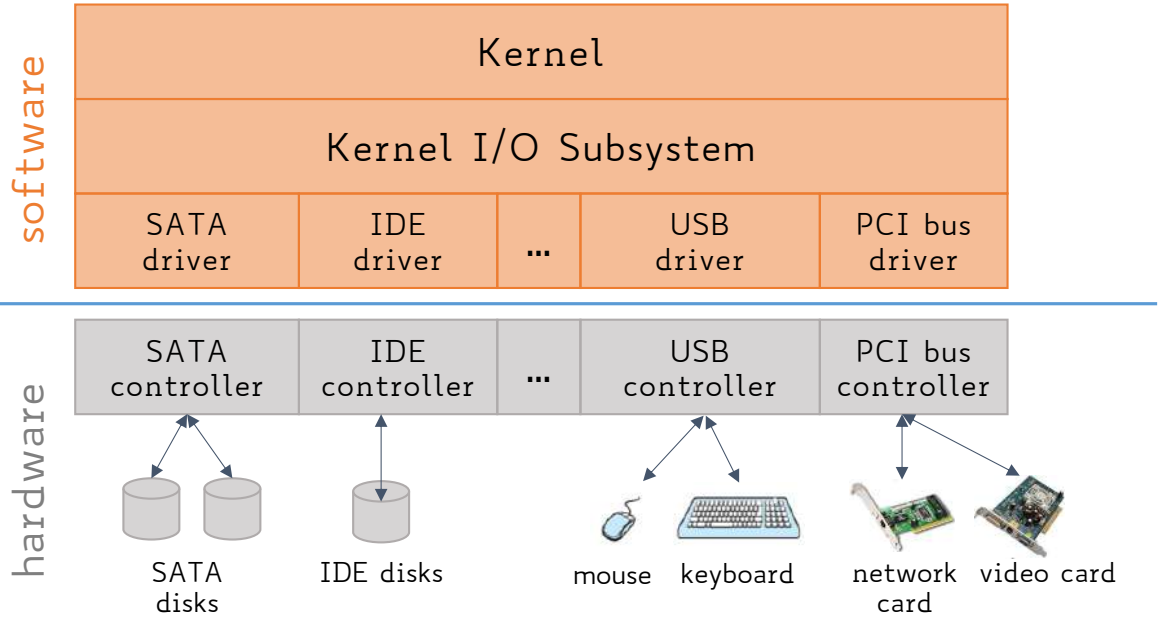
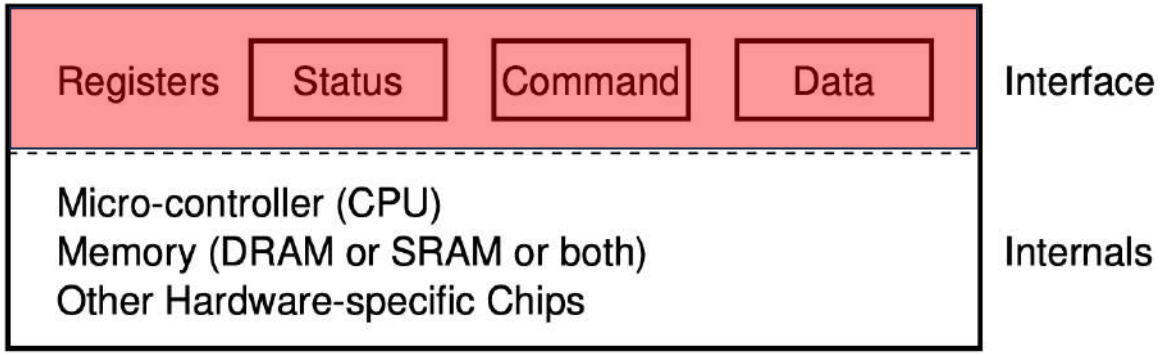
- OS talks to a device controller using a specific **device driver**

Device Drivers: OS Abstraction



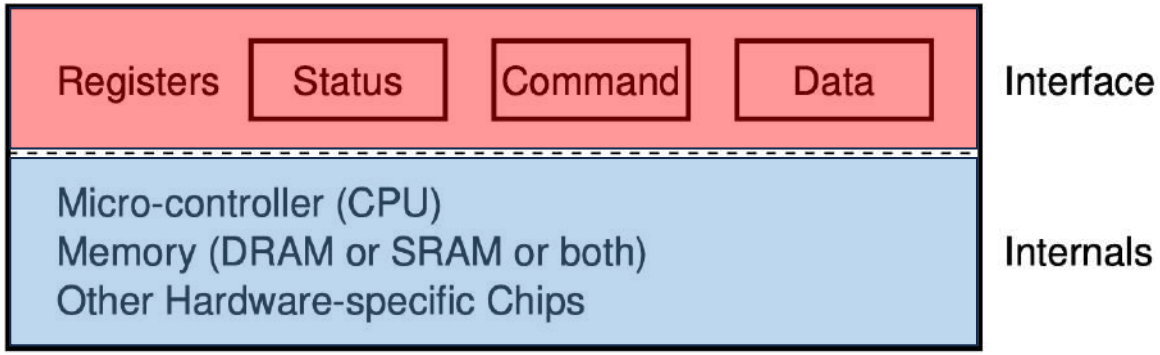
Device Controllers

- Every device controller has:
  - an **interface** → a number of dedicated registers to communicate with it



Device Controllers

- Every device controller has:
  - an **interface** → a number of dedicated registers to communicate with it
  - an **internal structure** → logic circuitry (vendor-specific)



Device Controllers

- **Status registers** → provide status information to the CPU about the I/O device (e.g., idle, ready for input, busy, error, transaction complete)
- **Command/Configuration/Control registers** → used by the CPU to configure and control the device
- **Data registers** → used to read data from or write data to the I/O device

The Basic Protocol: OS-I/O

```
While (STATUS == BUSY)
    ; // wait until device is not busy
Write data to DATA register
Write command to COMMAND register
    (starts the device and executes the command)
While (STATUS == BUSY)
    ; // wait until device is done with your request
```

The OS waits until the device is ready by repeatedly checking the STATUS register

polling

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Send some data to the DATA register
(e.g., a 4KiB page to disk)

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Issue the command

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The OS waits for the device to finish again by polling in a loop

polling

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The CPU is responsible for the whole data transfer

Programmed I/O

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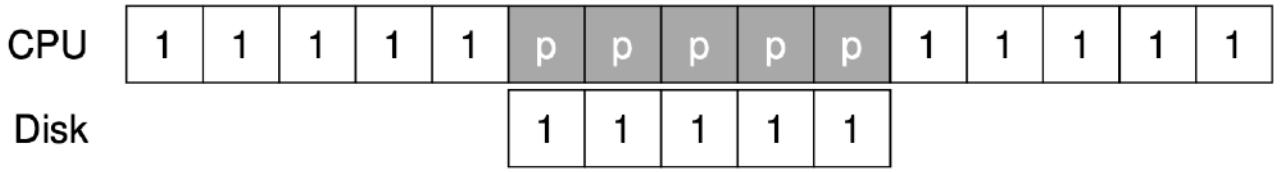
The CPU wastes a lot of time checking a possibly slow I/O device

Programmed I/O + Polling

Lowering CPU Waste: How?

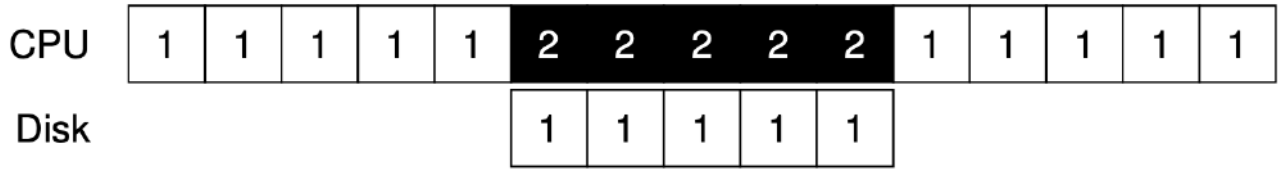
Polling: wastes CPU cycles waiting on a condition



Process 1 runs for some time, issues the I/O request and, while the request is being served, the OS repeatedly checks the status of the device (**p**)

Lowering CPU Waste: Interrupts!

Interrupt-driven I/O: allows overlap between CPU and I/O



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The I/O device will send an interrupt when done!

Lowering CPU Waste: Interrupts!

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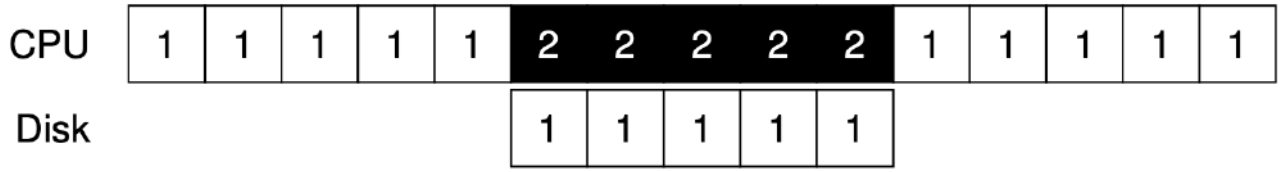

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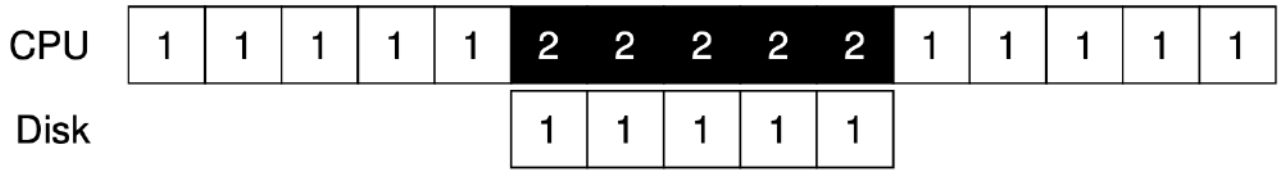

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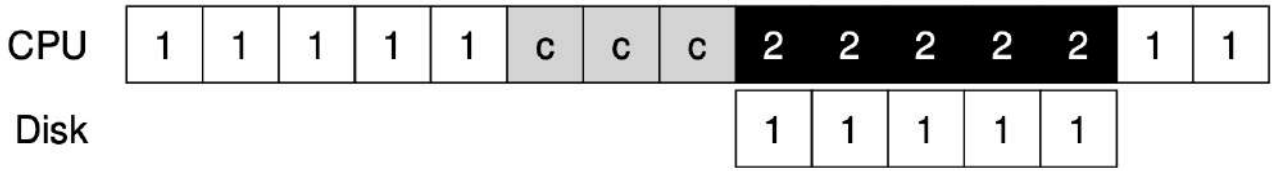
Is Interrupt-driven I/O **always** better than Programmed I/O + Polling?

NO! It depends on the speed of the I/O device/task

Beyond Programmed-I/O

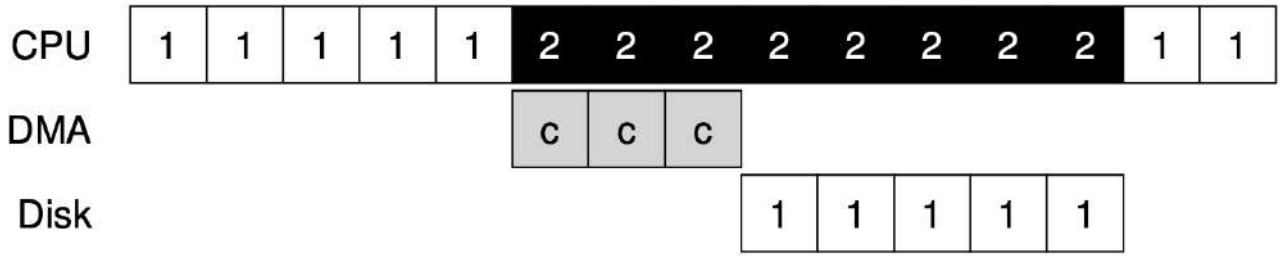
Programmed I/O: the CPU actually transfers data to I/O devices



Process 1 runs for some time, starts the I/O request by copying data from main memory to the I/O device one word at a time (c); when this is done the I/O begins and the OS switches to **Process 2**

Direct Memory Access (DMA)

DMA: a dedicated component to orchestrate memory-I/O transfers



Process 1 runs for some time, the OS starts the I/O by issuing a DMA request, then immediately switches to Process 2. Once the whole I/O task is done, the DMA controller sends an interrupt

To Wrap Up: Performing I/O Tasks

- **Polling**
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HOW?

