ECE 550D
Fundamentals of Computer Systems and Engineering

Fall 2023

Input/Output (IO)

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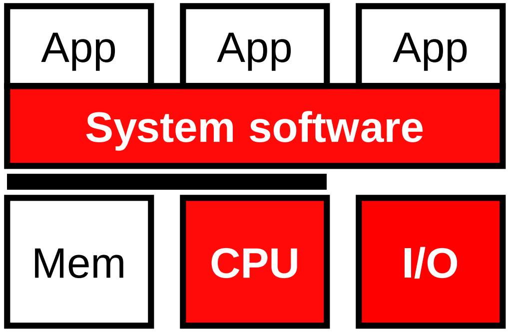
Slides are derived from work by
Andrew Hilton, Tyler Bletsch and Rabih Younes (Duke)

IO: Interacting with the outside world

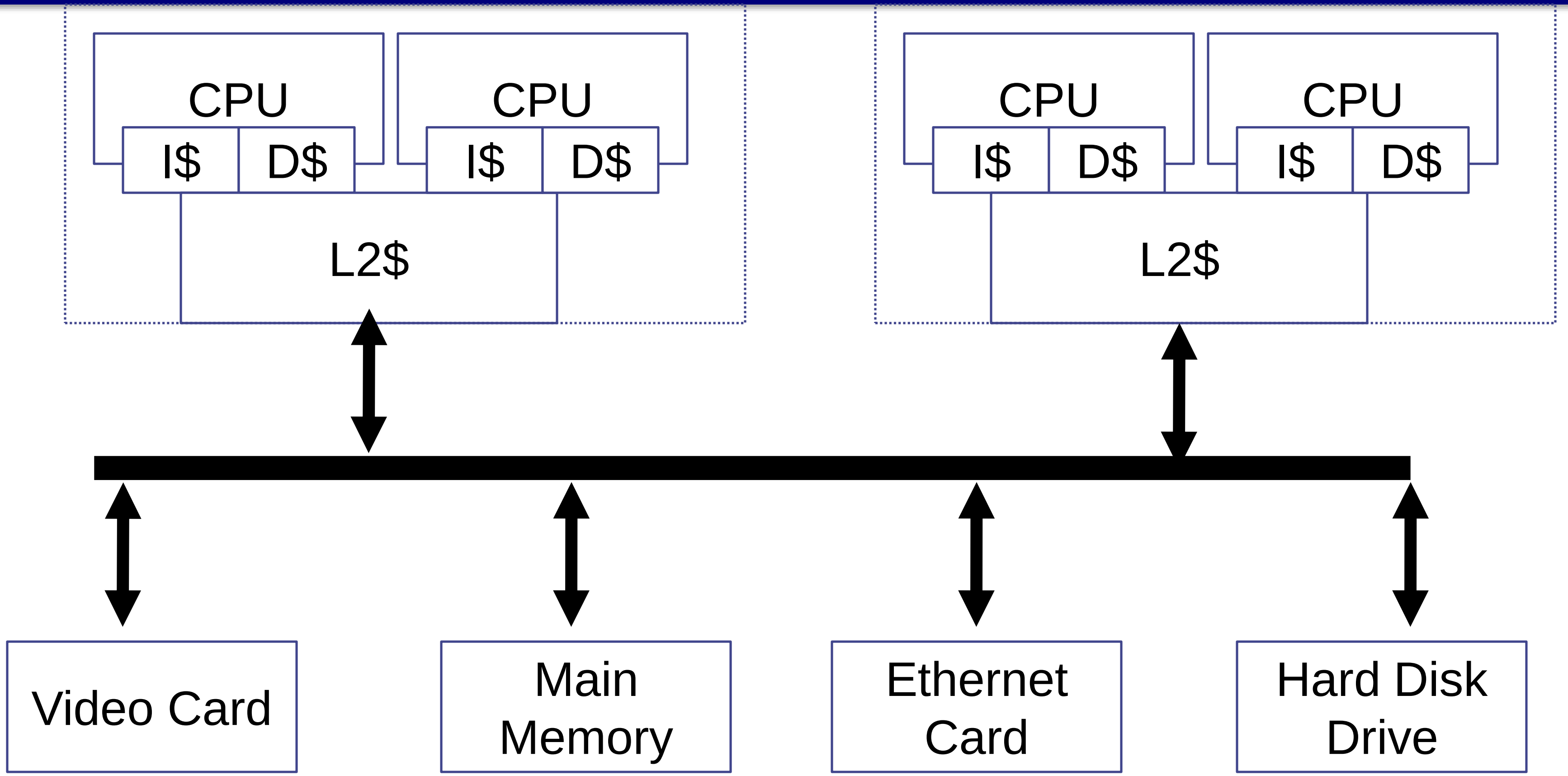


- Input and Output Devices
  - Video
  - Disk
  - Keyboard
  - Sound
  - …

Communication with IO devices

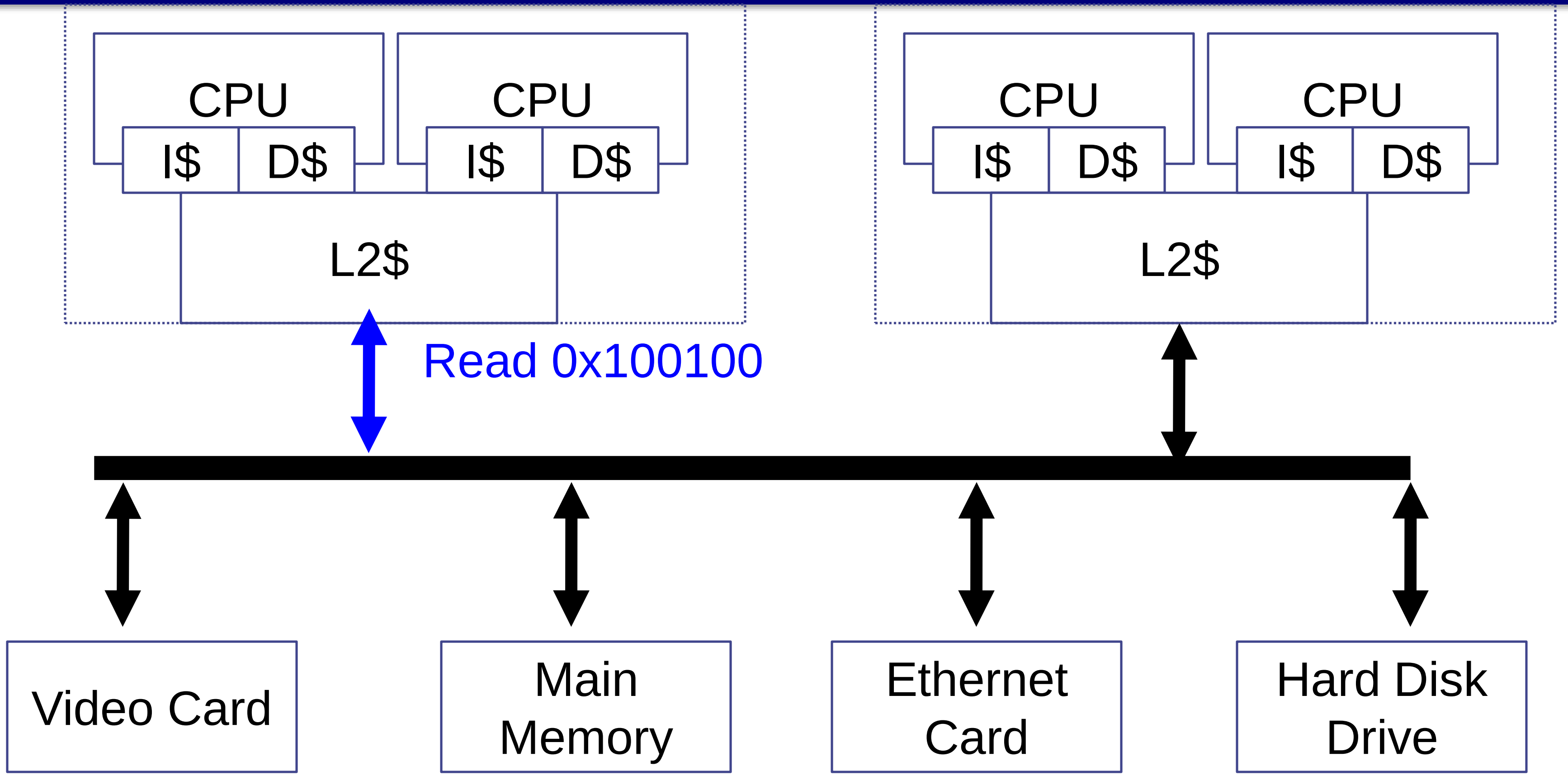
