I/O

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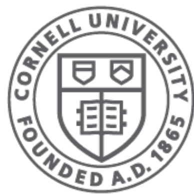

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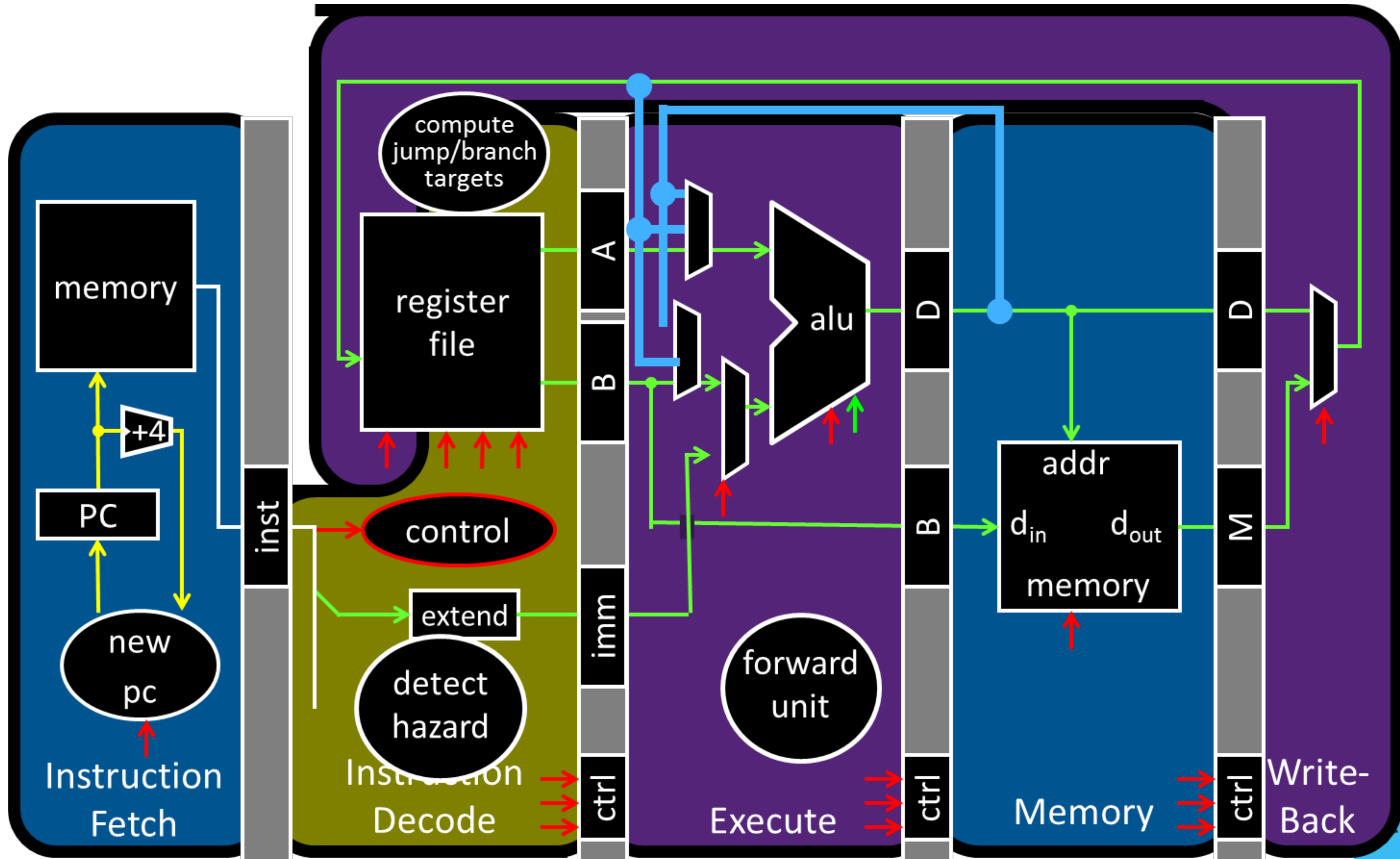
COMPUTING AND INFORMATION SCIENCE