- **Programmed I/O**
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To Wrap Up: Performing I/O Tasks

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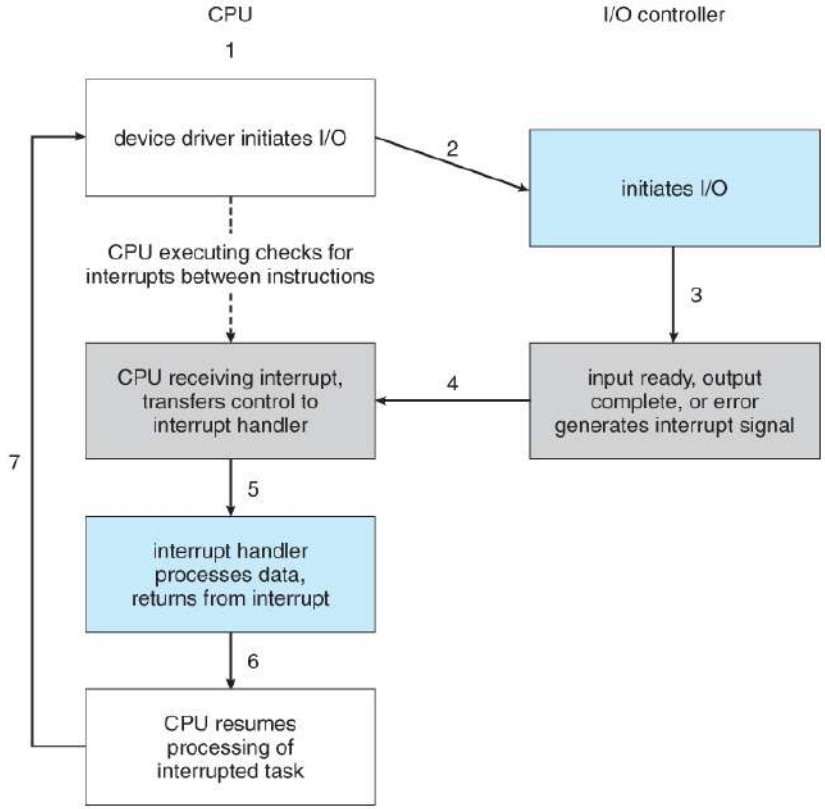
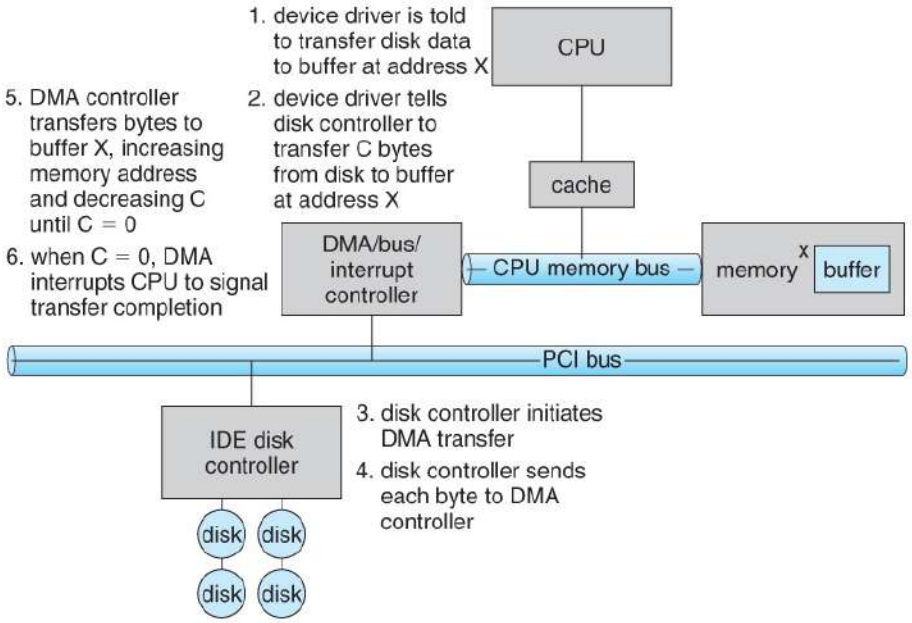


Who: Direct Memory Access (DMA)



Overcome the limitation of Programmed I/O

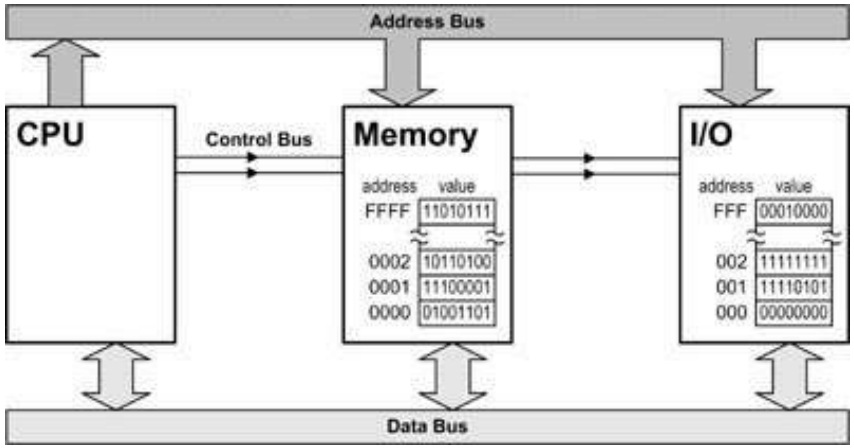
Maybe wasteful to tie up the CPU transferring data in and out of registers one word at a time

Useful for devices that transfer large quantities of data (such as disk controllers)

Typically, used in combination with interrupt-driven I/O

But how does the CPU/OS actually communicate with I/O devices?

Addressing Using the System Bus



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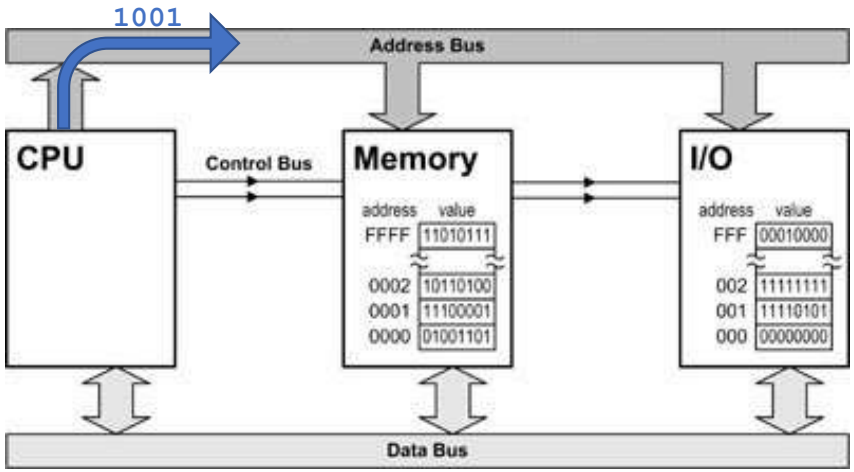

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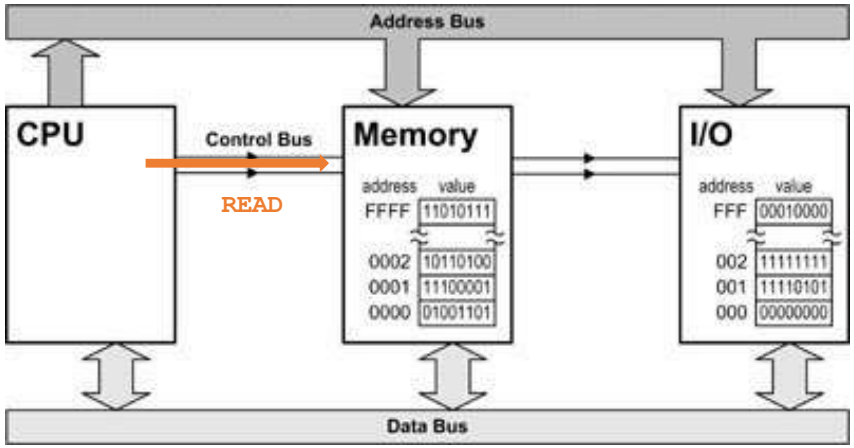

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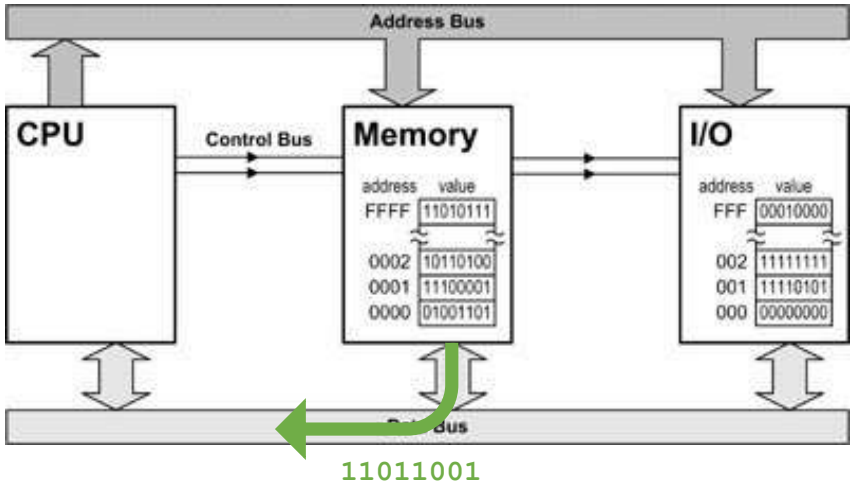

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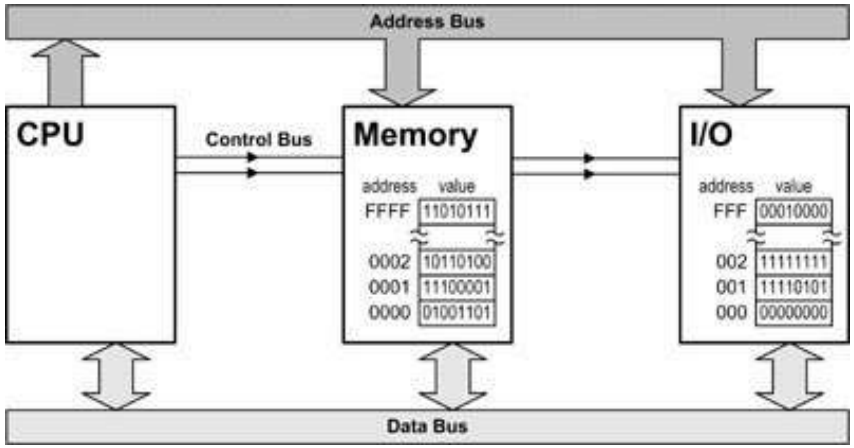

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How about I/O devices? How to distinguish between Memory and I/O devices?

