ECE/CS 250
Computer Architecture

Summer 2023

I/O

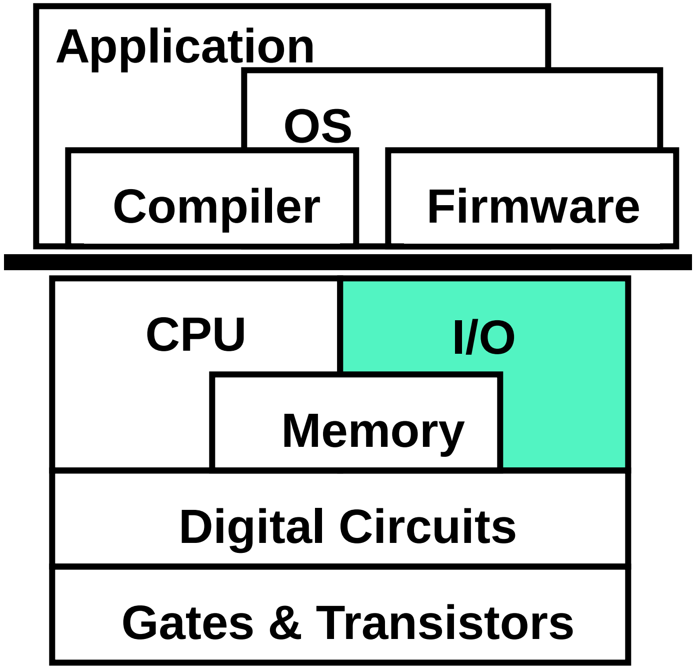
Tyler Bletsch
Duke University

Includes material adapted from Dan Sorin (Duke) and Amir Roth (Penn).
SSD material from Andrew Bondi (Colorado State).

Where We Are in This Course Right Now

- So far:
  - We know how to design a processor that can fetch, decode, and execute the instructions in an ISA
  - We understand how to design caches and memory
- Now:
  - We learn about the lowest level of storage (disks)
  - We learn about input/output in general
- Next:
  - Faster processor cores
  - Multicore processors

This Unit: I/O



- I/O system structure
  - Devices, controllers, and buses
- Device characteristics
  - Disks: HDD and SSD
- I/O control
  - Polling and interrupts
  - DMA

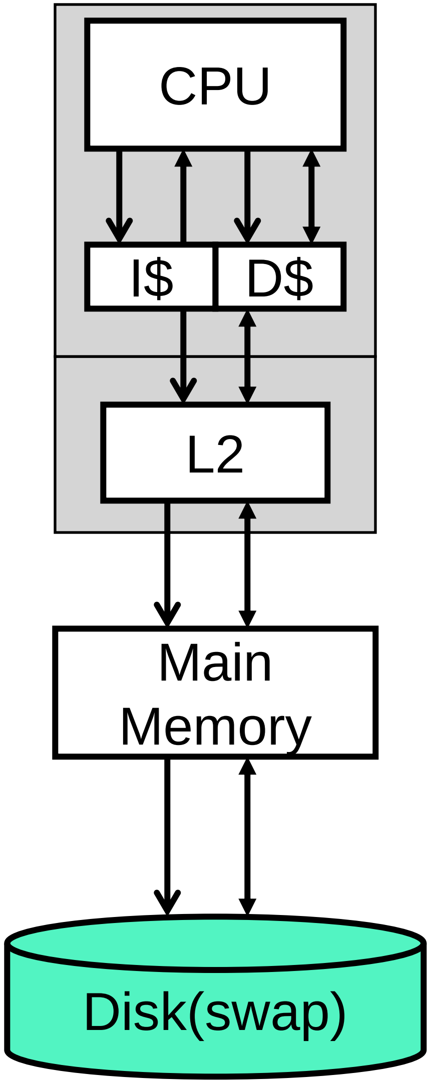
Readings

- Patterson and Hennessy dropped the ball on this topic
- It used to be covered in depth (in previous editions)
  - Now it’s sort of in Appendix A.8

Computers Interact with Outside World

- **Input/output (I/O)**
  - Otherwise, how will we ever tell a computer what to do…
  - …or exploit the results of its work?
- Computers without I/O are not useful
- ICQ: What kinds of I/O do computers have?

One Instance of I/O

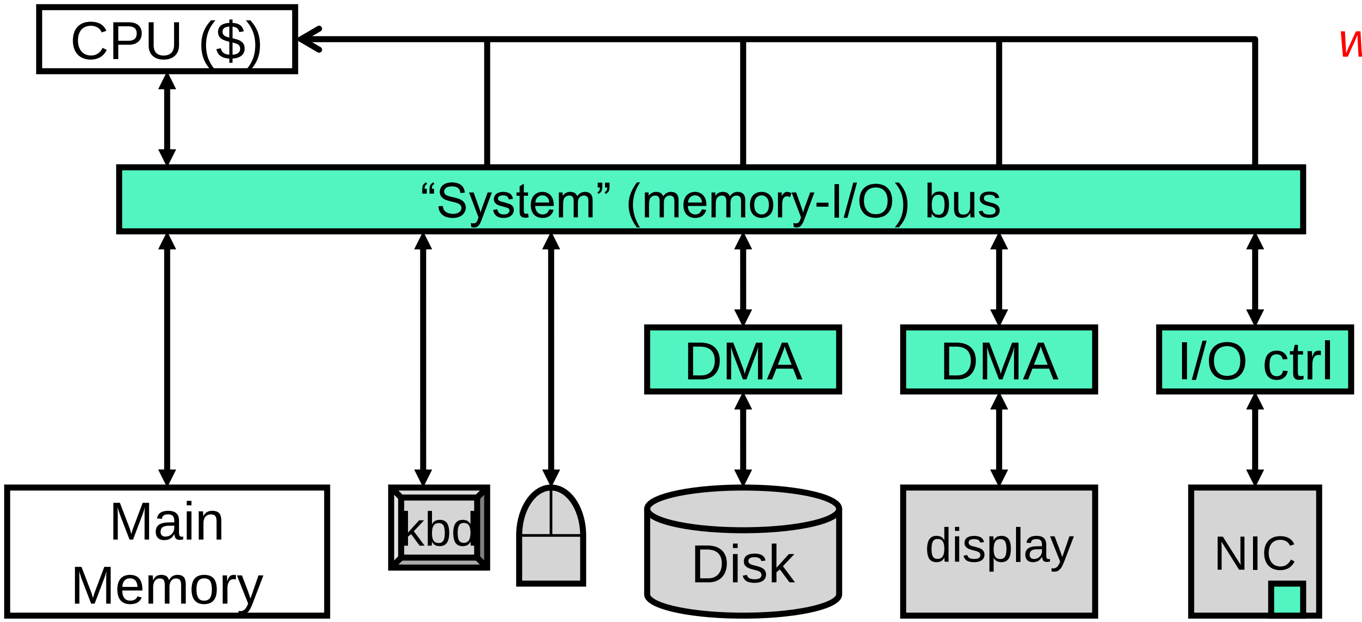


- Have briefly seen one instance of I/O
  - **Disk**: bottom of memory hierarchy
  - Holds whatever can’t fit in memory
  - ICQ: What else do disks hold?