[Weatherspoon, Bala, Bracy, McKee, and Sirer]

Big Picture: Input/Output (I/O)

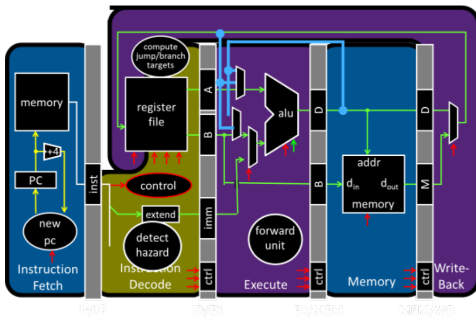
How does a processor interact with its environment?

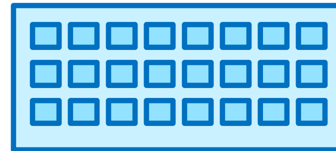


Big Picture: Input/Output (I/O)

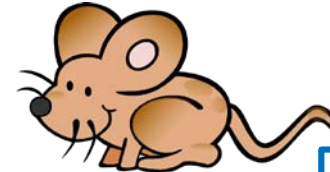
How does a processor interact with its environment?

Computer System =
Memory + Datapath + Control + Input + Output

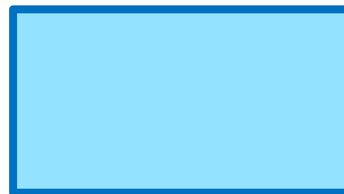




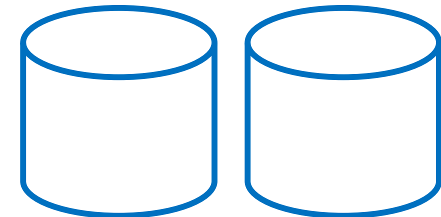
Keyboard



Network



Display