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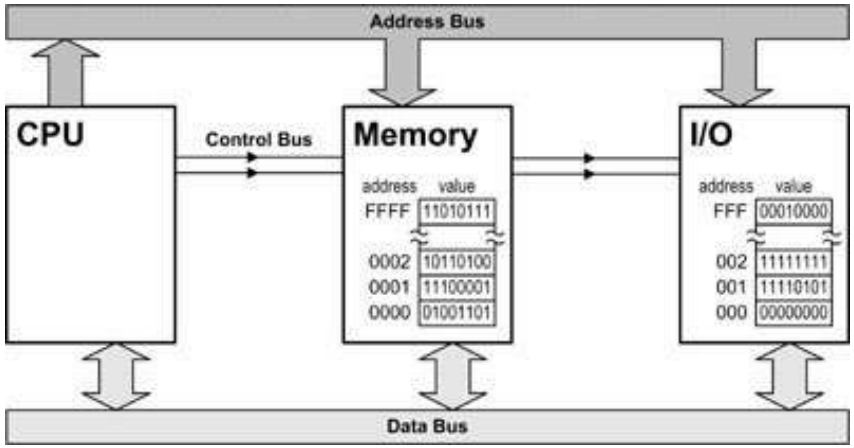

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If the **address bus is shared** between memory and I/O there is a special pin called "**M/IO**" that asserts whether the CPU wants to talk to memory (**M/IO = 0**) or an I/O device (**M/IO = 1**)

Port- vs. Memory-Mapped I/O

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- CPU can talk to a device controller in **2 ways**:
  - Port-mapped I/O (PMIO) → referencing controller's registers using a separate I/O address space
  - **Memory-mapped I/O (MMIO)** → mapping controller's registers to the same address space used for main memory

Port-Mapped I/O (PMIO)

- Each I/O device controller's register is mapped to a specific port (address) at boot-up time
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- With the **IN** or **OUT** instructions, **M/IO = 1**, so memory does not respond and the I/O chip does
- Mostly used for x86 legacy devices, much less common today

Port-Mapped I/O (PMIO): Example

```
IN   AL, 0x3F8        ; read from the serial port (COM1)
OUT  0x64, AL         ; write to keyboard controller
```

For **legacy devices**, the **port numbers** are historically **standardized**:

- COM1 → 0x3F8
- COM2 → 0x2F8
- Keyboard controller → 0x60/0x64
- Programmable Interrupt Controller (PIC) → 0x20 and 0xA0

These port ranges became *de facto* standards, so vendors conform to them for compatibility

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- The CPU uses `MOV`-like instructions to access I/O device registers
- The **`M/IO`** is not needed as every address requested by the CPU refers to main memory

Memory-Mapped I/O (MMIO): Example

```
MOV RAX, [0xF0000000]   ; read NIC register
MOV [0xF0000000], RAX   ; write NIC register
```

These addresses are **not hardcoded by the vendor**, they are discovered and allocated by firmware/OS

The OS enumerates PCI/PCIe devices and assigns MMIO addresses **dynamically**

The device advertises the size and number of required MMIO regions in its **PCI Base Address Registers (BARs)**

Port- vs. Memory-Mapped I/O

```
MOV DX,1234h
MOV AL,[DX]     ;reads memory address 1234h (memory address space)
IN AL,DX        ;reads I/O port 1234h (I/O address space)
```

Both put the value **1234h** on the CPU address bus, and both assert a **READ** operation on control bus

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MOV DX,1234h
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The first one will set **M/IO = 0** to indicate that the address belongs to memory address space

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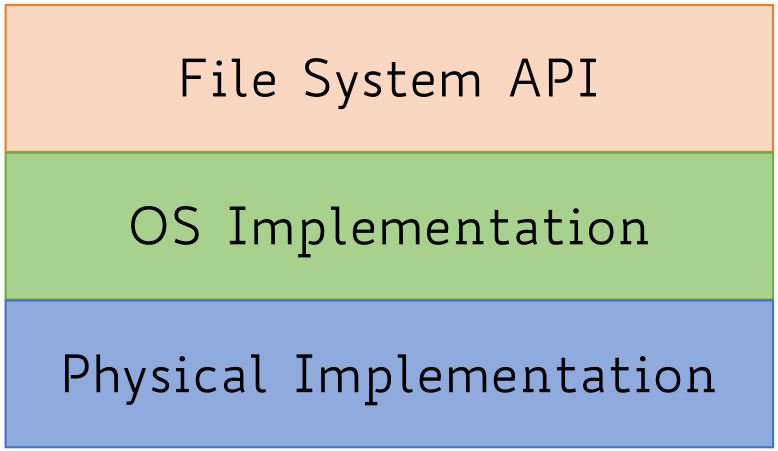
The second one will assert **M/IO = 1** to indicate that the address belongs to I/O address space

Port- vs. Memory-Mapped I/O

Feature	Port-Mapped I/O	Memory-Mapped I/O
Address space	Uses **separate I/O port space**	Uses **memory address space**
CPU instructions	`IN, OUT`	Normal loads/stores (`MOV`)
Hardware complexity	Separate I/O bus decoding	Requires memory bus decoding
Modern usage	Legacy (x86)	**Dominant** (PCI/PCIe)
Who assigns addresses?	Port numbers mostly **predefined historically**	OS/firmware assigns MMIO ranges based on device BARs

Part V: Storage Management

File System's Logical View



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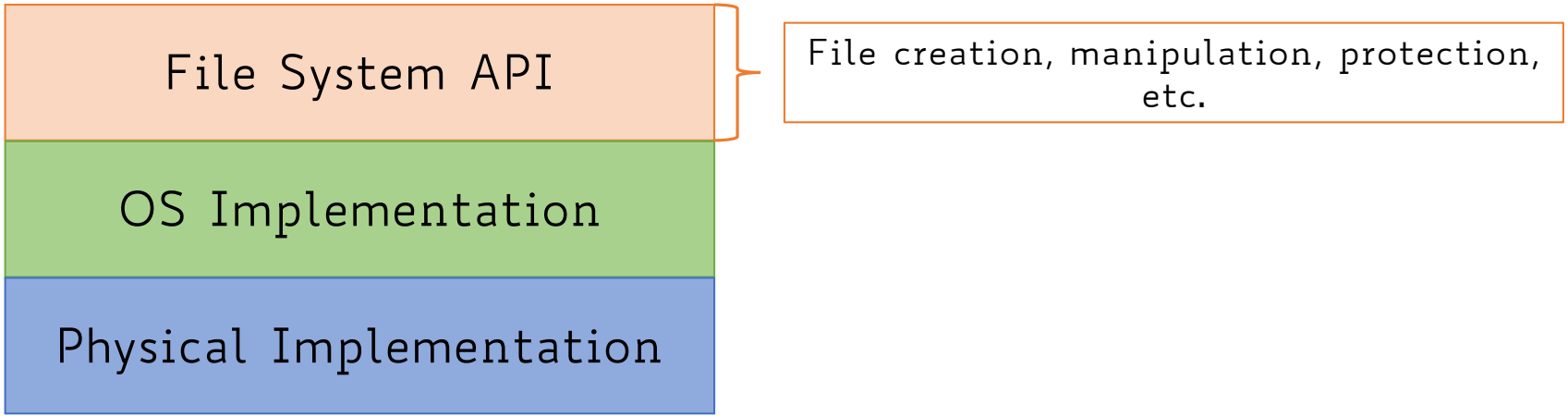

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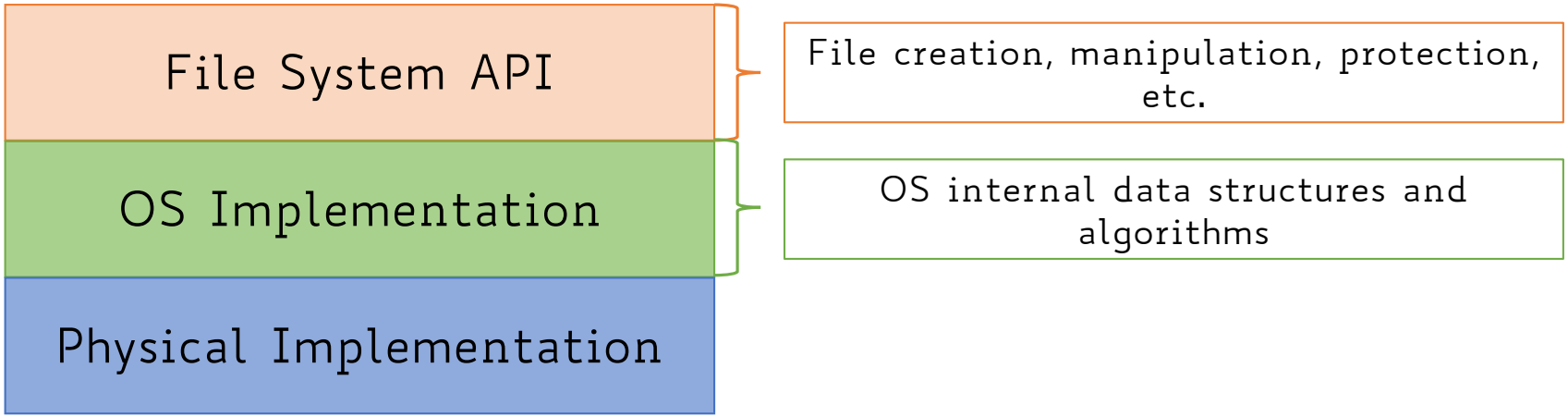

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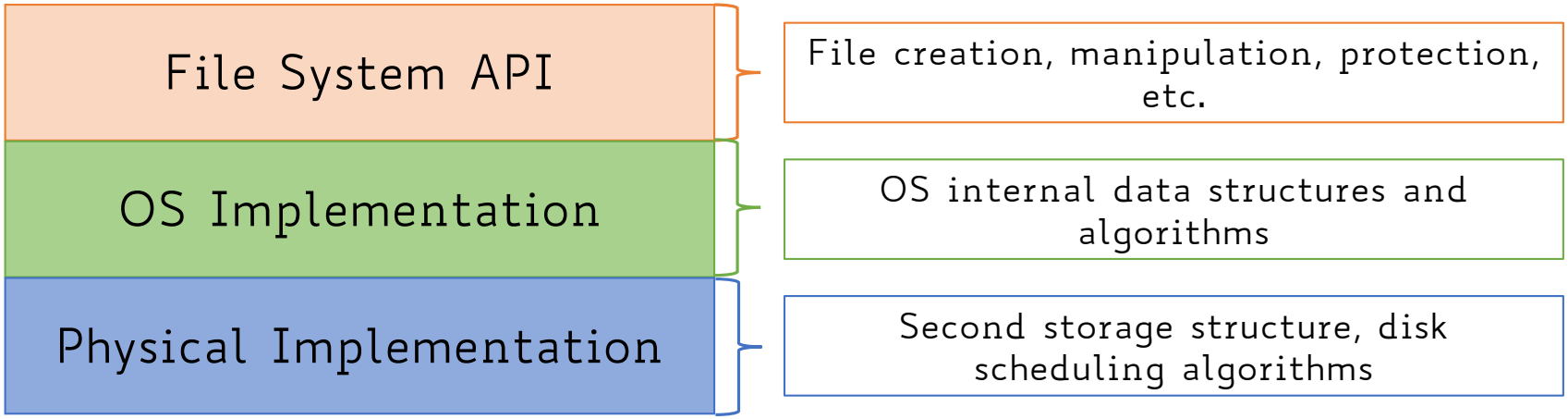

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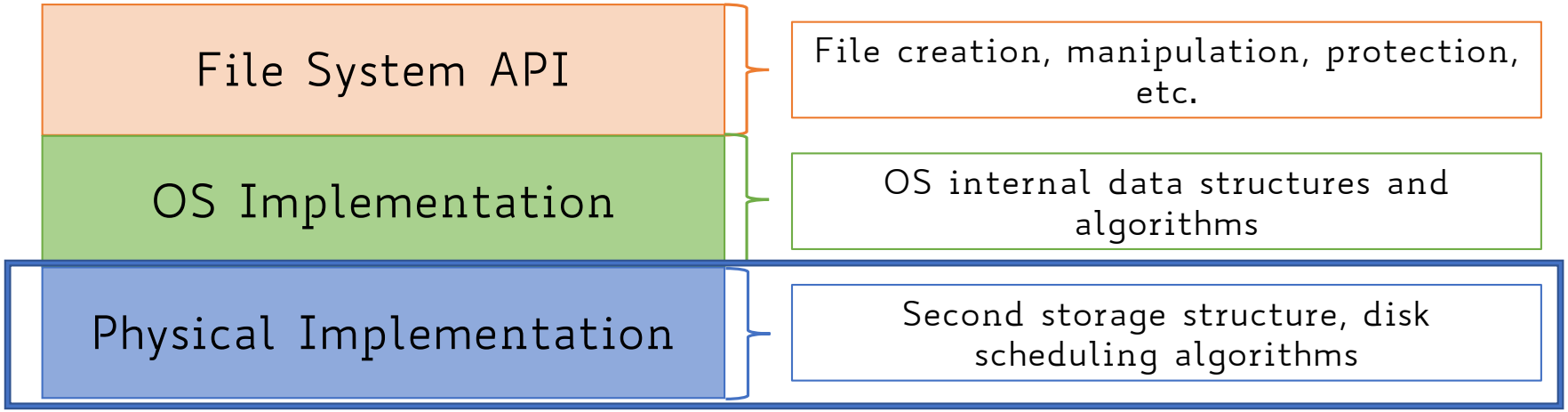