- Processor needs to get info to/from IO device
  - Two ways:
    - In/out instructions
      - Read/write value to "io port"
      - Devices have specific port numbers
    - Memory mapped
      - Regions of physical addresses not actually in DRAM
      - But mapped to IO device
        - **Stores to mapped addresses send info to device**
        - **Reads from mapped addresses get info from device**

A view of the world



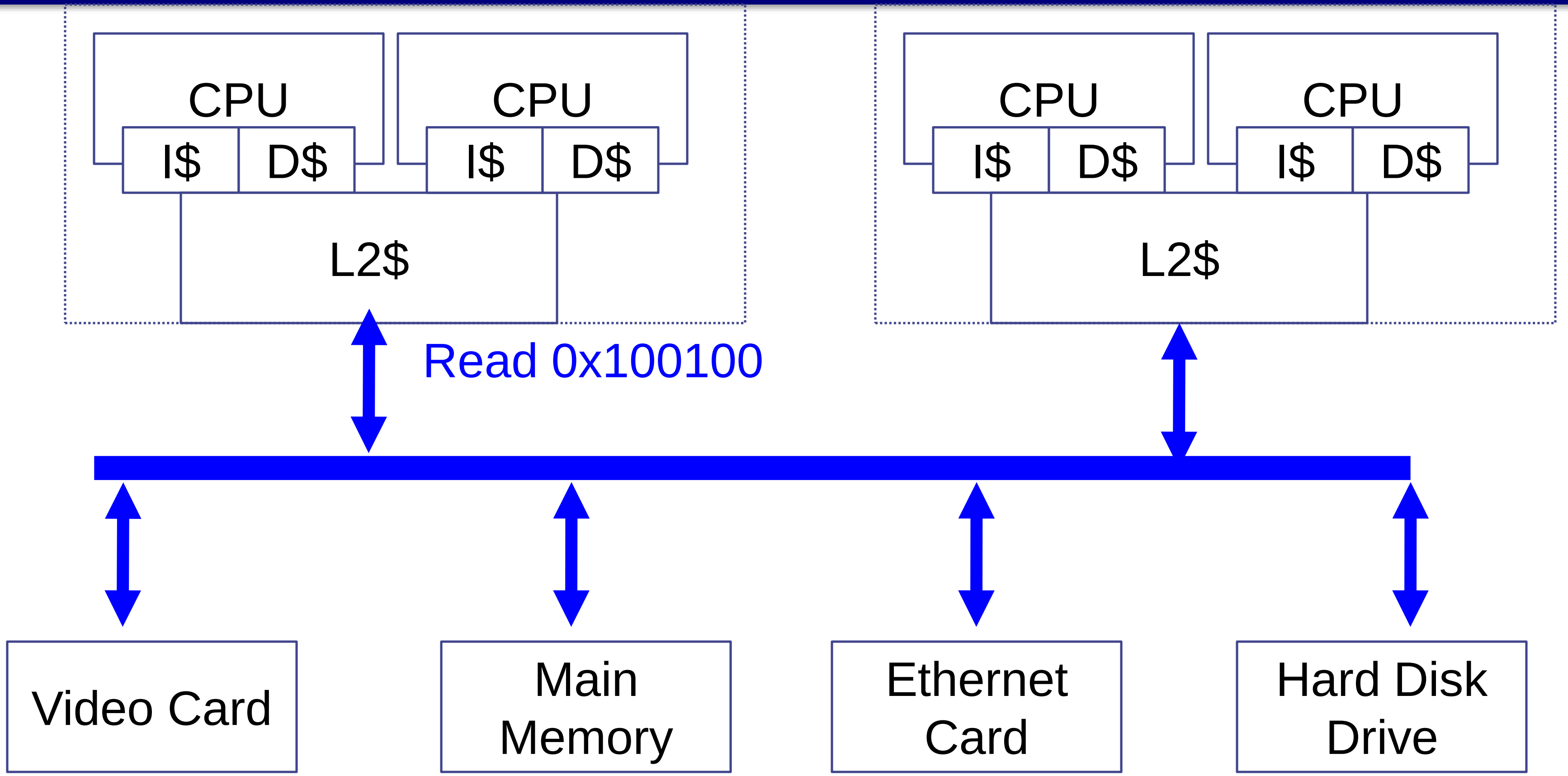
- 2 “socket” system (each with 2 cores)
- Real systems: more IO devices