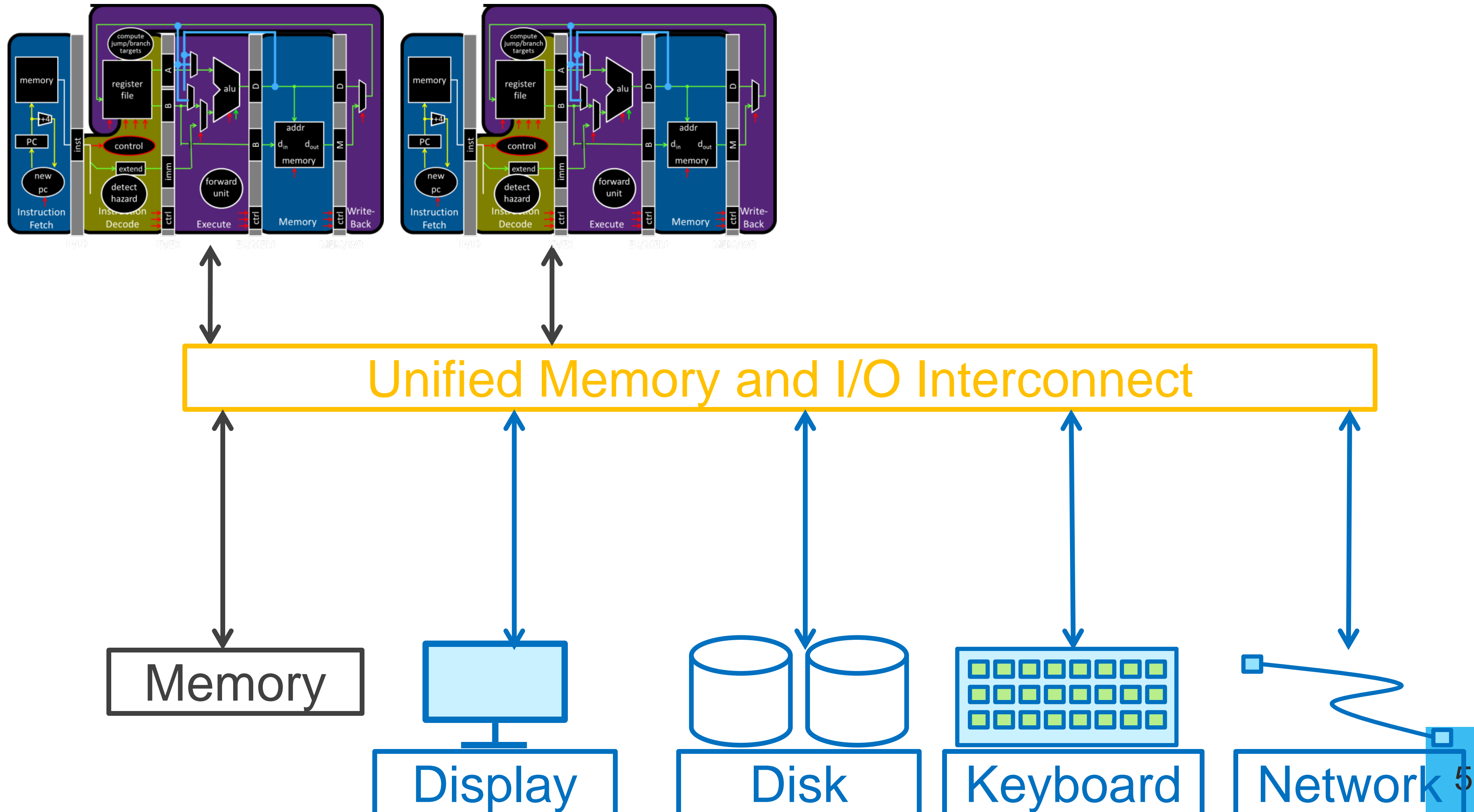
Disk

I/O Devices Enables Interacting with Environment

Device	Behavior	Partner	Data Rate (b/sec)
Keyboard	Input	Human	100
Mouse	Input	Human	3.8k
Sound Input	Input	Machine	3M
Voice Output	Output	Human	264k
Sound Output	Output	Human	8M
Laser Printer	Output	Human	3.2M
Graphics Display	Output	Human	800M – 8G
Network/LAN	Input/Output	Machine	100M – 10G
Network/Wireless LAN	Input/Output	Machine	11 – 54M
Optical Disk	Storage	Machine	5 – 120M
Flash memory	Storage	Machine	32 – 200M
Magnetic Disk	Storage	Machine	800M – 3G