Overview of Mass-Storage Structure

3 categories of mass-storage devices

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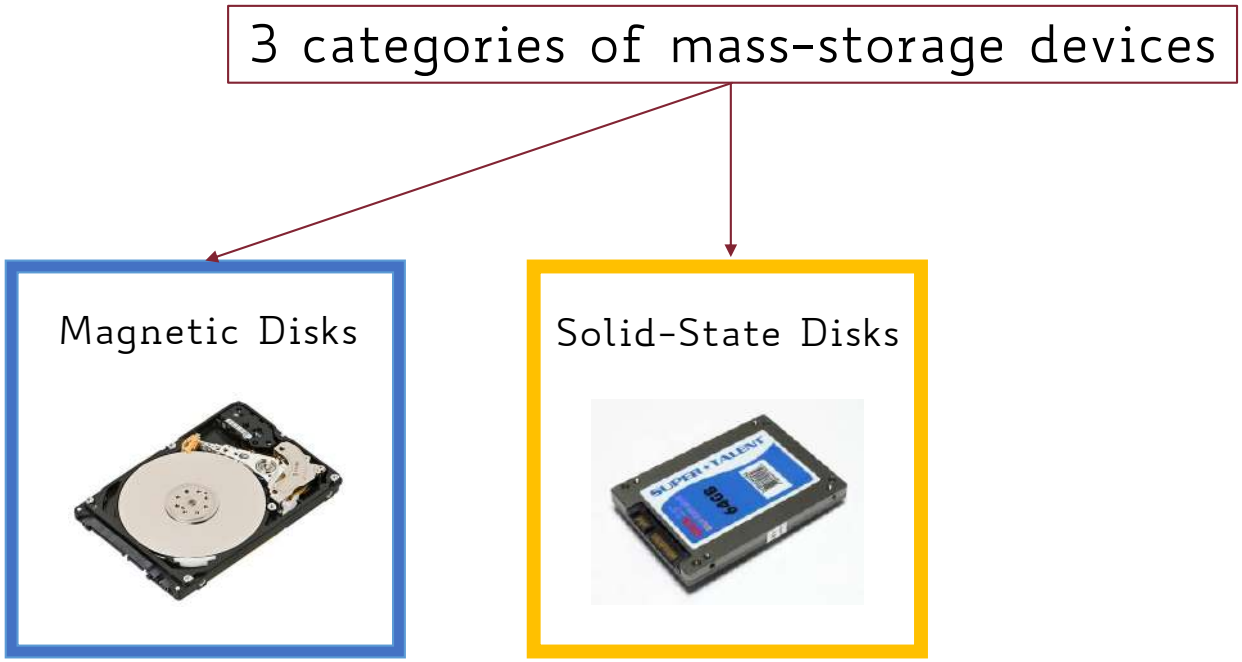
Magnetic Disks

Overview of Mass-Storage Structure



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Magnetic Disks

Solid-State Disks

Magnetic Tapes

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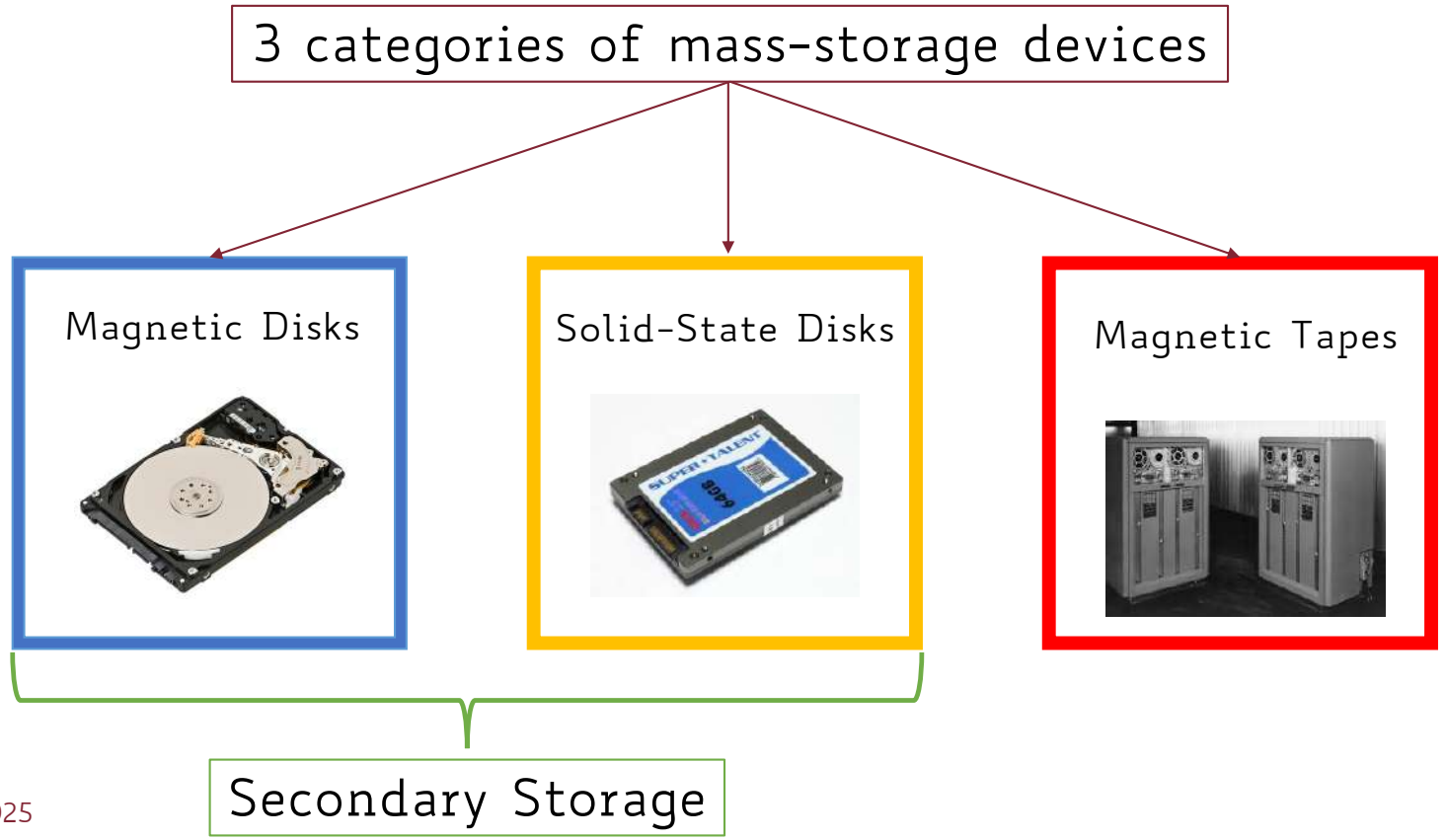

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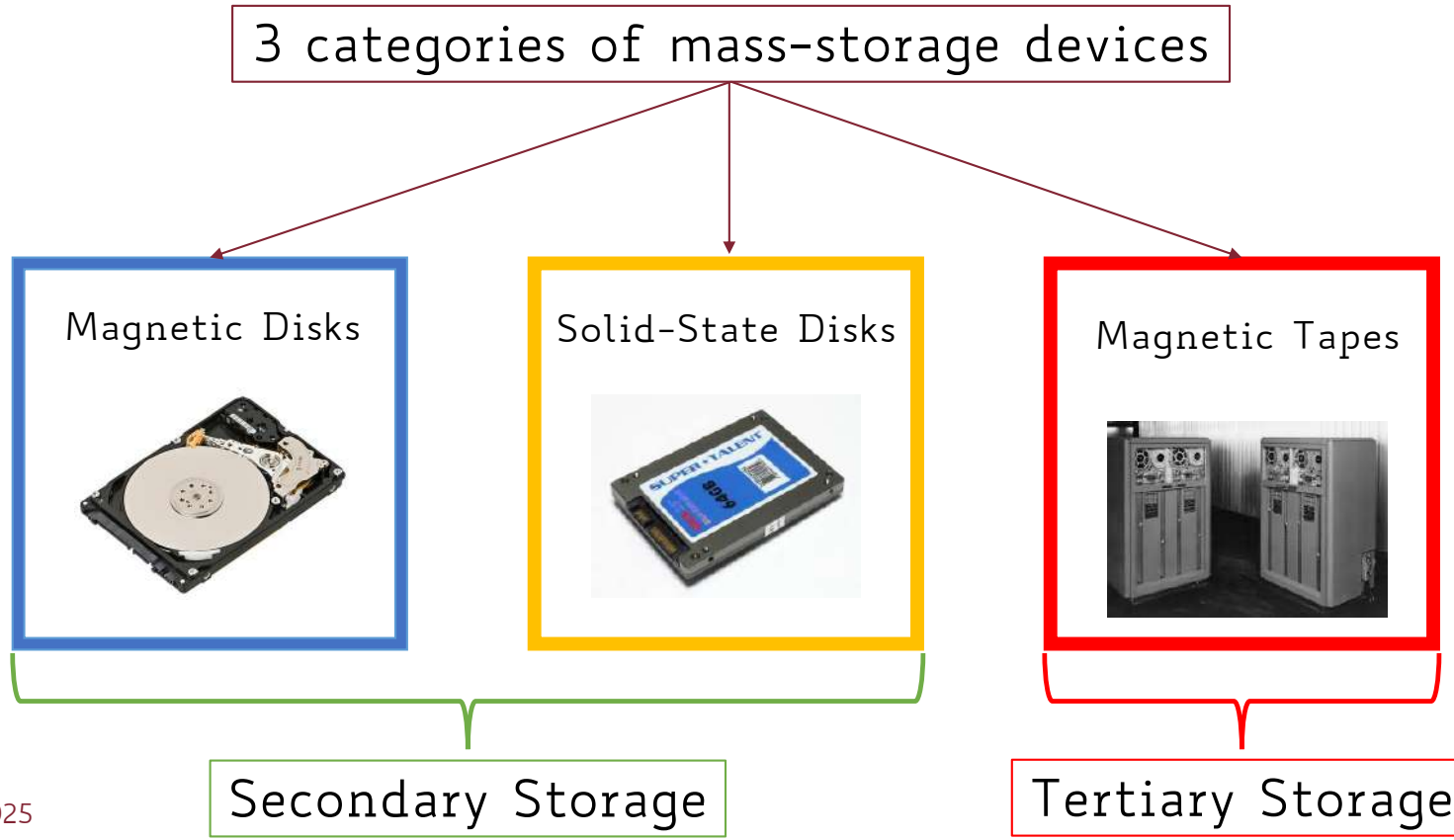