A view of the world



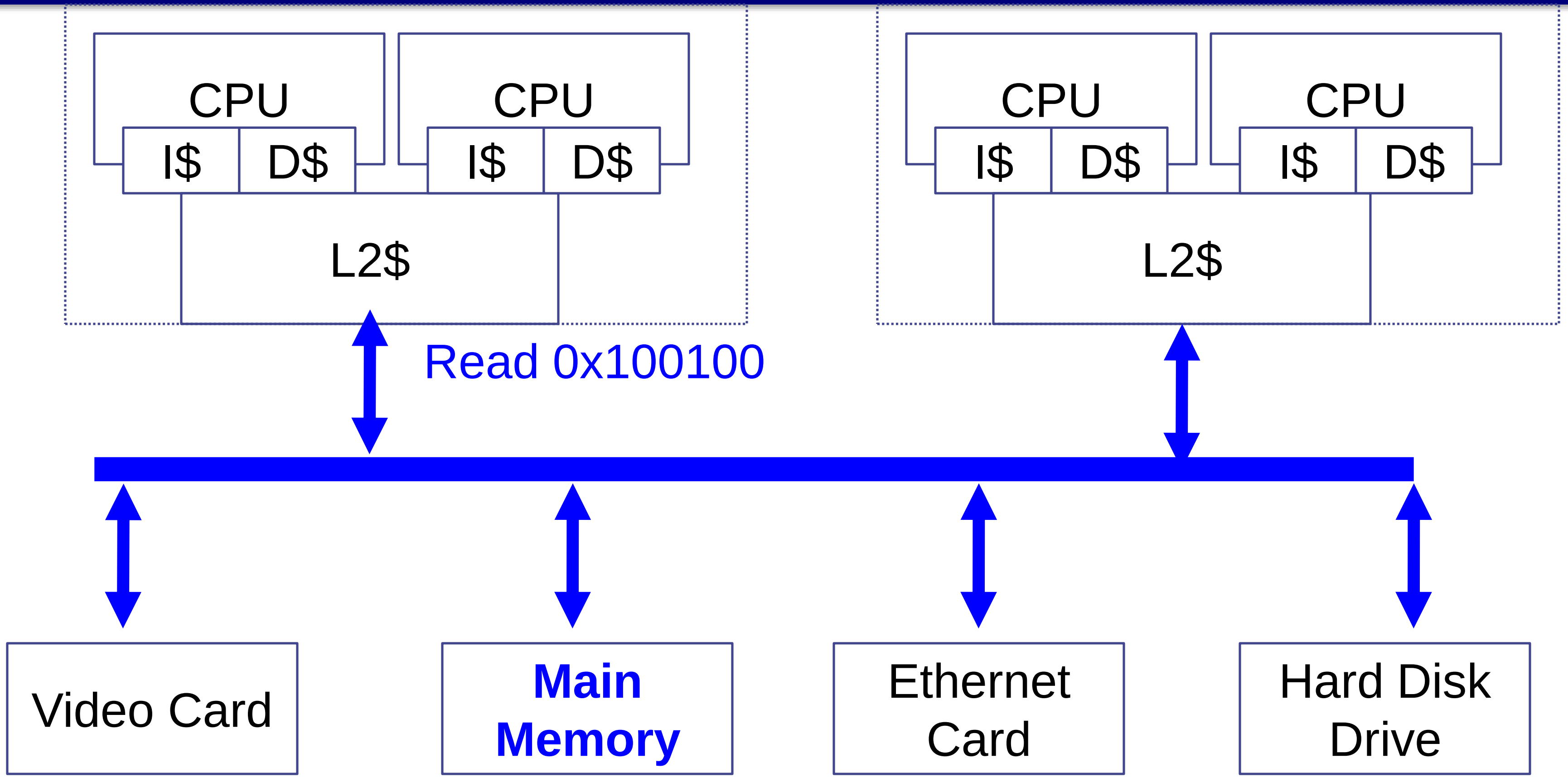
- Chip 0 requests read of 0x100100

A view of the world



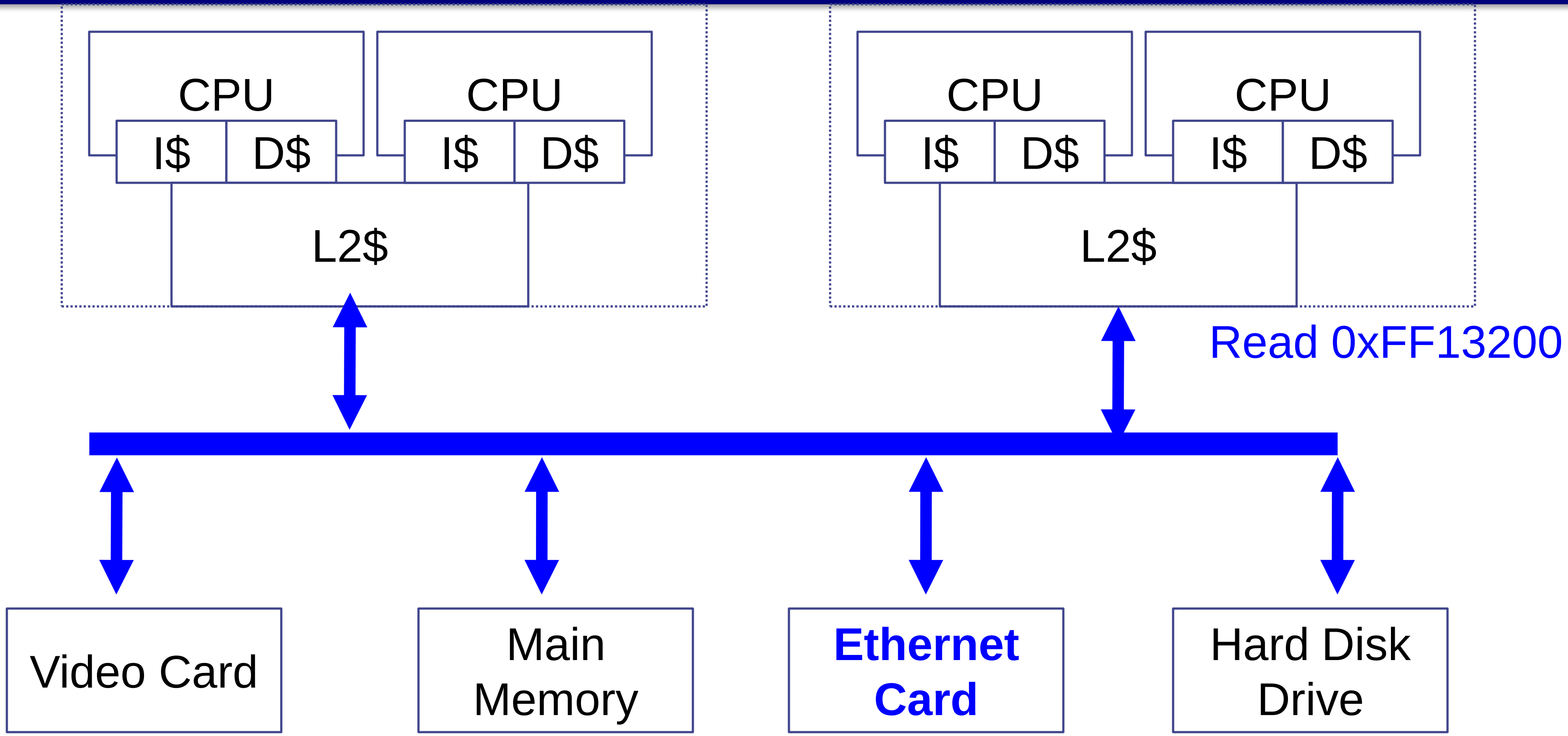
- Chip 0 requests read of 0x100100
- Request goes to all devices