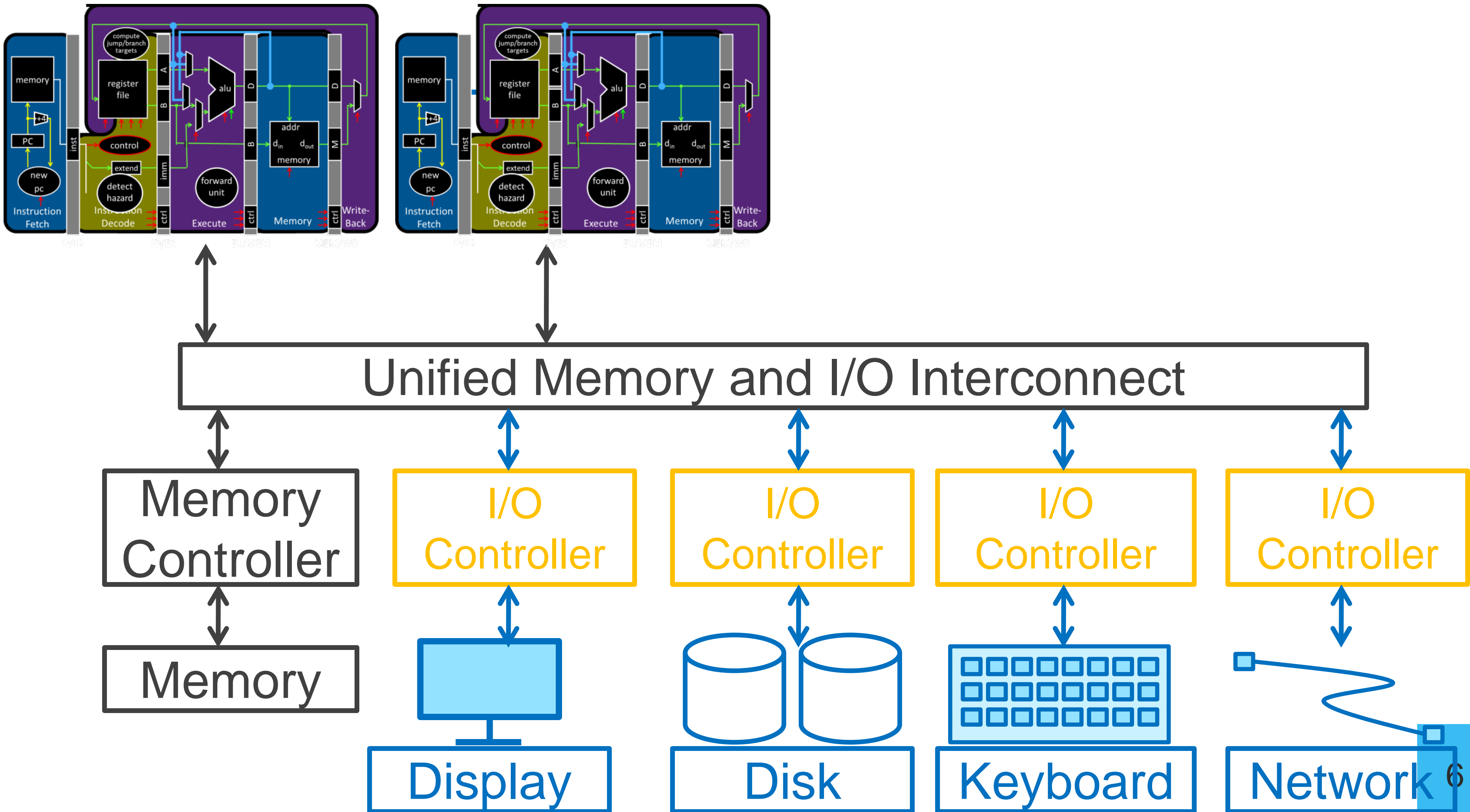
Round 1: All devices on one interconnect

Replace ***all*** devices as the interconnect changes
e.g. keyboard speed == main memory speed ?!