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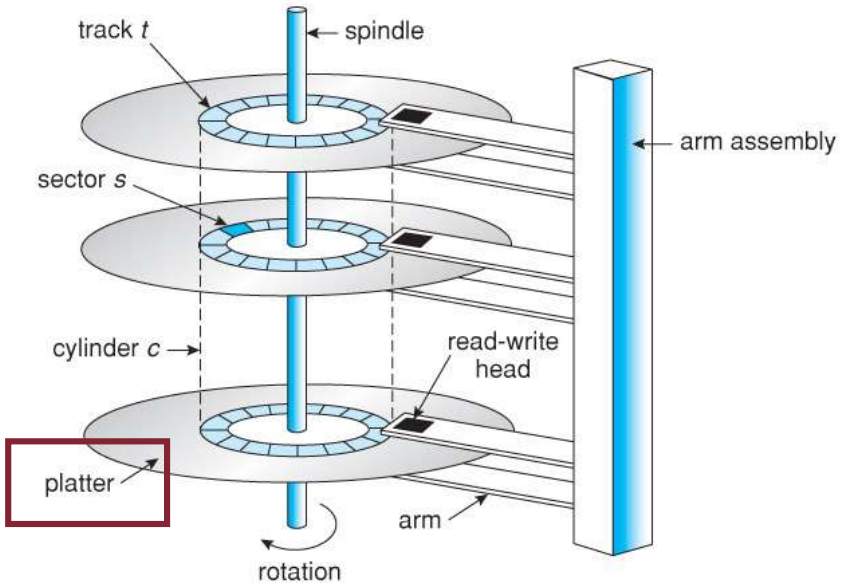
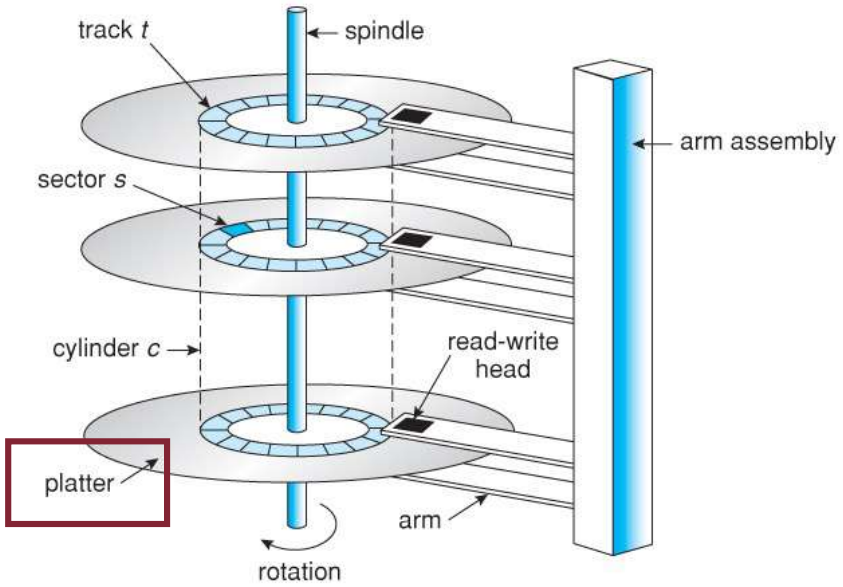
Magnetic Disks: Structure



One or more platters covered with magnetic media

Magnetic Disks: Structure



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Hard disk
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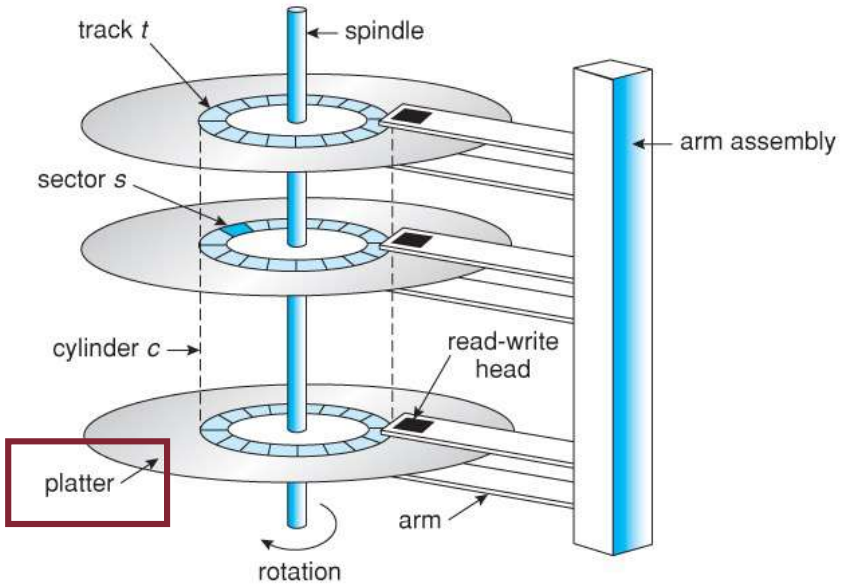

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- Hard disk: rigid metal
- Floppy disk: flexible plastic

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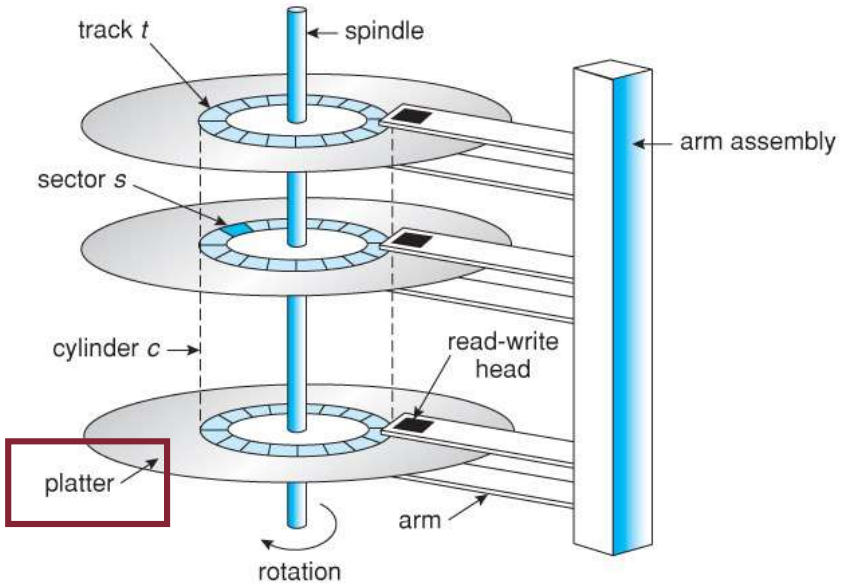

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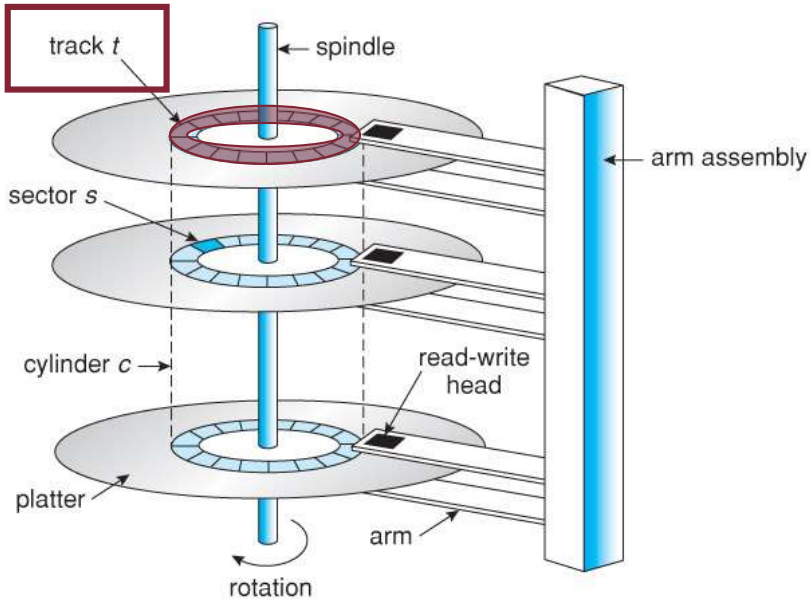
Hard disk
rigid metal

Floppy disk
flexible plastic

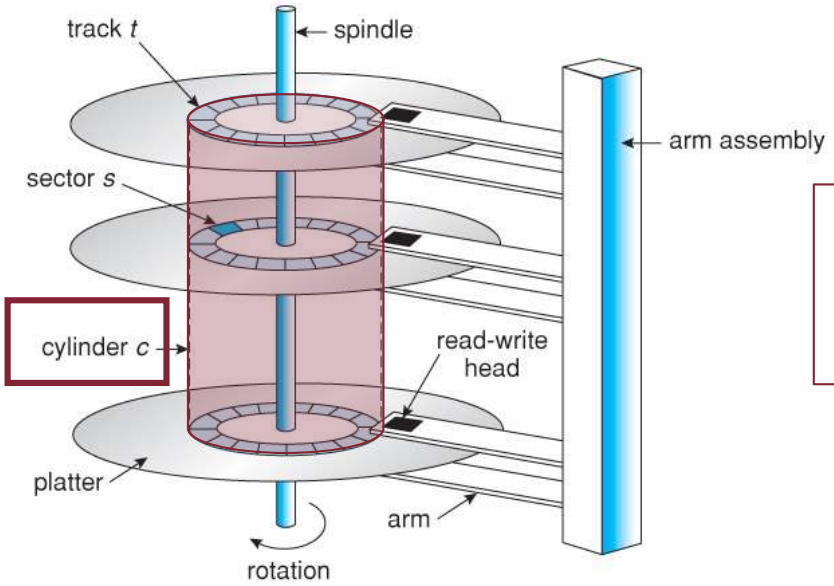
Each platter has 2 working surfaces

Magnetic Disks: Tracks and Cylinders



Each surface is divided into a number of concentric rings, called tracks

Magnetic Disks: Tracks and Cylinders



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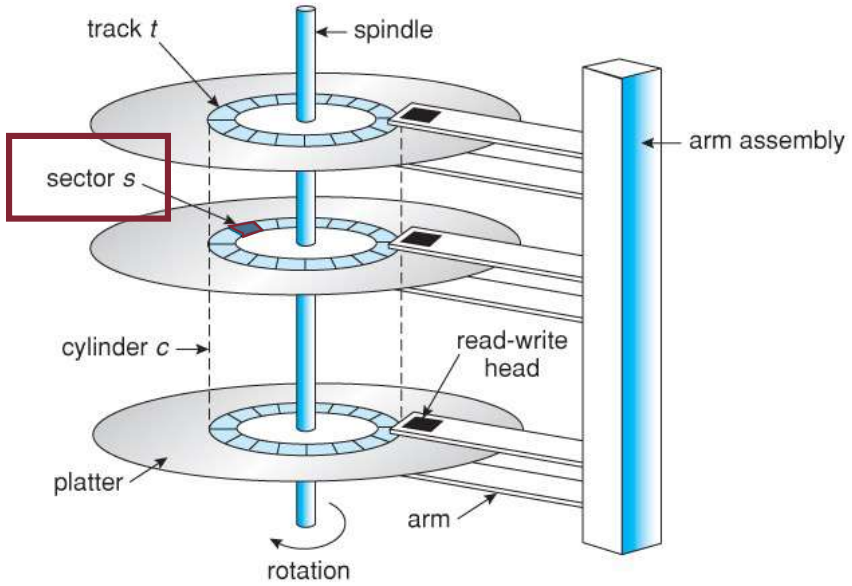
The set of all tracks that are the same distance from the edge of the platter is called a cylinder

Magnetic Disks: Sectors



Each track is further divided into sectors

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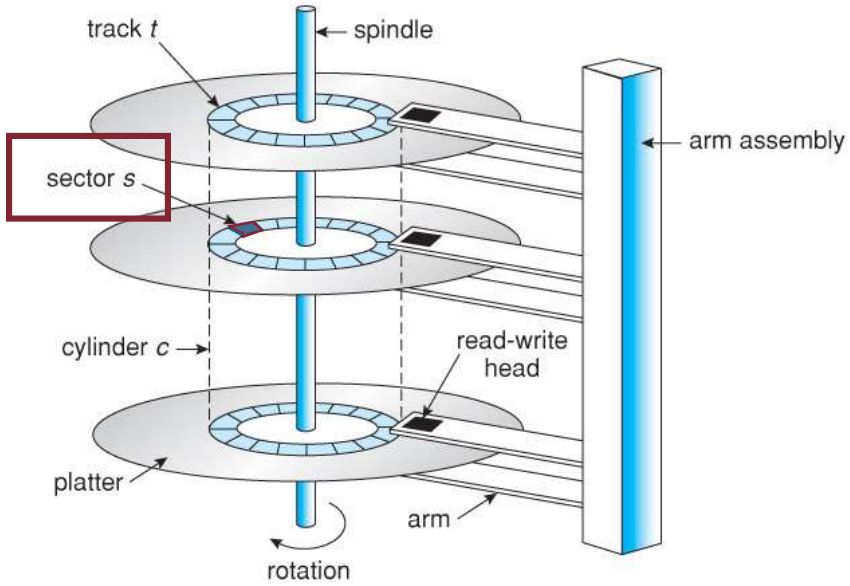