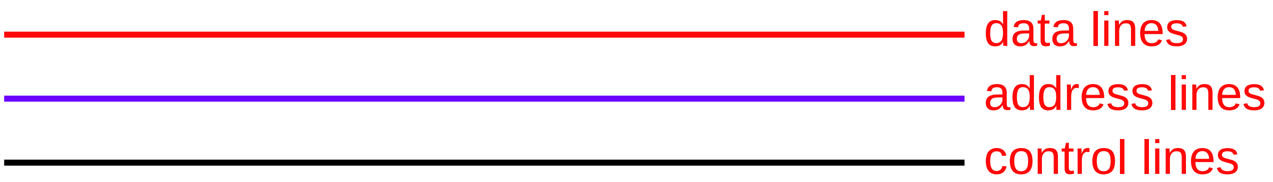
A More General/Realistic I/O System

- A computer system
  - CPU, including cache(s)
  - Memory (DRAM)
  - **I/O peripherals**: disks, input devices, displays, network cards, ...
    - With built-in or separate I/O (or DMA) controllers
  - All connected by a **system bus**

will define DMA later



Bus Design



data lines

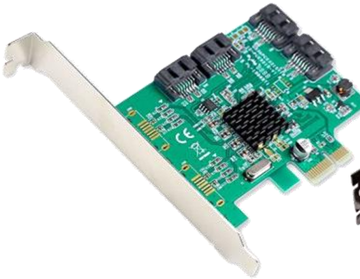
address lines

control lines

- Goals
  - **High Performance**: low latency and high bandwidth
  - **Standardization**: flexibility in dealing with many devices
  - **Low Cost**
    - Processor-memory bus emphasizes performance, then cost
    - I/O & backplane emphasize standardization, then performance
- Design issues
  1. **Width/multiplexing**: are wires shared or separate?
  2. **Clocking**: is bus clocked or not?
  3. **Switching**: how/when is bus control acquired and released?
  4. **Arbitration**: how do we decide who gets the bus next?

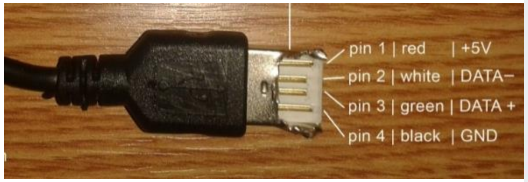
Standard Bus Examples

	PCIe	USB 2.0	USB 3.1
Type	Backplane	I/O	I/O
Width	1 bit per lane (1-16 lanes)	1 bit	4 bit
Multiplexed?	Yes	Yes	Yes
Clocking	2.5 – 8 GHz	Asynchronous	Asynchronous
Data rate	0.250 – 120 GB/s	60 MB/s	10 Gbit/s
Arbitration	Distributed	weird	weird
Maximum masters	255	127	127
Maximum length	~8 inches	–	–

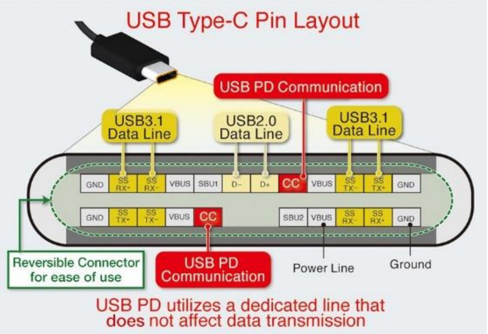


PCIe x1 SATA card

PCIe x16 GPU card

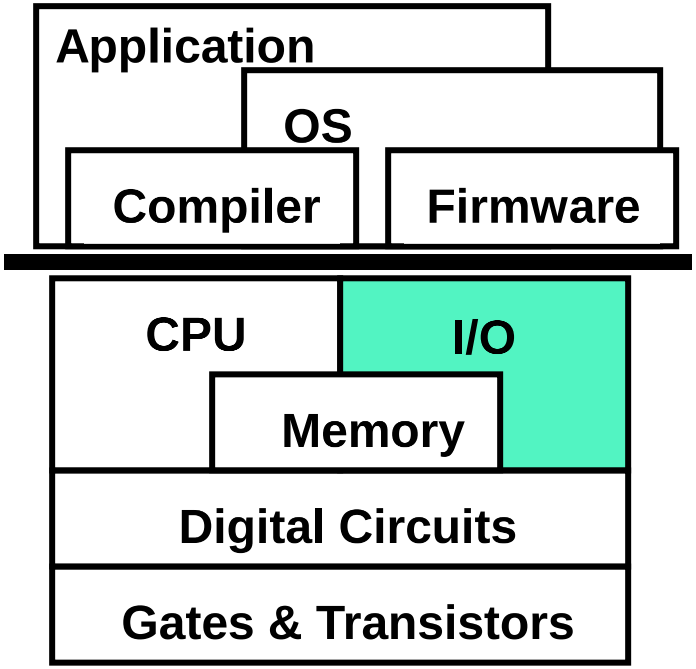


USB 2.0 ‘A’ plug



USB 3.1 ‘C’ plug

This Unit: I/O



- I/O system structure
  - Devices, controllers, and buses
- Device characteristics
  - Disks: HDD and SSD
- I/O control
  - Polling and interrupts
  - DMA

Operating System (OS) Plays a Big Role

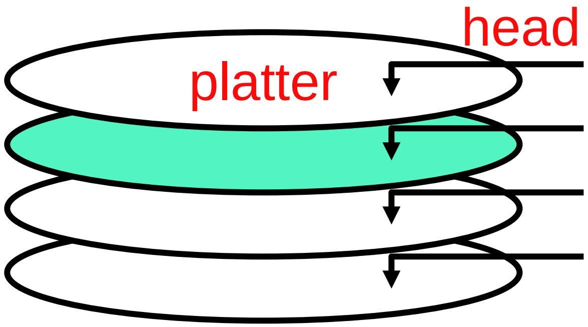
- I/O interface is typically under OS control
  - User applications access I/O devices indirectly (e.g., SYSCALL)
  - Why?
  - Device **drivers** are "programs" that OS uses to manage devices
- **Virtualization**: same argument as for memory
  - Physical devices shared among multiple programs
  - Direct access could lead to conflicts – example?
- **Synchronization**
  - Most have asynchronous interfaces, require unbounded waiting
  - OS handles asynchrony internally, presents synchronous interface
- **Standardization**
  - Devices of a certain type (disks) can/will have different interfaces
  - OS handles differences (via drivers), presents uniform interface