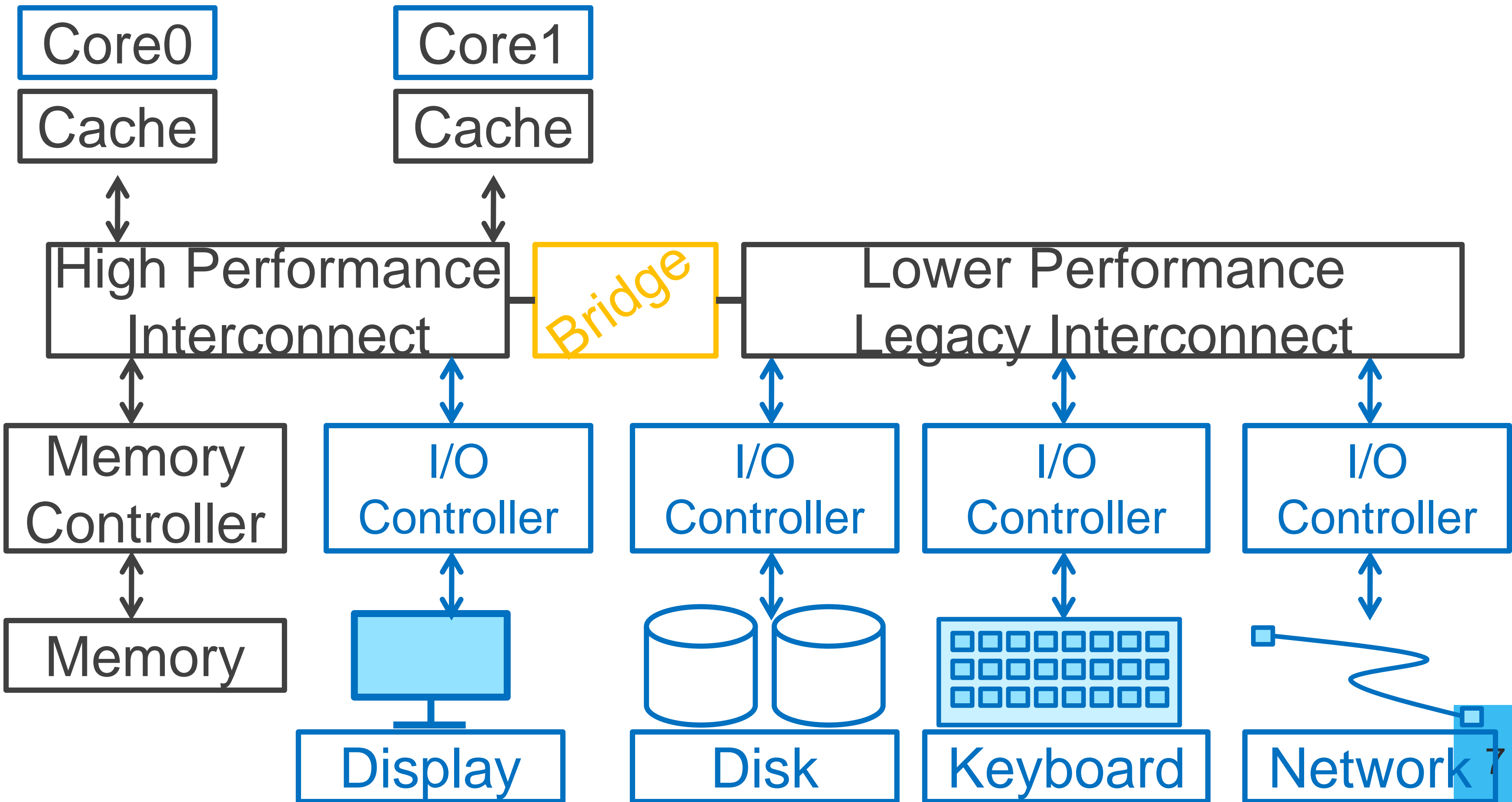
Round 2: I/O Controllers

Decouple I/O devices from Interconnect
Enable smarter I/O interfaces



Round 3: I/O Controllers + Bridge

Separate high-performance processor, memory, display interconnect from lower-performance interconnect



Bus Parameters

Width = number of wires

Transfer size = data words per bus transaction

Synchronous (with a bus clock)

or asynchronous (no bus clock / “self clocking”)

Bus Types

Processor – Memory ("Front Side Bus". Also QPI)