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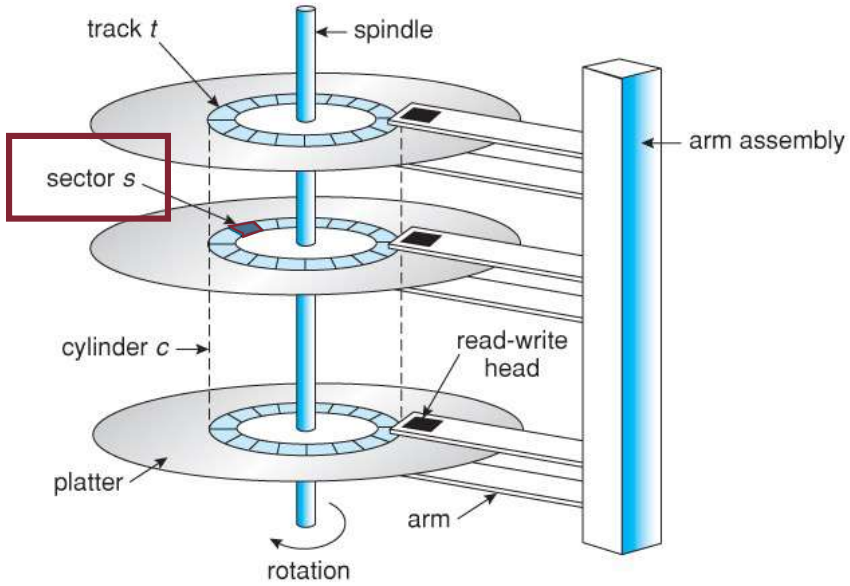

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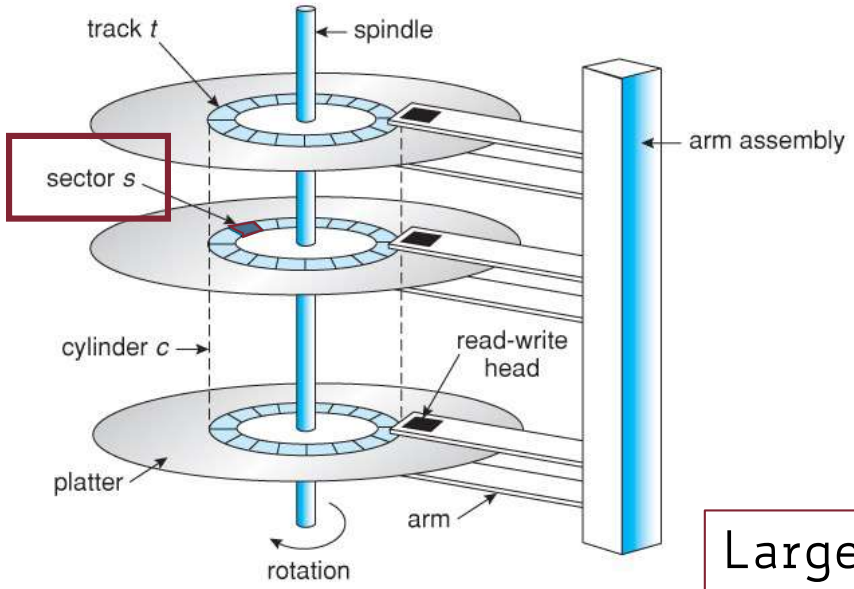

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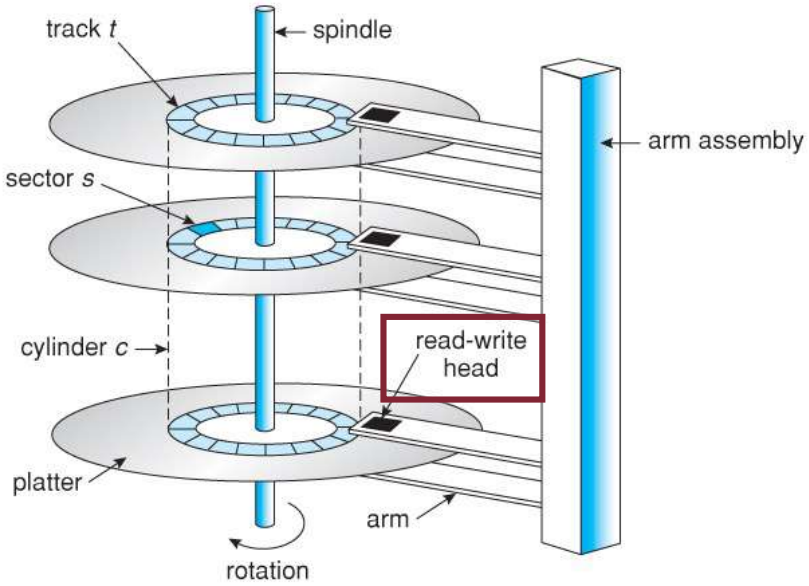
Larger sector sizes reduce the space wasted by headers and trailers, but increase internal fragmentation

Magnetic Disks: Heads



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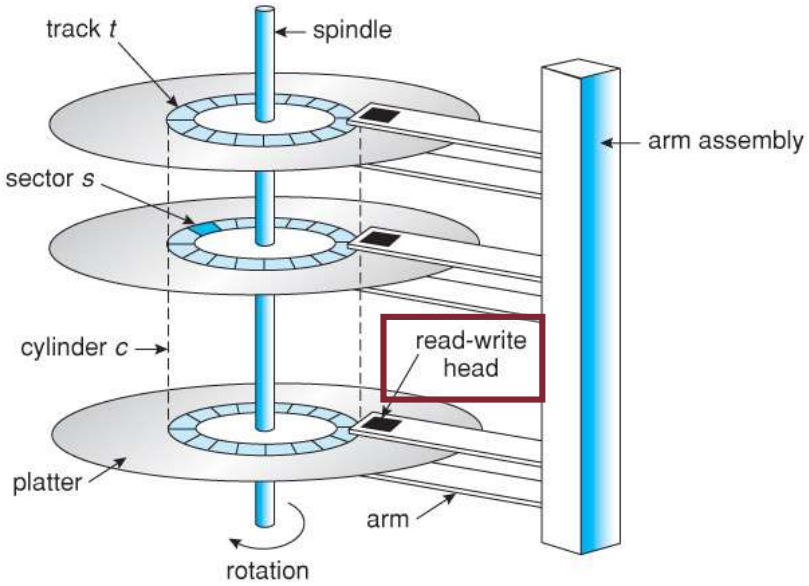
Magnetic Disks: Heads



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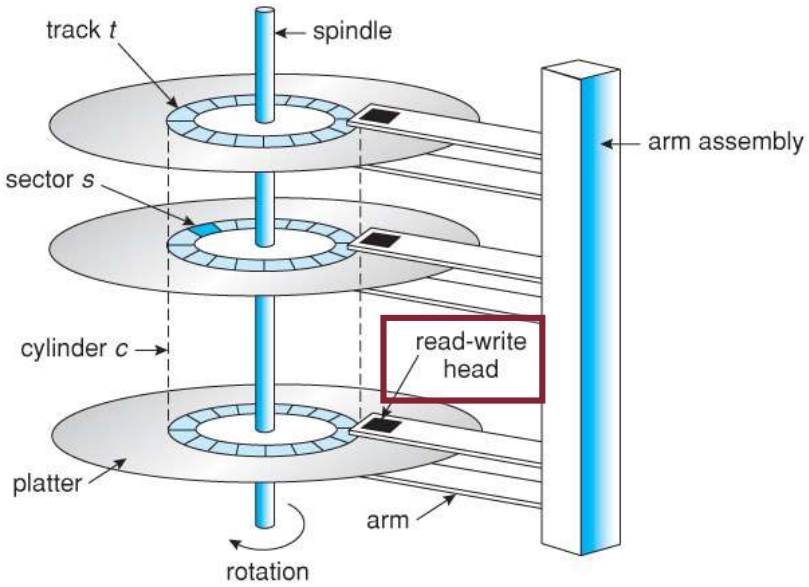

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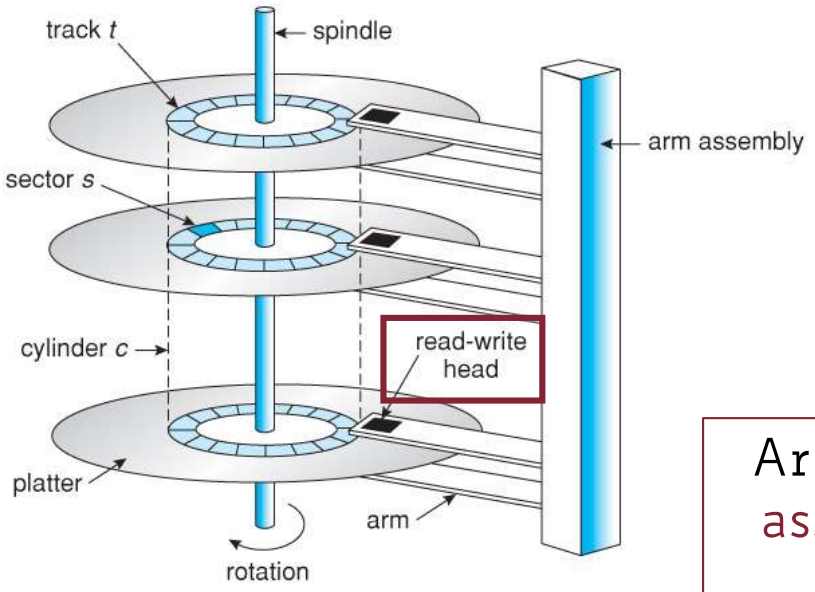

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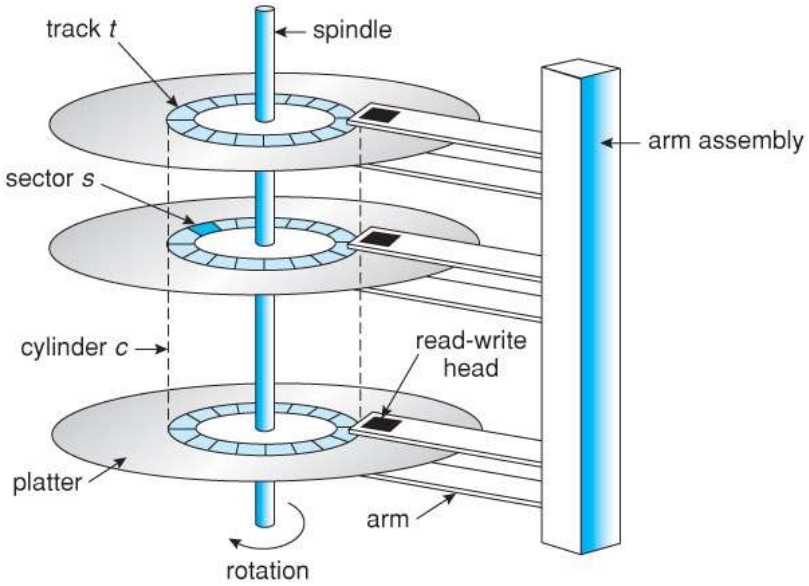
Arms are controlled by a common arm assembly moving simultaneously from one cylinder to another

Magnetic Disks: Storage Capacity

H = number of heads (working surfaces)



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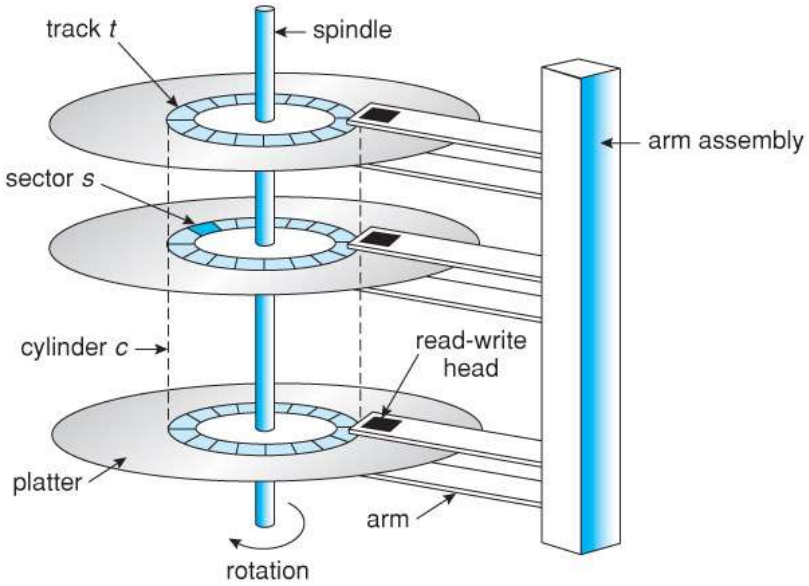