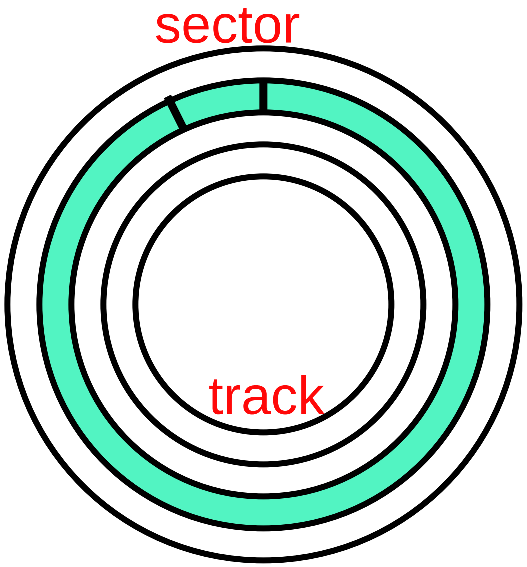
I/O Device Characteristics

- Primary characteristic
  - **Data rate** (aka **bandwidth**)
- Contributing factors
  - **Partner**: humans have slower output data rates than machines
  - **Input or output or both (input/output)**

Device	Partner	I? O?	Data Rate (KB/s)
Keyboard	Human	Input	0.01
Mouse	Human	Input	0.02
Speaker	Human	Output	0.60
Printer	Human	Output	200
Display	Human	Output	240,000
Modem (old)	Machine	I/O	7
Ethernet	Machine	I/O	~1,000,000
Disk	Machine	I/O	~50,000

I/O Device: Disk





- **Disk**: like stack of record players
- Collection of **platters**
  - Each with read/write head
- Platters divided into concentric **tracks**
  - Head seeks (forward/backward) to track
  - All heads move in unison
- Each track divided into **sectors**
  - ZBR (zone bit recording)
    - More sectors on outer tracks
  - Sectors rotate under head
- **Controller**
  - Seeks heads, waits for sectors
  - Turns heads on/off
  - May have its own cache (made w/DRAM)

Understanding disk performance

- One ⏱ equals 1 microsecond
- Time to read the “next” 512-byte sector (no seek needed):
  ⏱ ⏱ ~2μs
- Time to read a random 512-byte sector (with seek):

SEEKS
ARE
BAD!

~1840μs

Disk Bandwidth

- Disk is bandwidth-inefficient for page-sized transfers
    - Actual data transfer ($t_{transfer}$) a small part of disk access (and cycle)

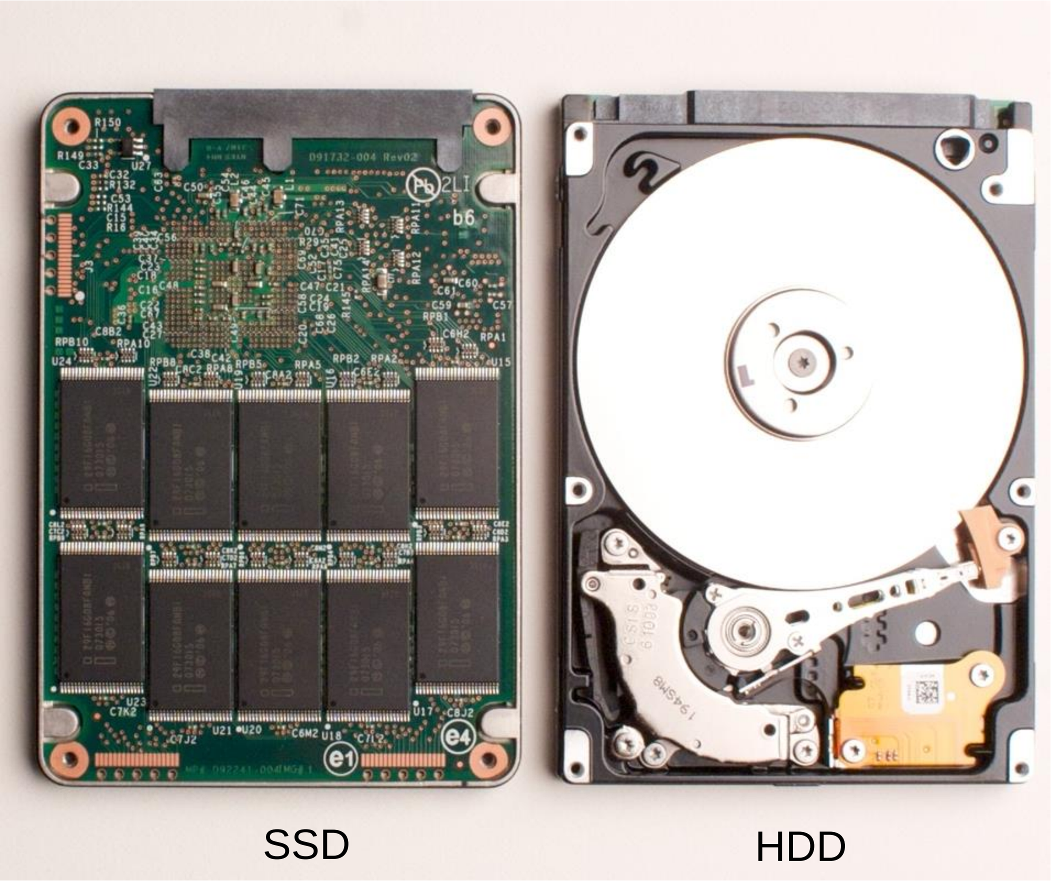
- Increase bandwidth: **stripe data across multiple disks**
    - Striping strategy depends on disk usage model
    - “File System” or “web server”: many small files
        - Map entire files to disks
    - “Supercomputer” or “database”: several large files
        - Stripe single file across multiple disks

- Both bandwidth and individual transaction latency important

Error Correction: RAID

- **Error correction**: more important for disk than for memory
  - Mechanical disk failures (entire disk lost) is common failure mode
  - Entire file system can be lost if files striped across multiple disks
- **RAID (redundant array of inexpensive disks)**
  - Similar to DRAM error correction, but…
  - Major difference: which disk failed is known
    - Even parity can be used to recover from single failures
    - Parity disk can be used to reconstruct data faulty disk
  - RAID design balances bandwidth and fault-tolerance
  - Many flavors of RAID exist
    - Tradeoff: extra disks (cost) vs. performance vs. reliability
    - Deeper discussion of RAID in ECE 552 and ECE 554;
      super-duper deep coverage in ECE 566
      ("Enterprise Storage Architecture")
  - RAID doesn't solve all problems → can you think of any examples?

What about Solid State Drives (SSDs)?