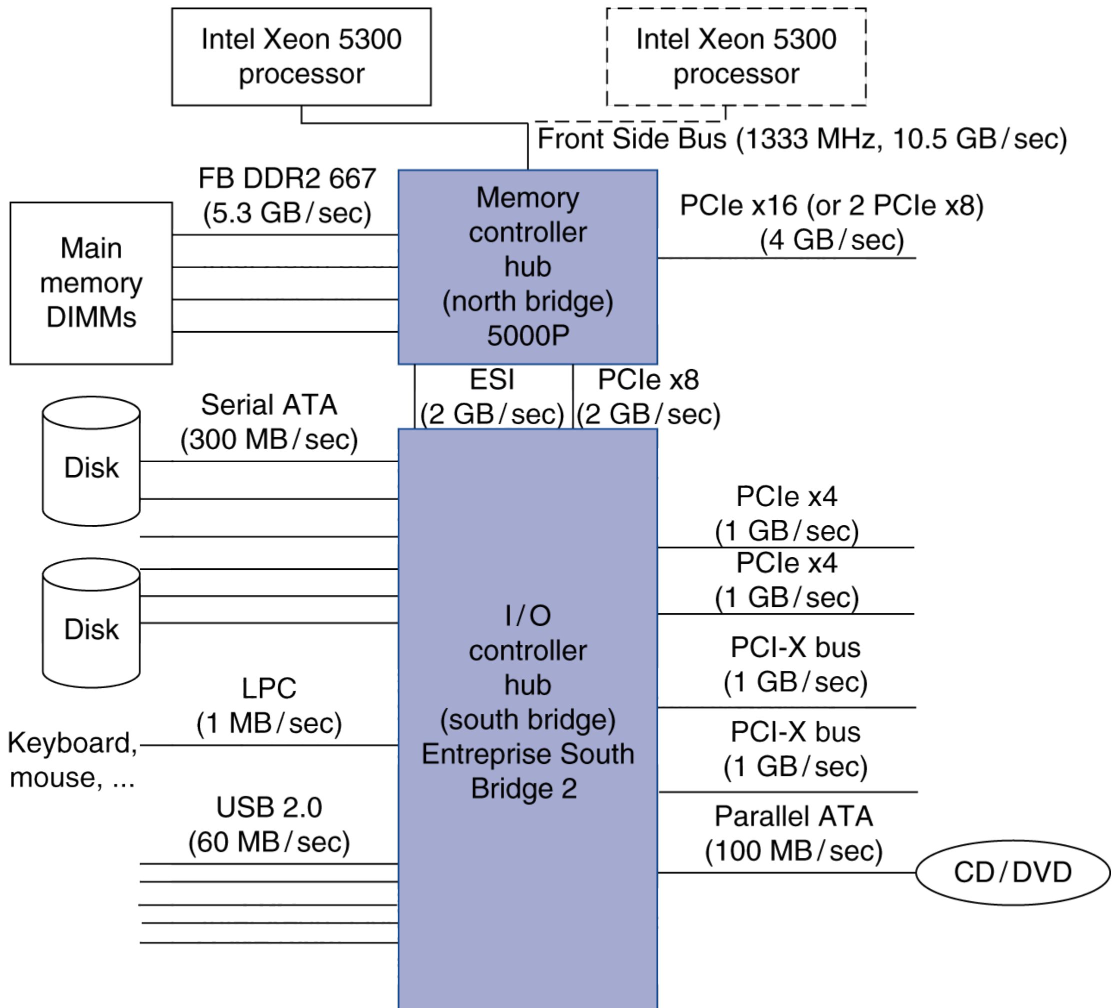
- Short, fast, & wide
- Mostly fixed topology, designed as a "chipset"
  - CPU + Caches + Interconnect + Memory Controller

I/O and Peripheral busses (PCI, SCSI, USB, LPC, …)

- Longer, slower, & narrower
- Flexible topology, multiple/varied connections
- Interoperability standards for devices
- Connect to processor-memory bus through a bridge

Round 3: I/O Controllers + Bridge

Separate high-performance processor, memory, display interconnect from lower-performance interconnect



Example Interconnects

Name	Use	Devices per channel	Channel Width	Data Rate (B/sec)
Firewire 800	External	63	4	100M
USB 2.0	External	127	2	60M
USB 3.0	External	127	2	625M
Parallel ATA	Internal	1	16	133M
Serial ATA (SATA)	Internal	1	4	300M
PCI 66MHz	Internal	1	32-64	533M
PCI Express v2.x	Internal	1	2-64	16G/dir
Hypertransport v2.x	Internal	1	2-64	25G/dir
QuickPath (QPI)	Internal	1	40	12G/dir