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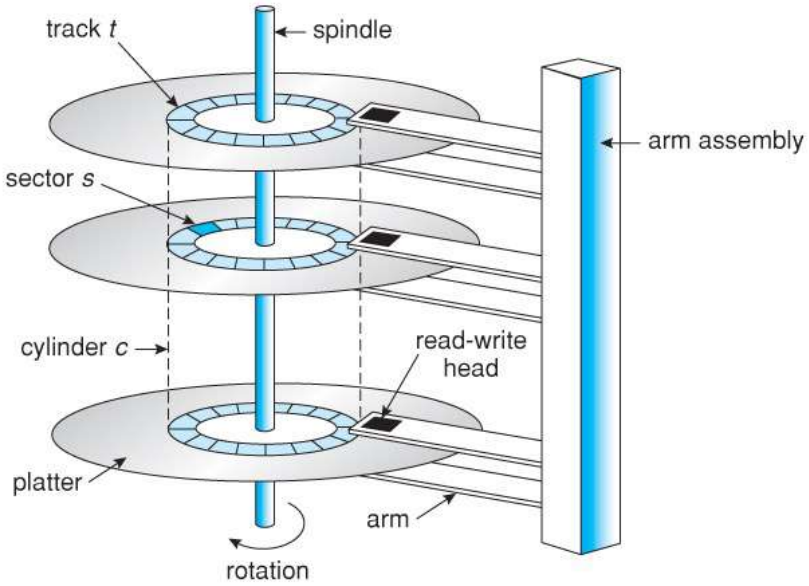

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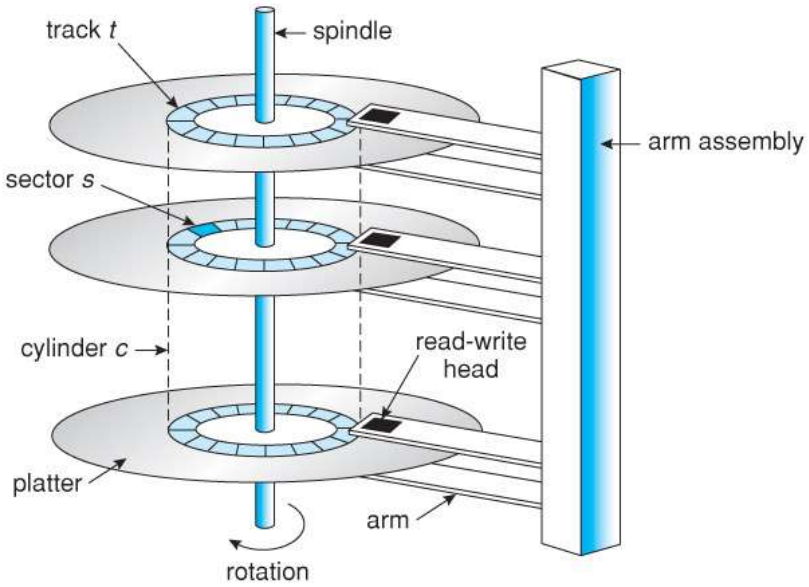

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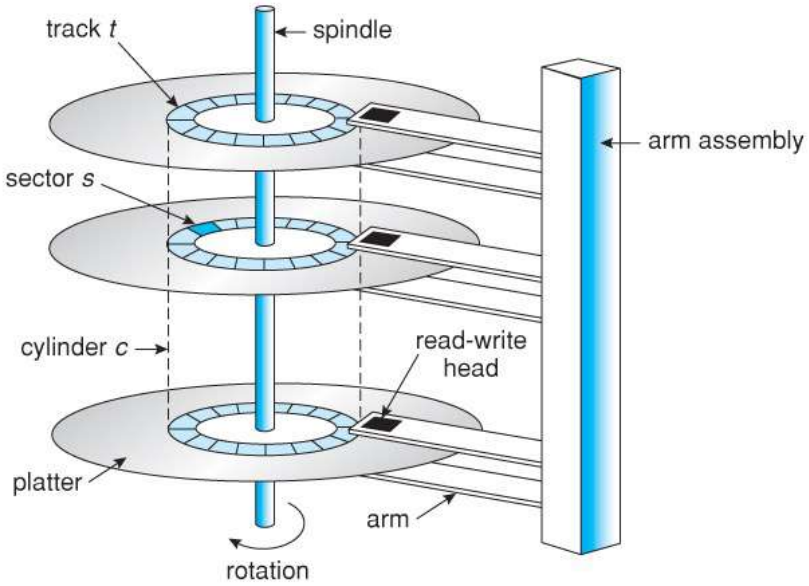

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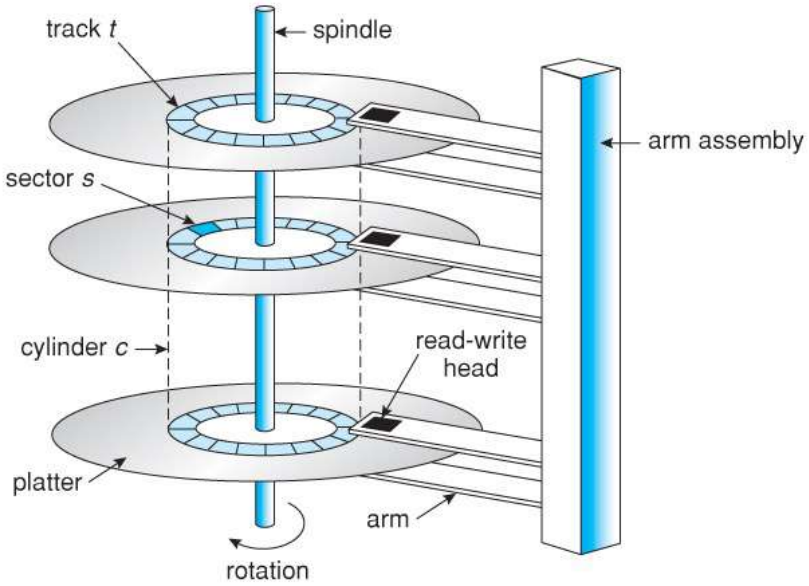
OVERALL CAPACITY

Magnetic Disks: Storage Capacity

Until the end of 1980s, every track had the same number of sectors with the same number of bits



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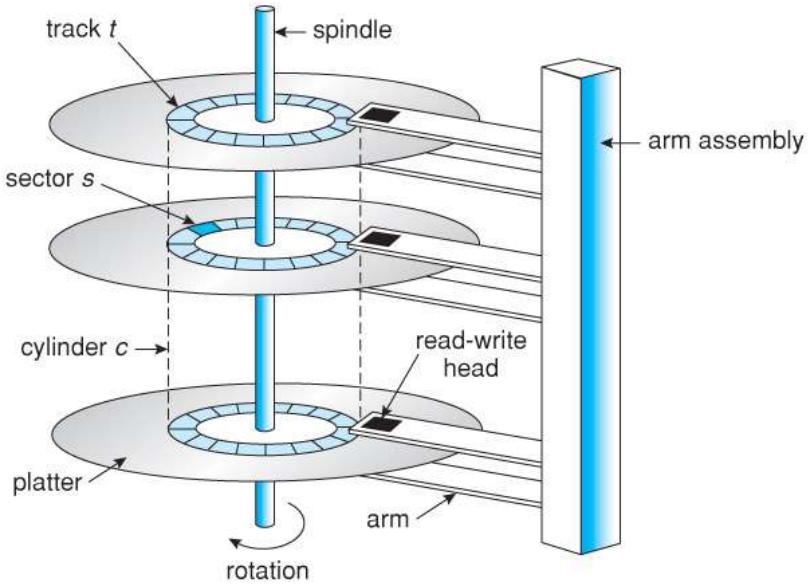

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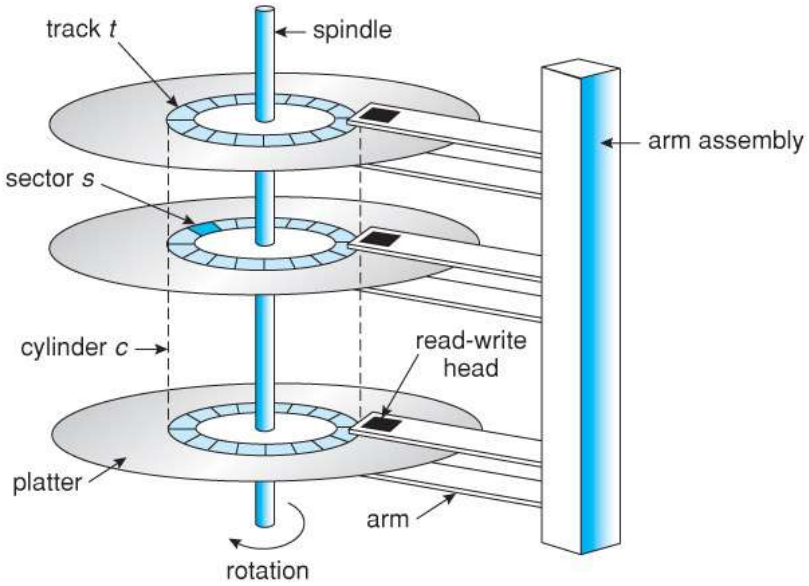

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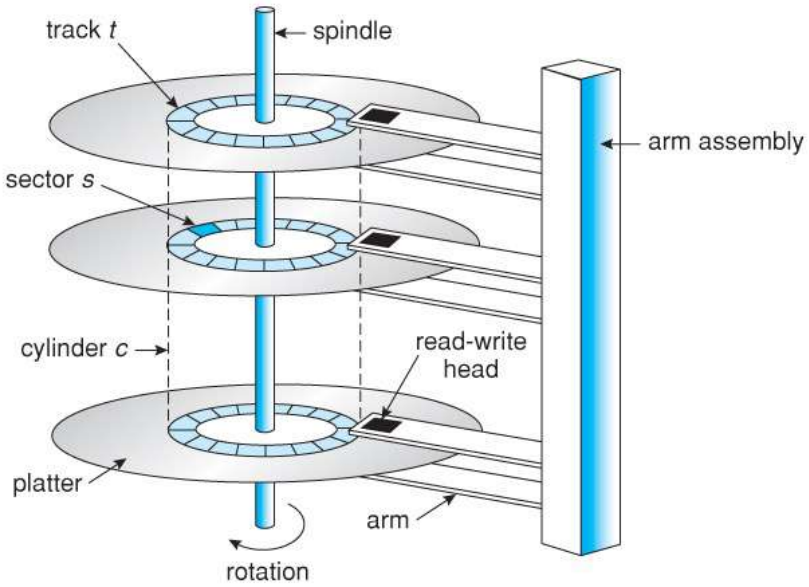

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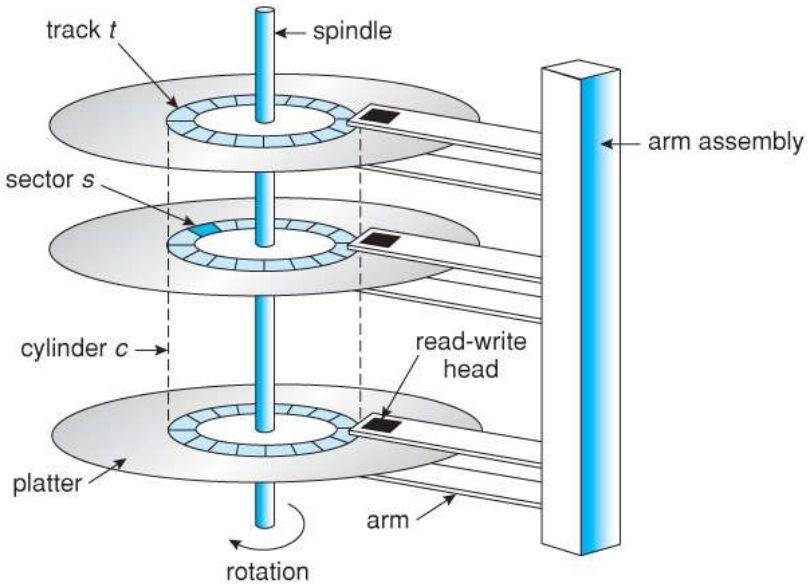