A view of the world



- Chip 0 requests read of 0x100100
- Request goes to all devices, which check address ranges

A view of the world



- Other address ranges may be for a particular device

Speaking of VGA video

- You all wrote a VGA controller early
  - Read a ROM with an image
  - Real ones: read a RAM
  - How to draw? CPU writes to physical memory mapped to video card RAM
  - Video card sees write and updates its internal RAM
  - The rest: FSM just like you did

Exploring Memory Mappings on Linux

- You can see what devices have what memory ranges on Linux with **`lspci -v`** (at least those on the PCI bus)

00:02.0 VGA compatible controller: Intel Corporation Core Processor Integrated Graphics Controller (rev 02)
    Subsystem: Lenovo Device 215a
    Flags: bus master, fast devsel, latency 0, IRQ 30
    Memory at f2000000 (64-bit, non-prefetchable) [**size=4M**]
    Memory at d0000000 (64-bit, prefetchable) [**size=256M**]
    I/O ports at 1800 [size=8]
    Capabilities: [90] Message Signalled Interrupts: Mask- 64bit- Queue=0/0 Enable+
    Capabilities: [d0] Power Management version 2
    Capabilities: [a4] PCIe advanced features <?>
    Kernel driver in use: i915
    Kernel modules: i915

A simple "IO device" example

- Read (physical) address 0xFFFF1000 for "ready"
- If ready, read address 0xFFFF1004 for data value
  - IO device will go to next value automatically on read

```
read_dev:
li $t0, 0xFFFF1000
loop:
   lw $t1, 0($t0)
   beqz $t1, loop
   lw $v0, 4($t0)
   jr $ra
```

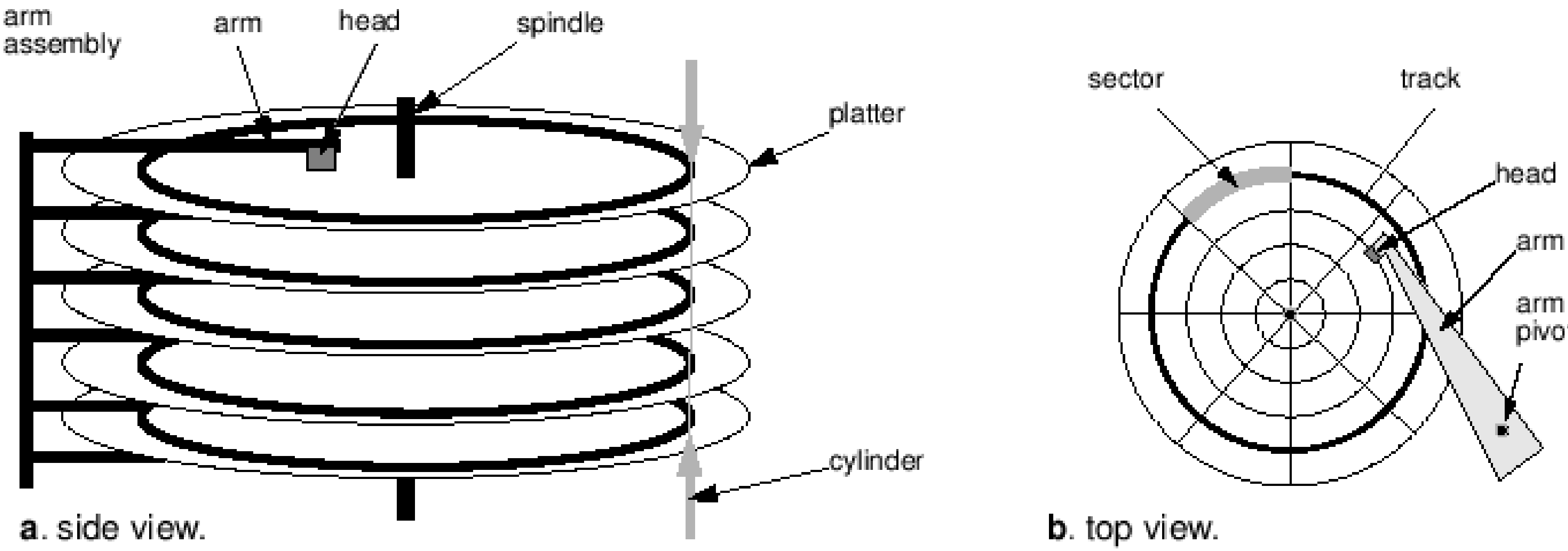
Who can remind us what this is called (last lecture)?

A handful of questions…

- How do we use physical addresses?
  - Programs only know about virtual addresses right?
  - Only OS accesses IO devices:
    - OS knows about physical addresses, and can use them