Adapted from “Solid State Drives” by Andrew Bondi

SSDs

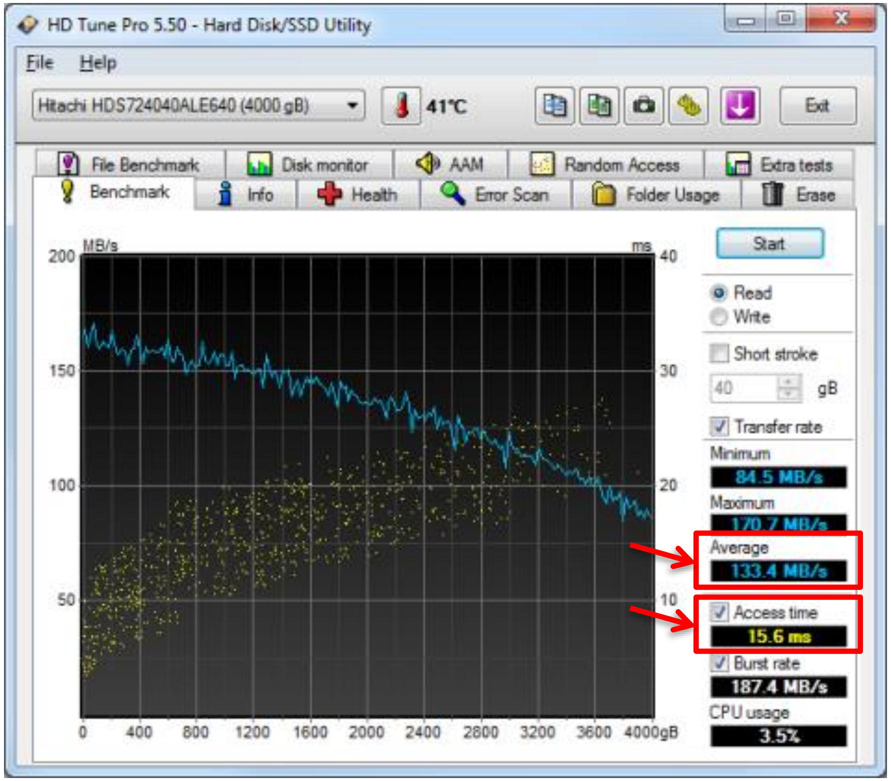
- Multiple NAND flash chips operated in parallel
- Pros:
  - Extremely good "seek" times (since "seek" is no longer a thing)
  - Almost instantaneous read and write times
  - The ability to read or write in multiple locations at once
  - The speed of the drive scales extremely well with the number of NAND ICs on board
  - Way cheaper than disk per IOP (performance)
- Cons:
  - Way more expensive than disk per GB (capacity)
  - Limited number of write cycles possible before it degrades (getting less and less of a problem these days)
  - Fundamental problem: Write amplification
    - You can *set* bits in "pages" (~4kB) fast (microseconds), but you can only *clear* bits in "blocks" (~512kB) slooow (milliseconds)
    - **Solution**: controller that is managing NAND cells tries to hide this

Adapted from "Solid State Drives" by Andrew Bondi

Typical read and write rates: SSD vs HDD

- Benchmark data from HD Tune (Windows benchmark)

HDD



Hitachi HDS724040ALE640 (4000 gB)

41°C

● Read

○ Write

□ Short stroke

40 gB

☑ Transfer rate

Minimum 84.5 MB/s

Maximum 170.7 MB/s

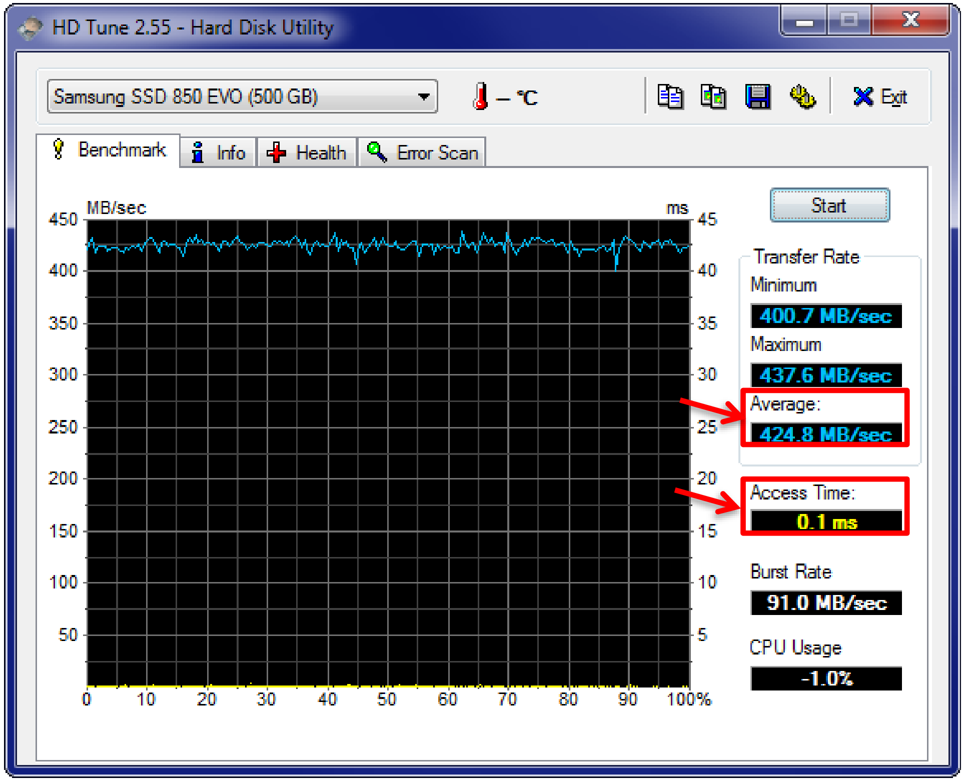
Average 133.4 MB/s

☑ Access time 15.6 ms

☑ Burst rate 187.4 MB/s

CPU usage 3.5%

SSD



Samsung SSD 850 EVO (500 GB)

– °C

Transfer Rate

Minimum 400.7 MB/sec

Maximum 437.6 MB/sec

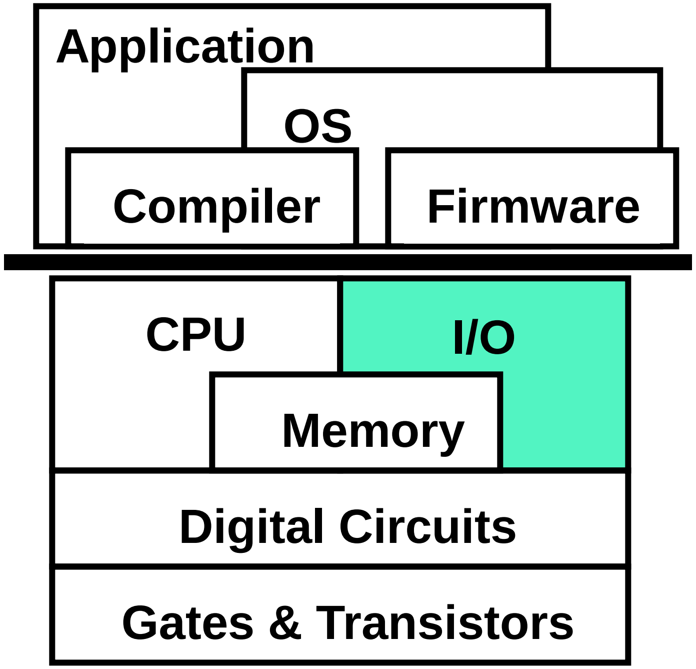
Average: 424.8 MB/sec

Access Time: 0.1 ms

Burst Rate 91.0 MB/sec

CPU Usage -1.0%

This Unit: I/O



- I/O system structure
  - Devices, controllers, and buses
- Device characteristics
  - Disks: HDD and SSD
- I/O control
  - Polling and interrupts
  - DMA