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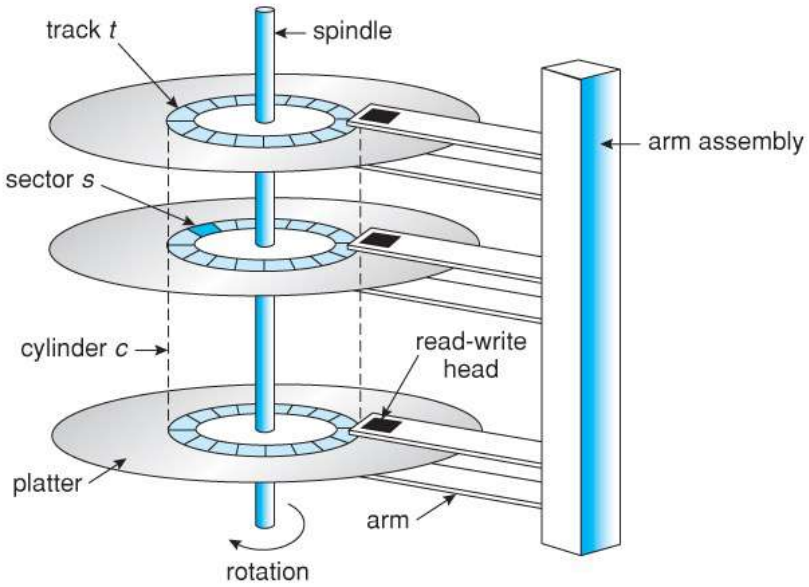
- Different frequencies and timing from innermost to outermost tracks

Magnetic Disks: Storage Capacity



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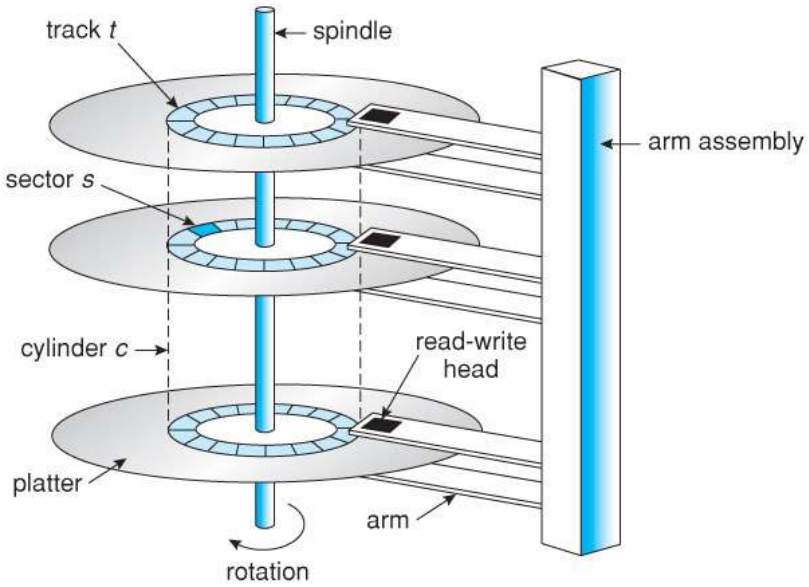

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The outermost track is larger and can hold more sectors than the inner ones

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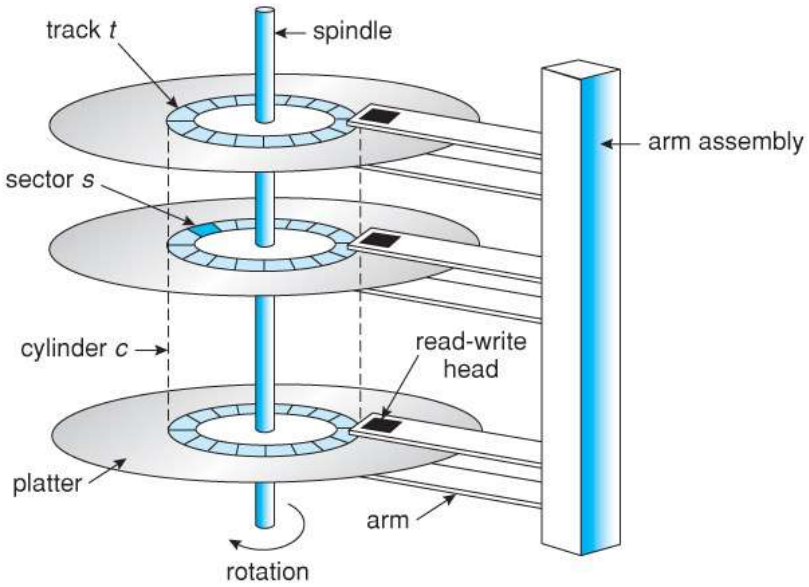

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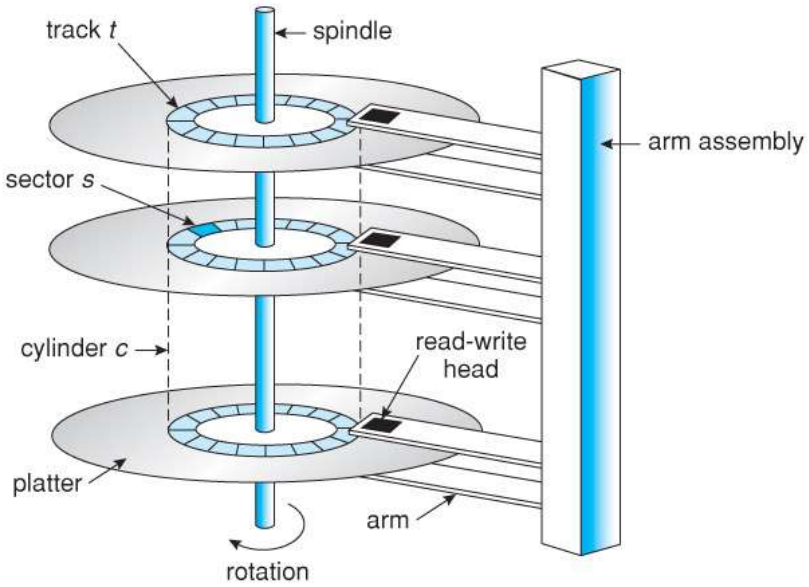

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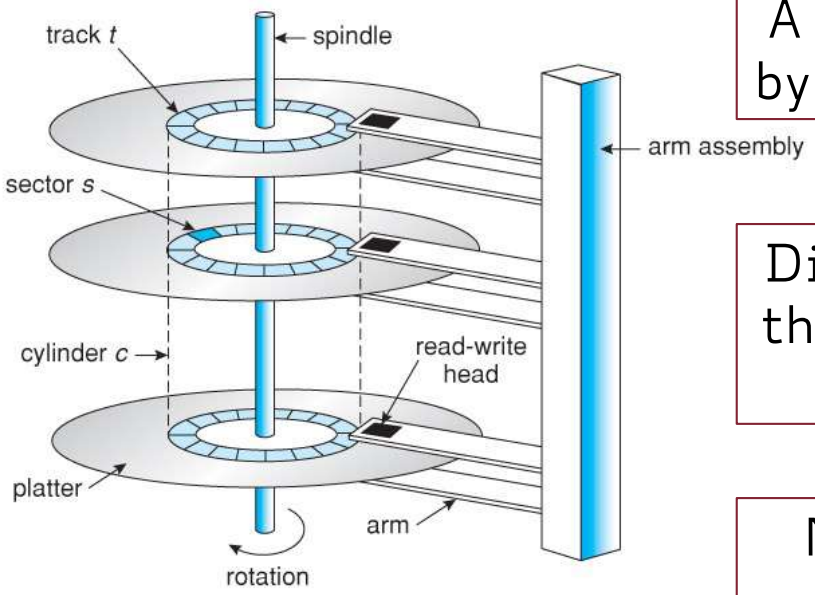
Bit density within the same zone is constant

Zone Bit Recording (ZBR)

Magnetic Disks: (Logical) Referencing



A physical block of data is specified by the (head, cylinder, sector) number

Disk blocks are numbered starting at the outermost cylinder, identified by 0

Note that cylinder coincides with track

Magnetic Disks: Data Transfer

- The disk rotates at **constant angular speed** (e.g., 7200 rpm = 120 rps)

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- Outer tracks spin **faster** than inner tracks (more sectors traversed in the same amount of time due to larger radius → more sectors per zone in ZBR)

Magnetic Disks: Data Transfer

- Data transfer from the disk to memory is made of **3 steps**:
  - positioning time (seek time or random access time)
  - rotational delay
  - transfer time

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mechanical

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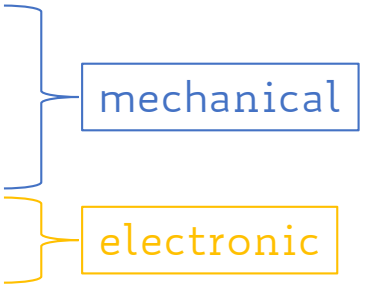

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- Depends on how fast the hardware moves the arm
- Typically, the slowest step in the entire process

Bottleneck of overall disk data transfer

Magnetic Disks: Rotational Delay

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- Can range from 0 up to one full revolution
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- On average, **0.5 revolutions** (r)
  - E.g., for a 7200 rpm (120 rps) disk this equals to 0.5 r/120 rps **~4 msec**

The second highest bottleneck

Magnetic Disks: Transfer Time

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Data Transfer Time = Seek Time + Rotational Delay + Transfer Time

Sometimes the term transfer rate is used to refer to the overall data transfer time

Magnetic Disks: Structure

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- Blocks are mapped onto physical disk sectors (**512 B ÷ 4 KiB**)

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- Then through other cylinders (from the outermost to innermost)

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- Head crash may permanently damage the disk or even destroy it
- To avoid such a risk, disk heads are "parked" when the computer is turned off

Magnetic Disks: Interfaces

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- Disk drives are connected to the computer via the I/O bus
- Some of the common interface formats include:
  - Enhanced Integrated Drive Electronics (EIDE);
  - Advanced Technology Attachment (ATA) and Serial ATA (SATA);
  - Universal Serial Bus (USB);
  - Fiber Channel (FC);
  - Small Computer Systems Interface (SCSI)

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- Data is transferred between the magnetic surface and onboard **cache** by the disk controller
- Finally, data is transferred from that cache to the host controller and the motherboard memory at electronic speeds

Minimize Data Transfer Time

- Mechanical components of magnetic disks cause bottleneck
  - Seek Time
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Minimize Data Transfer Time

- Mechanical components of magnetic disks cause bottleneck
  - Seek Time
  - Rotational Delay
- To minimize data transfer time from disk we need to minimize those

Minimize Data Transfer Time

- Smaller disks → lower seek time, since arms have to travel smaller distance

Minimize Data Transfer Time

- Smaller disks → lower seek time, since arms have to travel smaller distance
- Fast-spinning disks → lower rotational delay

Hardware Optimization

Minimize Data Transfer Time

- How can the OS help minimize data transfer time?
- Schedule disk operations so as to minimize head movement
- Lay out data on disk so that related data are located on close tracks
- Place commonly-used data on a specific portion of the disk
- Pick carefully the block size contained on each sector:
  - Too small → more seeks are needed to transfer the same amount of data
  - Too large → more internal fragmentation and space wasted

Summary

- Hard disks are slow devices compared to CPUs (and main memory)
- Manage those device efficiently is crucial
- Minimize seek and rotational delay on magnetic disks
- HW optimizations are limited → OS needs to take the lead here!