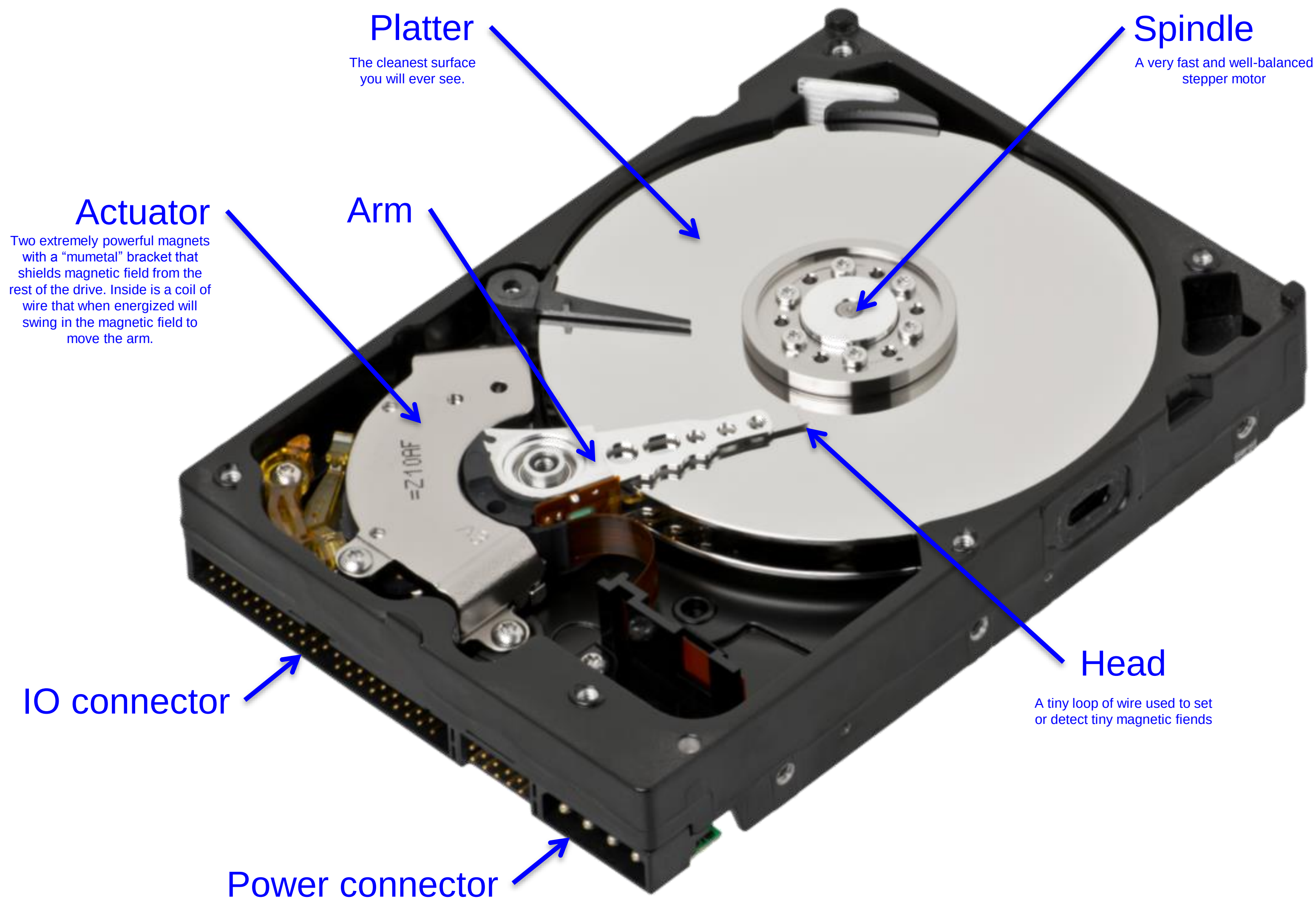
- What about caches?
  - Won't the first lw bring the current value of 0xFFFF1000 into the cache?
  - And then subsequent requests just hit the cache?
  - **Pages have attributes, including cacheability**
    - IO mapped pages marked non-cacheable
    - Also, prevent speculative loads (e.g., out-of-order)

Hard drives

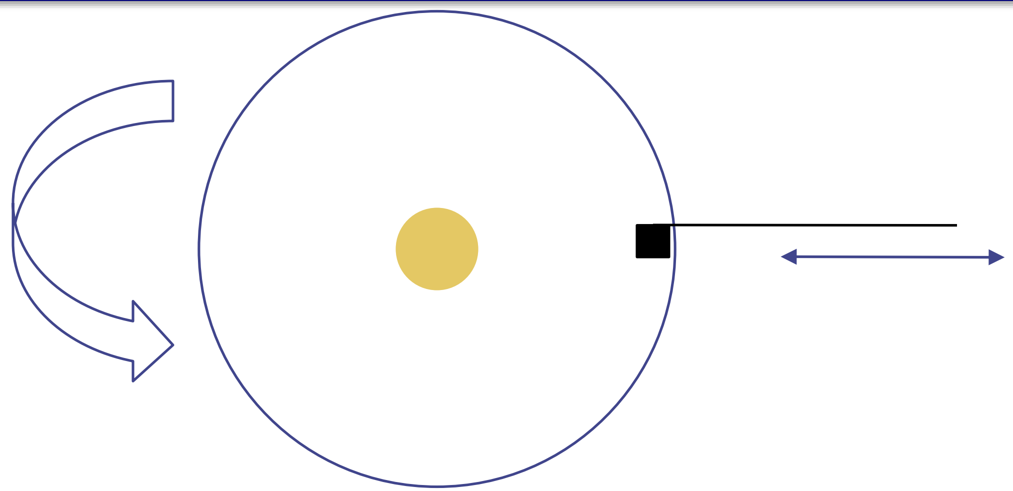


- Disks are circular platters of spinning metal
- Multiple tracks (concentric rings)
- Each track divided into sectors