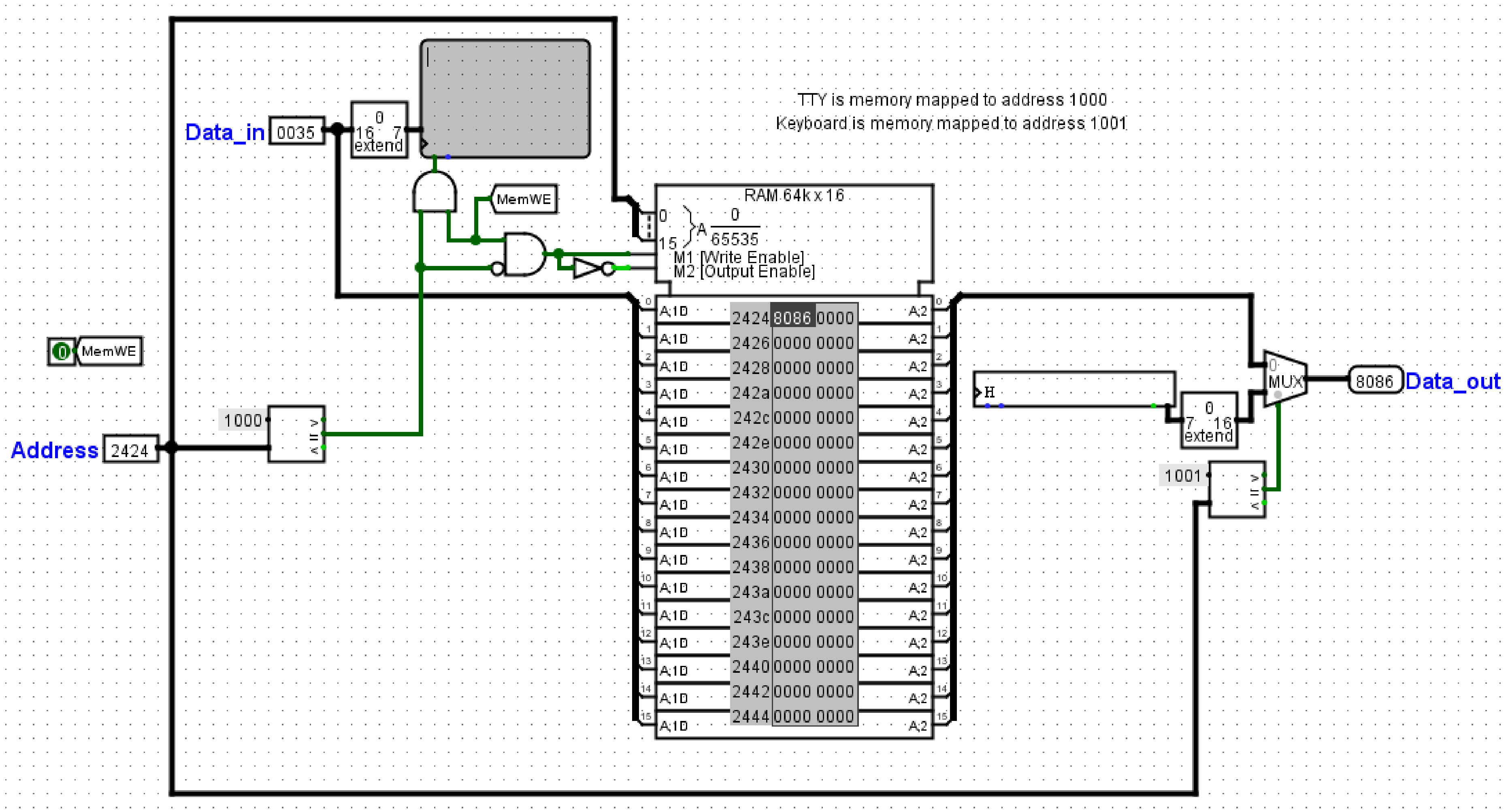
I/O Control and Interfaces

- Now that we know how I/O devices and buses work…
- How does I/O actually happen?
  - How does CPU give commands to I/O devices?
  - How do I/O devices execute data transfers?
  - How does CPU know when I/O devices are done?

Sending Commands to I/O Devices

- Remember: only OS can do this! Two options …
- **I/O instructions**
  - OS only? Instructions must be privileged (only OS can execute)
  - E.g., IA-32
- **Memory-mapped I/O**
  - Portion of **physical** address space reserved for I/O
  - OS maps physical addresses to I/O device control registers
  - Stores/loads to these addresses are commands to I/O devices
    - Main memory ignores them, I/O devices recognize and respond
    - Address specifies both I/O device and command
  - These address are not cached – why?
  - OS only? I/O physical addresses only mapped in OS address space
  - E.g., almost every architecture other than IA-32 (see pattern??)

Memory mapped IO example (1)