Hard drive internals

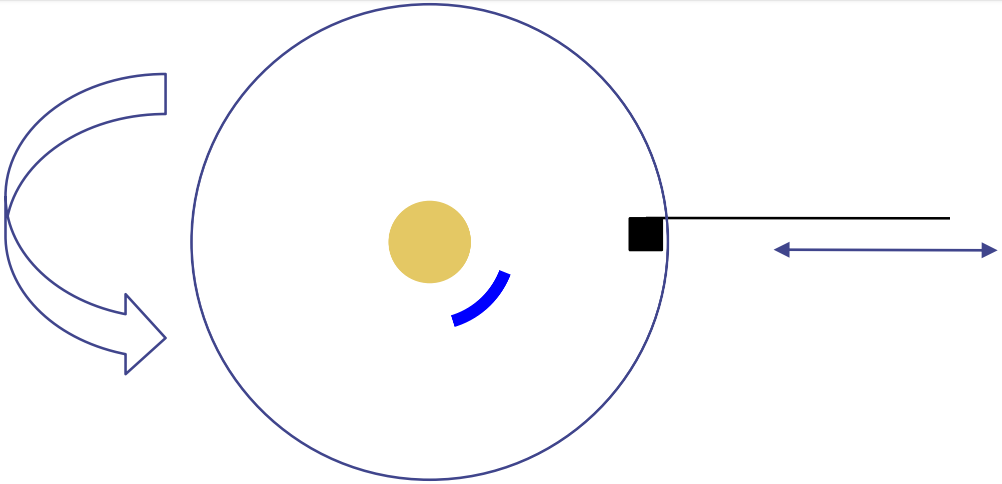


Hard disks



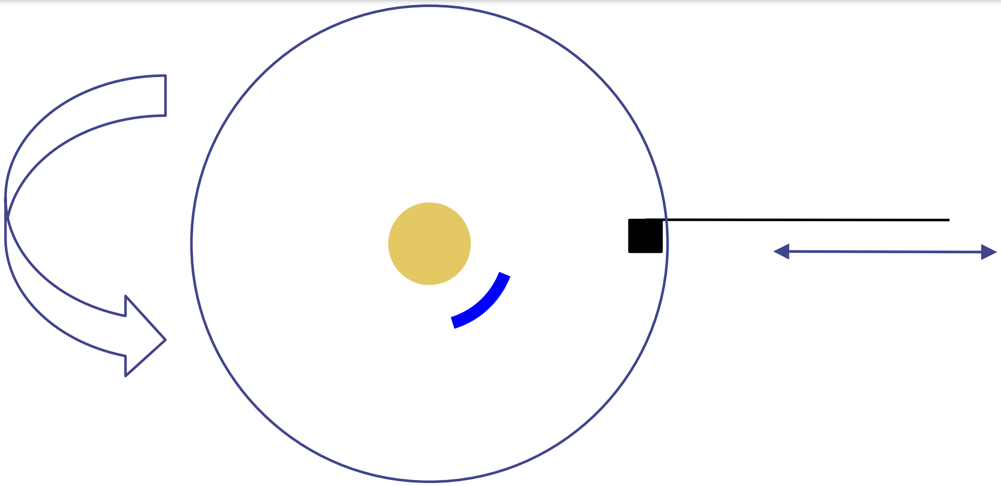
- Read/written by "head"
  - Moves across tracks **("seek")**
  - After seek completes, wait for proper sector to rotate under head.
  - Reads or writes magnetic medium by sensing/changing magnetic state (this takes time as the desired data 'spins under' the head)

Hard disks



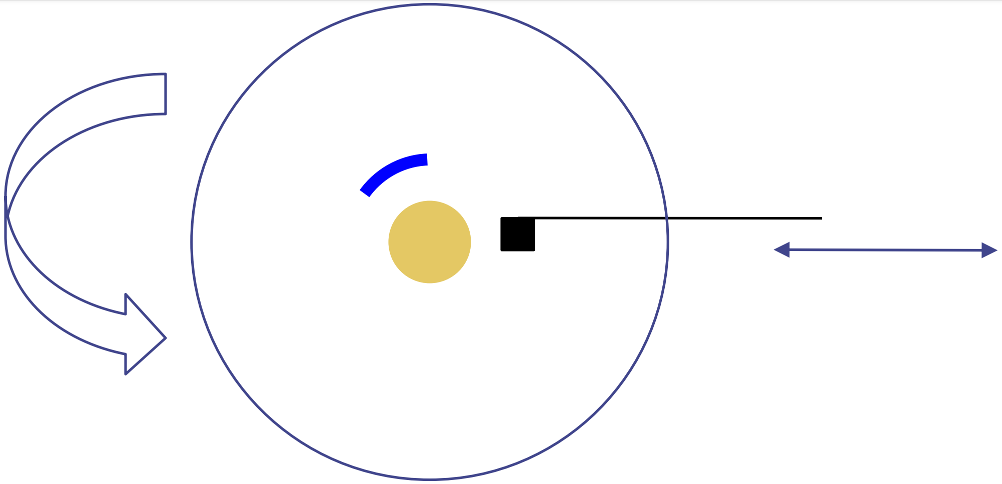
- Want to read data on blue curve

Hard disks



- Want to read data on blue curve
  - First step: seek—move head over right track
    - Takes time (Tseek), disk keeps spinning

Hard disks



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    - Now head over right track… but data needs to move under head
  - Second step: wait (Trotate)

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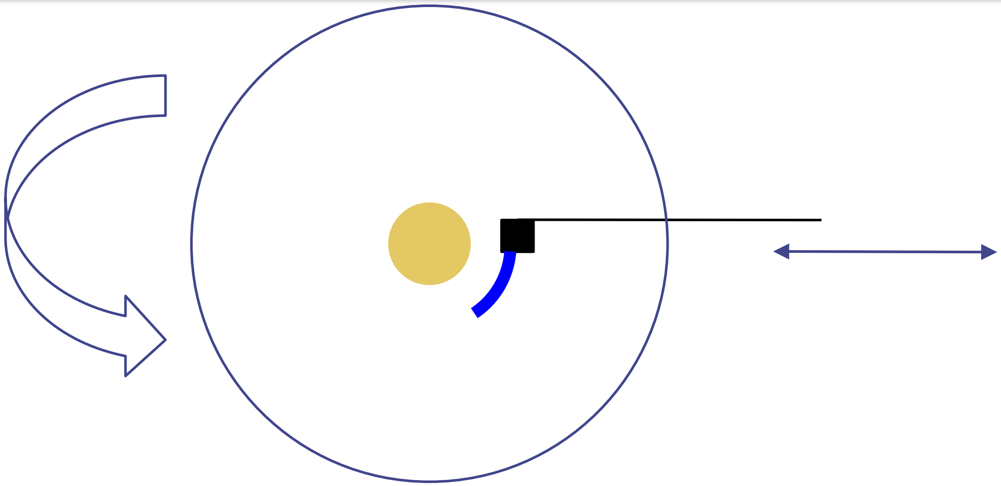

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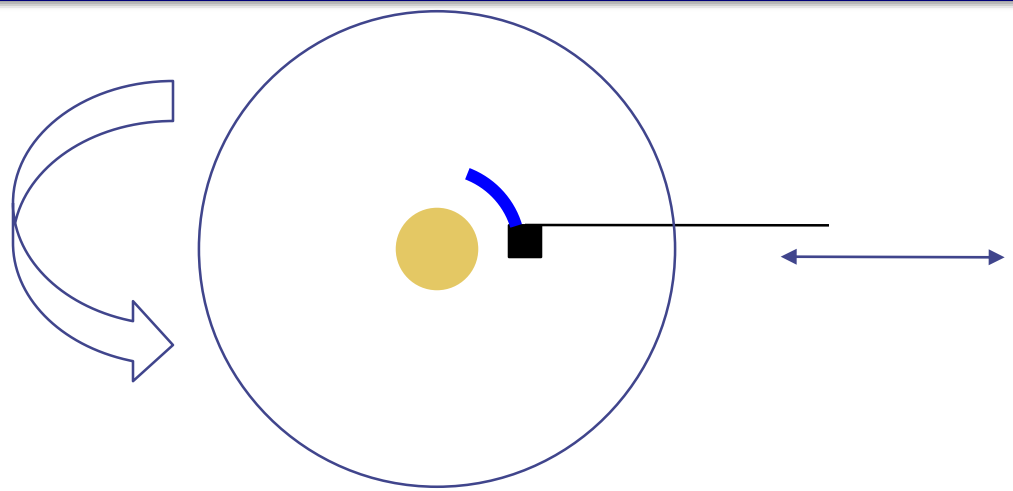
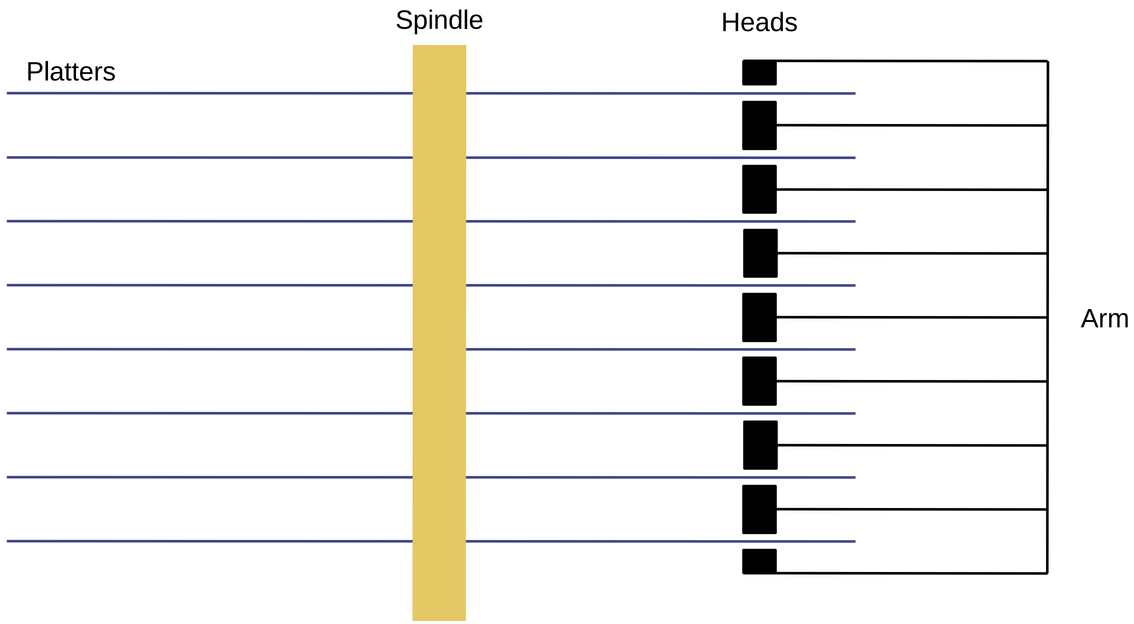
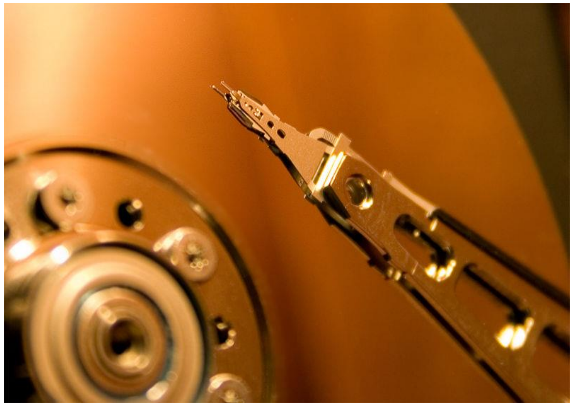
Hard disks

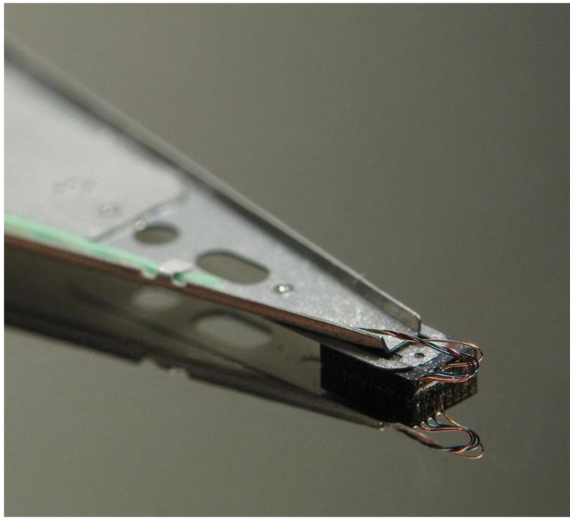


- Want to read data on blue curve (imagine circular arc)
  - First step: seek—move head over right track
    - Takes time (Tseek), disk keeps spinning
    - Now head over right track… but data needs to move under head
  - Second step: wait (Trotate)
  - Third step: as data comes under head, start reading
    - Takes time for data to pass under read head (Tread)

Hard Disks: from the side







- Multiple platters, each with a head above and below
  - Two sided surface
  - Heads all stay together ("cylinder")
  - Heads not actually touching platters: just **very** close (< 1mm)

A few things about HDD performance

- Tseek:
  - Depends on how fast heads can move
  - And how far they have to go
    - OS may try to schedule IO requests to minimize Tseek
- Trotate:
  - Depends largely on how fast disk spins (RPM, Revolutions per Minute)
  - Also, how far around the data must spin, but usually assume avg
    - OS cannot keep track of position, nor schedule for better
- Tread:
  - Depends on RPM + how much data to read

Disk Drive Performance

- Suppose on average
  - Tseek = 10 ms
  - Trotate = 3.0 ms
  - Tread = 5 usec/ 512-byte sector

- What is the average time to read one 512-byte sector?
  - 10 ms + 3 ms + 0.005 ms = 13.005 ms
  - Reading 1 sector: 512 byte/ 13.05 ms => **~40KB/sec**

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  - 1MB = 2048 sectors
  - 10 + 3 + 0.005 * 2048 =23.24 ms => **~43MB/sec**

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  - 1MB = 2048 sectors
  - 10 + 3 + 0.005 * 2048 =23.24 ms => ~43MB/sec
- Larger contiguous reads: approach **100MB/sec**
  - **Amortize** Tseek + Trotate (key to good disk performance)

Disk Performance

- Hard disks have caches (spatial locality)

- OS will also buffer disk in memory
  - Ask to read 16 bytes from a file?
  - OS reads multiple KB, buffers in memory

- "Defragmenting":
  - Improve locality by putting blocks for same files near each other

What about SSDs?