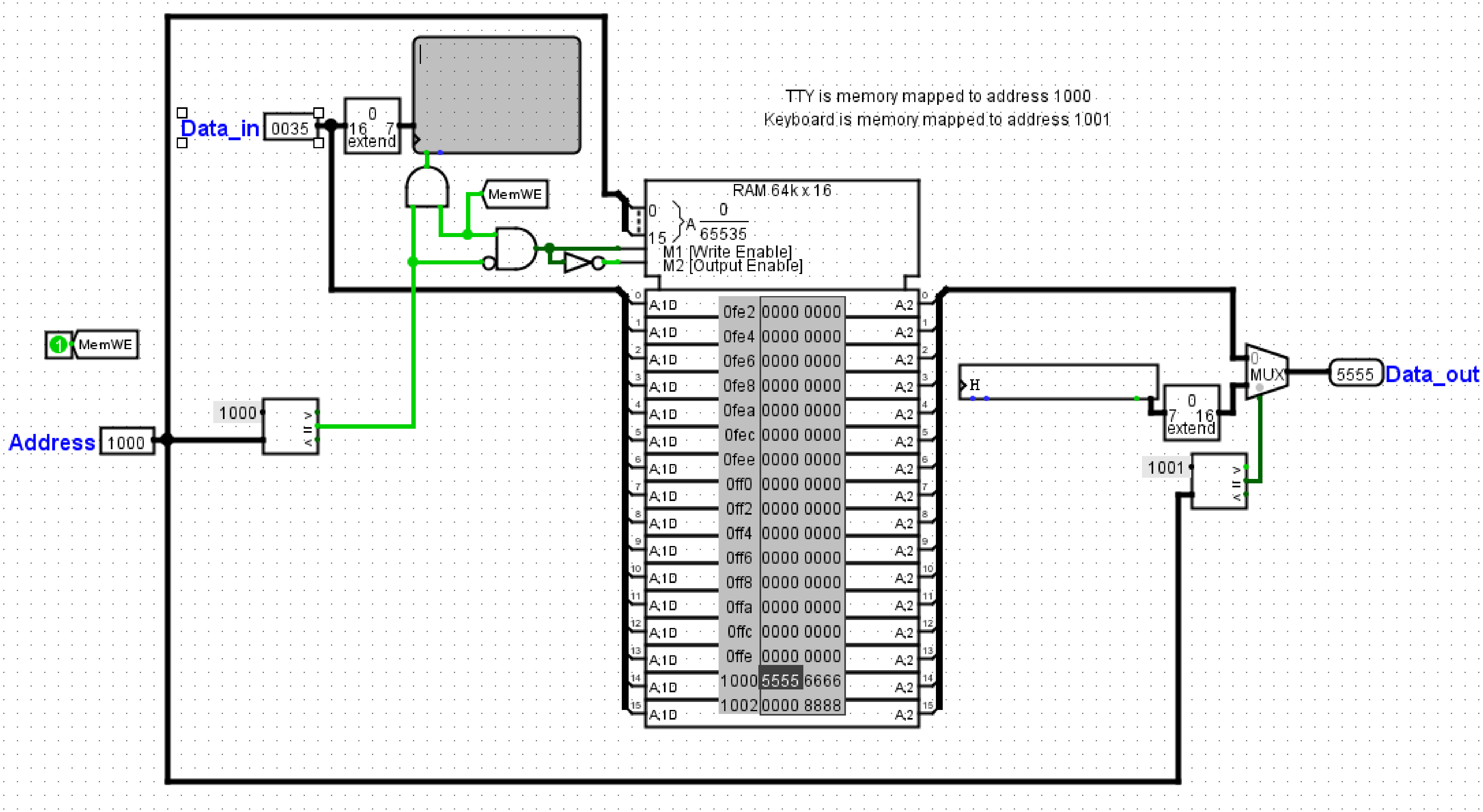


TTY is memory mapped to address 1000
Keyboard is memory mapped to address 1001

```
2424 8086 0000
2426 0000 0000
2428 0000 0000
242a 0000 0000
242c 0000 0000
242e 0000 0000
2430 0000 0000
2432 0000 0000
2434 0000 0000
2436 0000 0000
2438 0000 0000
243a 0000 0000
243c 0000 0000
243e 0000 0000
2440 0000 0000
2442 0000 0000
2444 0000 0000
```

- Non-special read – comes from memory

Memory mapped IO example (2)

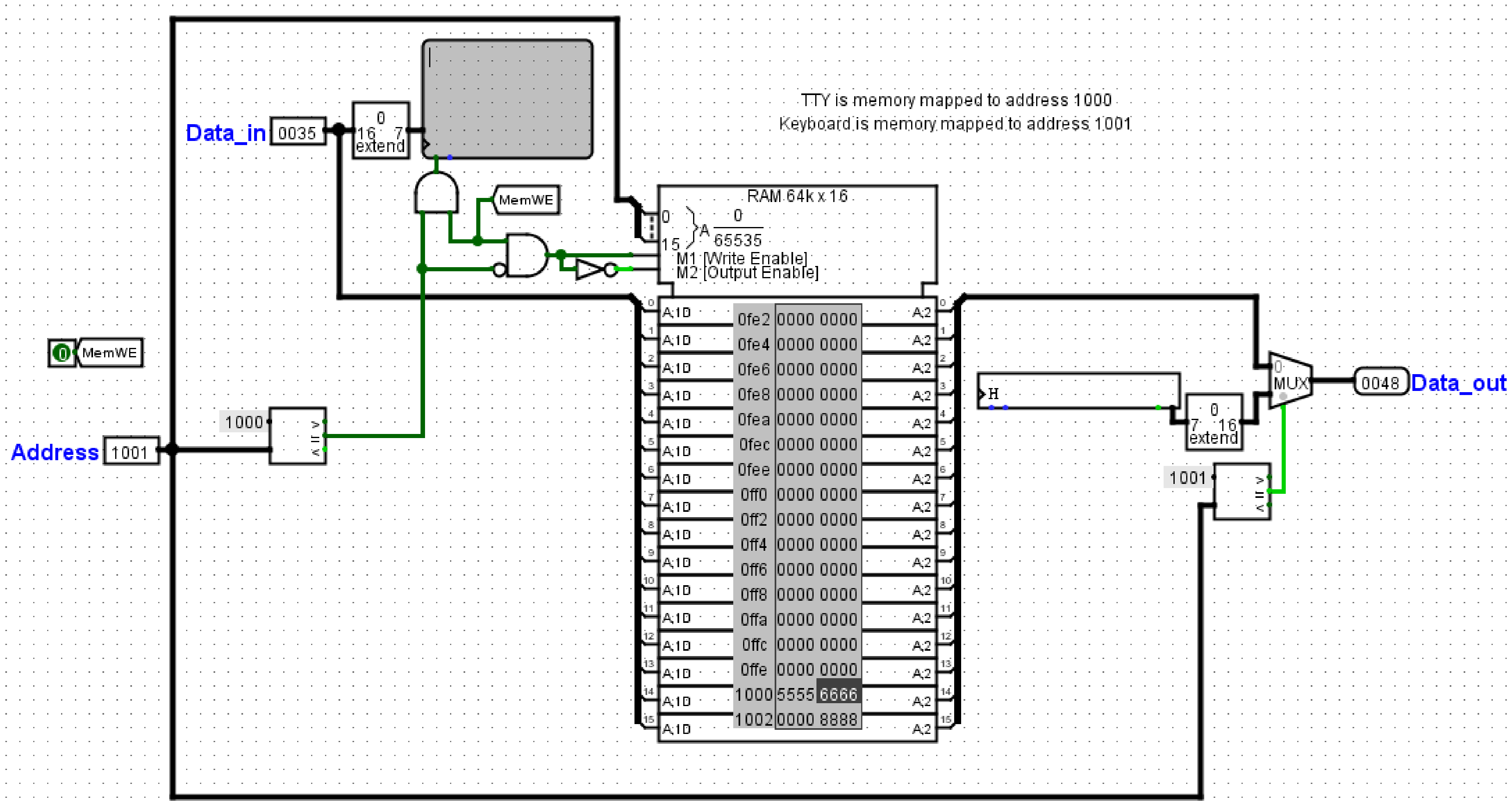


TTY is memory mapped to address 1000
Keyboard is memory mapped to address 1001

```
0fe2 0000 0000
0fe4 0000 0000
0fe6 0000 0000
0fe8 0000 0000
0fea 0000 0000
0fec 0000 0000
0fee 0000 0000
0ff0 0000 0000
0ff2 0000 0000
0ff4 0000 0000
0ff6 0000 0000
0ff8 0000 0000
0ffa 0000 0000
0ffc 0000 0000
0ffe 0000 0000
1000 5555 6666
1002 0000 8888
```