- Solid state drive (SSD)
  - Storage drives with no mechanical component
  - Internal storage similar to our logic-gate based memory (NAND gates), but persistent!
  - SSD Controller implements Flash Translation Layer (FTL)
    - Emulates a hard disk
    - Exposes logical blocks to the upper level components
    - Performs additional functionality

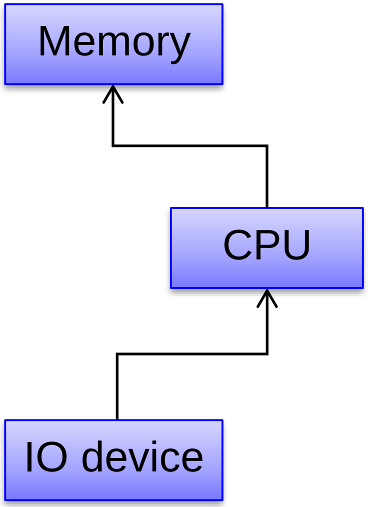
Source: wikipedia

SSDs summarized

- Tradeoffs of SSDs:
  - \+ No expensive seek, uniform access latency
  - – Due to physics, can WRITE small data blocks (~4kB) but can only ERASE big data blocks (~1MB, also slow).
    - Complicated controller logic does tons of hidden tricks to make it seem like a regular hard drive while hiding all the weirdness
  - – More expensive per GB capacity
  - \+ Less expensive per unit of IO performance

Transferring the data to memory

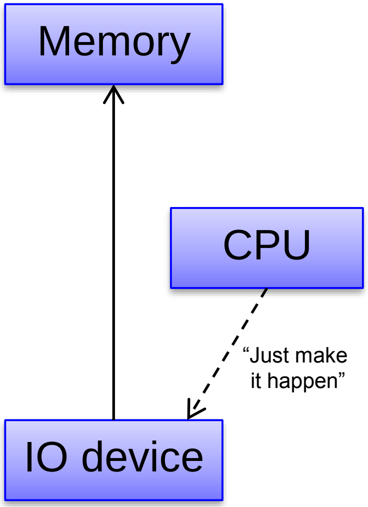
- OS asks disk to read data
  - Disk read takes a long time (15 ms => millions of cycles)
  - Does OS poll disk for 15M cycles looking for data?
  - No—disk interrupts OS when data is ready.
- Ready: version 1
  - Disk has data, needs it transferred to memory
  - OS does "memcpy" like routine:
    - Read hdd memory mapped IO
    - Write appropriate location in main memory
    - Repeat
    - For many KB to a few MB



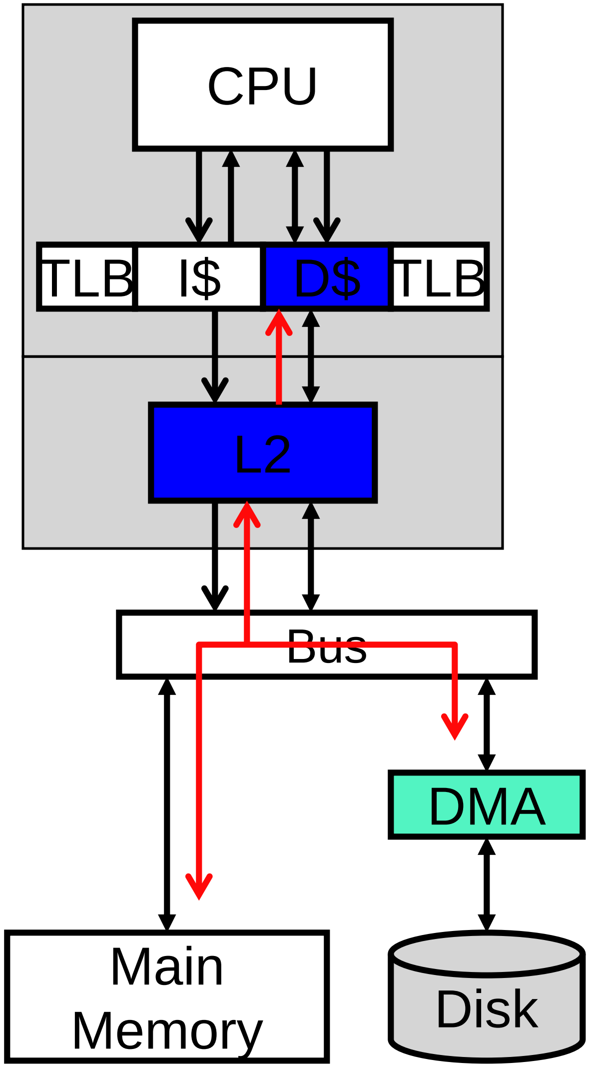
DMA: Direct Memory Access

- Alternative: DMA
  - When OS requests disk read, sets up DMA
  - "Read this data from the disk, and put it in memory for me"
  - DMA controller handles "memcpy"
  - Ready (version 2.0): data is in memory

  - Frees up CPU to do useful things



Cache coherence



- Caches introduce a **coherence problem** for DMA
  - Update DRAM, but not on-chip cache
- Simple solution: Disallow caching of I/O data
- Fancy solution: D$ and L2 **"snoop"** bus traffic
  - Observe transactions
  - Check if written addresses are resident
  - **Self-invalidate** those blocks

Hard disk: reliability

- Hard disks fail relatively easily
  - Spinning piece of metal
  - With head hovering <1mm from platter
- Hard drive failures: major pain..
  - Anyone ever have one?

Reliability

- Solution to functionality problem?
  - Level of indirection
- Solution to performance problem?
  - Add a cache
- Solution to a reliability problem?
  - Add error checking and correction
    - For HDD’s checking is easy: “wont read data”
    - Simplest correction: keep 2 copies

RAID: Reliability

- Redundant Array of Inexpensive Disks (RAID)
  - Keep 2 hard-drives with identical copies of the data
  - One fails? Replace it, copy the other drive to it, resume
    - Can work from other drive while waiting for replacement
  - Performance?
    - Writes to both drives in parallel (no cost)
    - Reads from **either** drive
      - Improve performance: twice the bandwidth
  - Downside?
    - Cost: need to buy 2x as many disks for 1x the space
    - Still: pretty popular
    - Also very easy

RAID: All sorts of things

- Mirroring data (prev slides): “RAID 1”
- Tons of other RAID configurations:
  - RAID 0: striping—performance, not reliability
  - Parity schemes: reduce overhead for num disks > 2
    - Still give reliability and good performance
- Many covered in detail in your book
  - Good to know they exist, may be good solution to a problem one day

Other devices

- Wide variety of IO devices
  - Most basically work the same way from high-level
  - Read/write proper physical memory location(s)

  - Reality: each device has its own protocol
    - Requires device driver: Software module that handles protocol details of specific device
      - Which memory locations to read/write etc
    - Example of
      Abstraction!

Next Up: OSes

- Working our way up the system
  - Just talked about how data is stored on disks…
  - Next time: how do we make a coherent filesystem?

- Followed up by various other bits of OS knowledge
  - How does the system boot?
  - How are programs scheduled?
  - Etc.