- Write to address 1000 – routed to TTY!
  - Mem write disabled, TTY write enabled; signal goes to both

Memory mapped IO example (3)



TTY is memory mapped to address 1000
Keyboard is memory mapped to address 1001

```
0fe2 0000 0000
0fe4 0000 0000
0fe6 0000 0000
0fe8 0000 0000
0fea 0000 0000
0fec 0000 0000
0fee 0000 0000
0ff0 0000 0000
0ff2 0000 0000
0ff4 0000 0000
0ff6 0000 0000
0ff8 0000 0000
0ffa 0000 0000
0ffc 0000 0000
0ffe 0000 0000
1000 5555 6666
1002 0000 8888
```

- Read from address 1001 – data comes from keyboard
  - Mux switches to keyboard for that address

Querying I/O Device Status

- Now that we've sent command to I/O device …
- How do we query I/O device status?
  - So that we know if data we asked for is ready?
  - So that we know if device is ready to receive next command?

- **Polling**: Ready now? How about now? How about now???
  - Processor queries I/O device status register (e.g., with MM load)
    - Loops until it gets status it wants (ready for next command)
    - Or tries again a little later

  + Simple

  – Waste of processor's time
    - Processor much faster than I/O device

Polling Overhead: Example #1

- Parameters
  - 500 MHz CPU
  - Polling event takes 400 cycles

- Overhead for polling a mouse 30 times per second?
  - Cycles per second for polling = (30 poll/s)*(400 cycles/poll)
  - → 12000 cycles/second for polling
  - (12000 cycles/second)/(500 M cycles/second) = 0.002% overhead

  + Not bad

Polling Overhead: Example #2

- Same parameters
  - 500 MHz CPU, polling event takes 400 cycles

- Overhead for polling a 4 MB/s disk with 16 B interface?
  - Must poll often enough not to miss data from disk
  - Polling rate = (4MB/s)/(16 B/poll) >> mouse polling rate
  - Cycles per second for polling=[(4MB/s)/(16 B/poll)]*(400 cyc/poll)
  - → 100 M cycles/second for polling
  - (100 M cycles/second)/(500 M cycles/second) = 20% overhead
  - – Bad
  - This is the overhead of polling, not actual data transfer
    - Really bad if disk is not being used (pure overhead!)

Interrupt-Driven I/O

- **Interrupts**: alternative to polling
  - I/O device generates interrupt when status changes, data ready
  - OS handles interrupts just like exceptions (e.g., page faults)
    - Identity of interrupting I/O device recorded in ECR
      - ECR: exception cause register

  - I/O interrupts are **asynchronous**
    - Not associated with any one instruction
    - Don't need to be handled immediately

  - I/O interrupts are **prioritized**
    - Synchronous interrupts (e.g., page faults) have highest priority
    - High-bandwidth I/O devices have higher priority than low-bandwidth ones

Interrupt Overhead

- Parameters
  - 500 MHz CPU
  - Polling event takes 400 cycles
  - Interrupt handler takes 400 cycles
  - Data transfer takes 100 cycles
  - 4 MB/s, 16 B interface disk, transfers data only 5% of time

Note: when disk is transferring data, the interrupt rate is same as polling rate

- Percent of time processor spends transferring data
  - **0.05** * (4 MB/s)/(16 B/xfer)*[(100 c/xfer)/(500M c/s)] = 0.25%
- Overhead for polling?
  - (4 MB/s)/(16 B/poll) * [(400 c/poll)/(500M c/s)] = 20%
- Overhead for interrupts?

  + **0.05** * (4 MB/s)/(16 B/int) * [(400 c/int)/(500M c/s)] = 1%

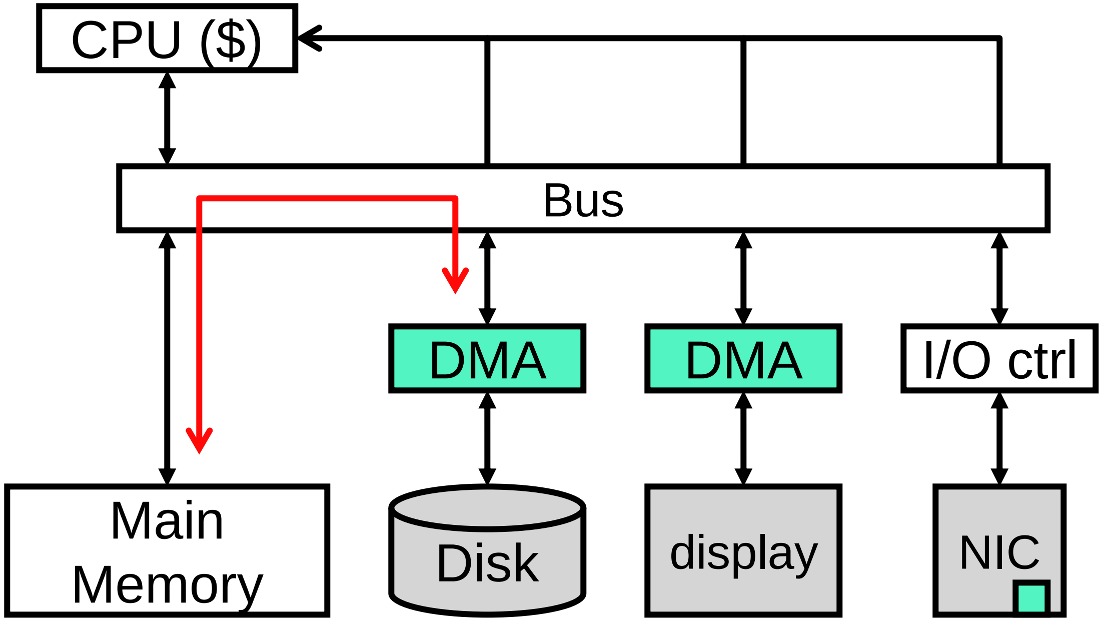
Direct Memory Access (DMA)

- Interrupts remove overhead of polling…
- But still requires OS to transfer data one word at a time
  - OK for low bandwidth I/O devices: mice, microphones, etc.
  - Bad for high bandwidth I/O devices: disks, monitors, etc.

- **Direct Memory Access (DMA)**
  - Transfer data between I/O and memory without processor control
  - Transfers entire blocks (e.g., pages, video frames) at a time
    - Can use bus "burst" transfer mode if available
  - Only interrupts processor when done (or if error occurs)

DMA Controllers

- To do DMA, I/O device attached to **DMA controller**
  - Multiple devices can be connected to one DMA controller
  - Controller itself seen as a memory mapped I/O device
    - Processor initializes start memory address, transfer size, etc.
  - DMA controller takes care of bus arbitration and transfer details
    - So that's why buses support arbitration and multiple masters!



DMA Overhead

- Parameters
  - 500 MHz CPU
  - Interrupt handler takes 400 cycles
  - Data transfer takes 100 cycles
  - 4 MB/s, 16 B interface, disk transfers data 50% of time
  - DMA setup takes 1600 cycles, transfer 1 16KB page at a time

- Processor overhead for interrupt-driven I/O?
  - 0.5 * (4M B/s)/(**16** B/xfer)*[(**500** c/xfer)/(500M c/s)] = 12.5%
- Processor overhead with DMA?
  - Processor only gets involved once per page, not once per 16 B

  + 0.5 * (4M B/s)/(**16K** B/page) * [(**2000** c/page)/(500M c/s)] = 0.05%

DMA and Memory Hierarchy

- DMA is good, but is not without challenges

- Without DMA: processor initiates all data transfers
  - All transfers go through address translation
    - + Transfers can be of any size and cross virtual page boundaries
  - All values seen by cache hierarchy
    - + Caches never contain stale data

- With DMA: DMA controllers initiate data transfers
  - Do they use virtual or physical addresses?
  - What if they write data to a cached memory location?

DMA and Caching

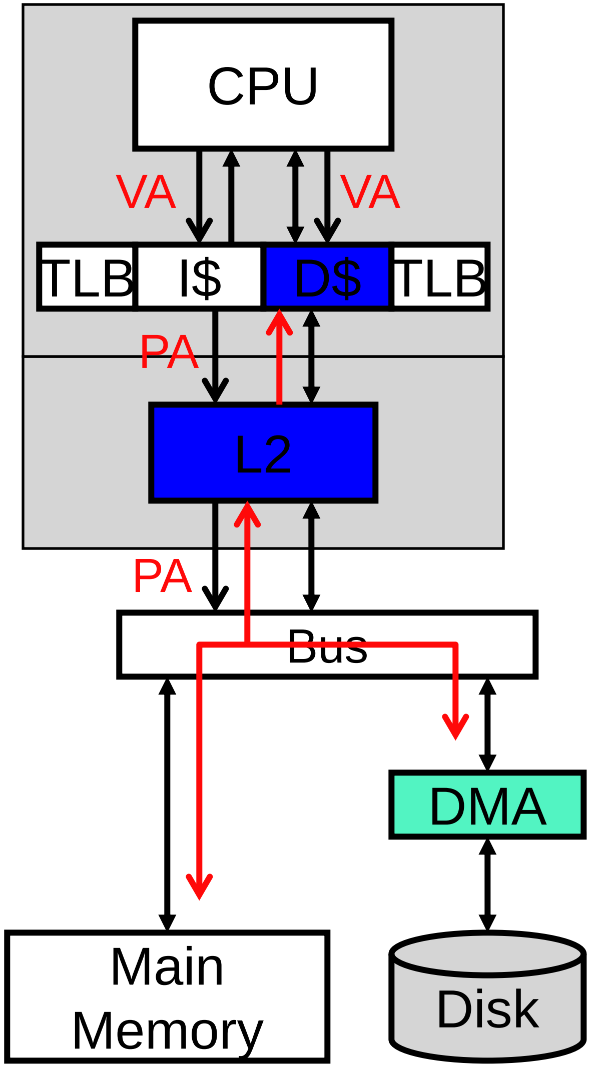
- Caches are good
  - Reduce CPU’s observed instruction and data access latency
  - + But also, reduce CPU’s use of memory…
  - + …leaving majority of memory/bus bandwidth for DMA I/O

- But they also introduce a **coherence problem** for DMA
  - Input problem
    - DMA write into memory version of cached location
    - Cached version now stale
  - Output problem: write-back caches only
    - DMA read from memory version of “dirty” cached location
    - Output stale value

Solutions to Coherence Problem

- Route all DMA I/O accesses to cache?
  - + Solves problem
  - – Expensive: CPU must contend for access to caches with DMA
- Disallow caching of I/O data?
  - + Also works
  - – Expensive in a different way: CPU access to those regions slow
- Selective flushing/invalidations of cached data
  - Flush all dirty blocks in "I/O region"
  - Invalidate blocks in "I/O region" as DMA writes those addresses
  - + The high performance solution
    - **Hardware cache coherence** mechanisms for doing this
  - – Expensive in yet a third way: must implement this mechanism

H/W Cache Coherence (more later on this)



- D$ and L2 **"snoop"** bus traffic
  - Observe transactions
  - Check if written addresses are resident
  - **Self-invalidate** those blocks

  + Doesn't require access to data part

  – Does require access to tag part
    - May need 2nd copy of tags for this
    - That's OK, tags smaller than data
- Bus addresses are physical
  - L2 is easy (physical index/tag)
  - D$ is harder (**virtual index**/physical tag)

Summary

- Storage devices
  - **HDD**: Mechanical disk. *Seeks are bad*. Cheaper per GB.
  - **SSD**: Flash storage. Cheaper per performance.
  - Can combine drives with **RAID** to get aggregate performance/capacity plus fault tolerance (can survive individual drive failures).
- Connectivity
  - A **bus** is shared between CPU, memory, and/or and multiple IO devices
- How does CPU talk to IO devices?
  - **Special instructions** or **memory-mapped IO** (certain addresses don't lead to RAM, they lead to IO devices)
    - Either requires OS privilege to use
  - Methods of interaction:
    - **Polling** (simple but wastes CPU)
    - **Interrupts** (saves CPU but transfers tiny bit at a time)
    - **DMA**+interrupts (saves CPU+fast, but requires caches to snoop traffic to not become wrong)

EXTRA MATERIAL

Disk Parameters

	Seagate 6TB Enterprise HDD (2016)	Seagate Savvio (~2005)	Toshiba MK1003 (early 2000s)
Diameter	3.5″	2.5″	1.8″
Capacity	6 TB	73 GB	10 GB
RPM	7200 RPM	10000 RPM	4200 RPM
Cache	128 MB	8 MB	512 KB
Platters	~6	2	1
Average Seek	4.16 ms	4.5 ms	7 ms
Sustained Data Rate	216 MB/s	94 MB/s	16 MB/s
Interface	SAS/SATA	SCSI	ATA
Use	Desktop	Laptop	Ancient iPod

Density improving

Caches improving

Seek time not really improving!

Disk Read/Write Latency

- Disk read/write latency has four components
  - **Seek delay (t_{seek})**: head seeks to right track
    - Fixed delay plus proportional to distance
  - **Rotational delay ($t_{rotation}$)**: right sector rotates under head
    - Fixed delay on average (average = half rotation)
  - **Controller delay ($t_{controller}$)**: controller overhead (on either side)
    - Fixed cost
  - **Transfer time ($t_{transfer}$)**: data actually being transferred
    - Proportional to amount of data