Interconnecting Components

Interconnects are (were?) busses

- parallel set of wires for data and control
- shared channel
  - multiple senders/receivers
  - everyone can see all bus transactions
- bus protocol: rules for using the bus wires

e.g. Intel Xeon

Alternative (and increasingly common):

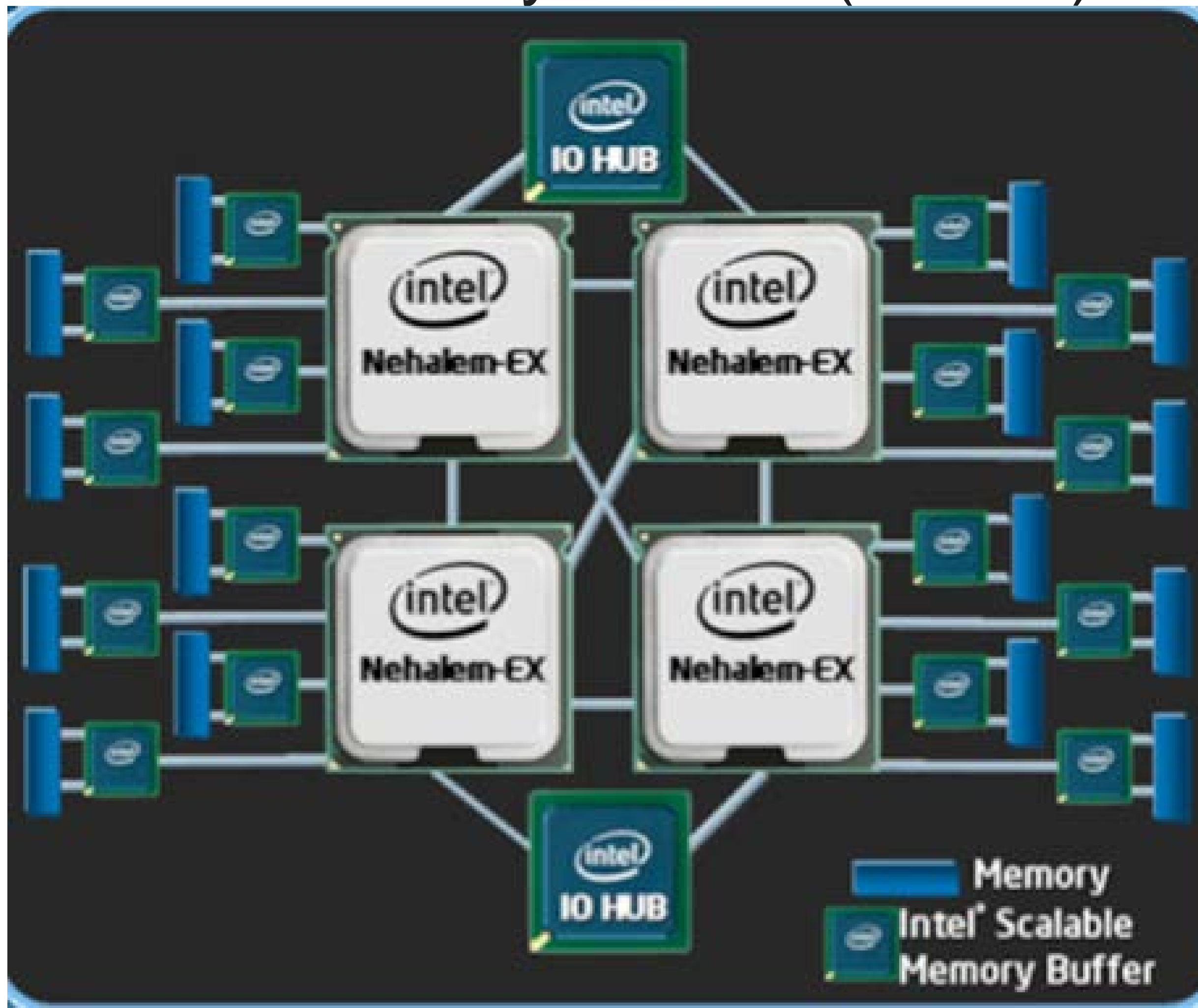
- dedicated point-to-point channels

e.g. Intel Nehalem

Round 4: I/O Controllers+Bridge+ NUMA

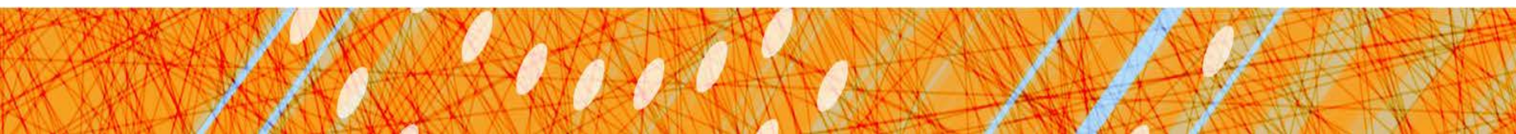
Remove bridge as bottleneck with Point-to-point interconnects

E.g. Non-Uniform Memory Access (NUMA)



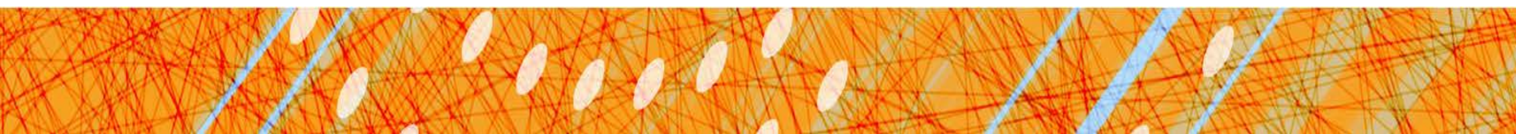
Takeaways

Diverse I/O devices require hierarchical interconnect which is more recently transitioning to point-to-point topologies.



Next Goal

How does the processor interact with I/O devices?



I/O Device Driver Software Interface

Set of methods to write/read data to/from device and control device
Example: Linux Character Devices

```
// Open a toy " echo " character device
int fd = open("/dev/echo", O_RDWR);
// Write to the device
char write_buf[] = "Hello World!";
write(fd, write_buf, sizeof(write_buf));
// Read from the device
char read_buf [32];
read(fd, read_buf, sizeof(read_buf));
// Close the device
close(fd);
// Verify the result
assert(strcmp(write_buf, read_buf)==0);
```

I/O Device API

Typical I/O Device API

- a set of read-only or read/write register

Command registers

- writing causes device to do something

Status registers

- reading indicates what device is doing, error codes, …

Data registers

- Write: transfer data to a device
- Read: transfer data from a device

Every device uses this API

I/O Device API

Simple (old) example: AT Keyboard Device

8-bit Status:

PE	TO	AUXB	LOCK	AL2	SYSF	IBS	OBS

IBS: Input Buffer Status
OBS: Input Buffer Status

8-bit Command:

0xAA = “self test”
0xAE = “enable kbd”
0xED = “set LEDs”
…

8-bit Data:

scancode (when reading)
LED state (when writing) or …

Communication Interface

Q: How does ~~program~~ ~~OS~~ code talk to device?

A: special instructions to talk over special busses

Programmed I/O ← Interact with cmd, status, and data device registers directly

- inb xa, 0x64 ← kbd status register
- outb xa, 0x60 ← kbd data register
- Specifies: device, data, direction
- Protection: only allowed in kernel mode

Kernel boundary crossing is expensive

*x86: $a implicit; also inw, outw, inh, outh, …

Communication Interface

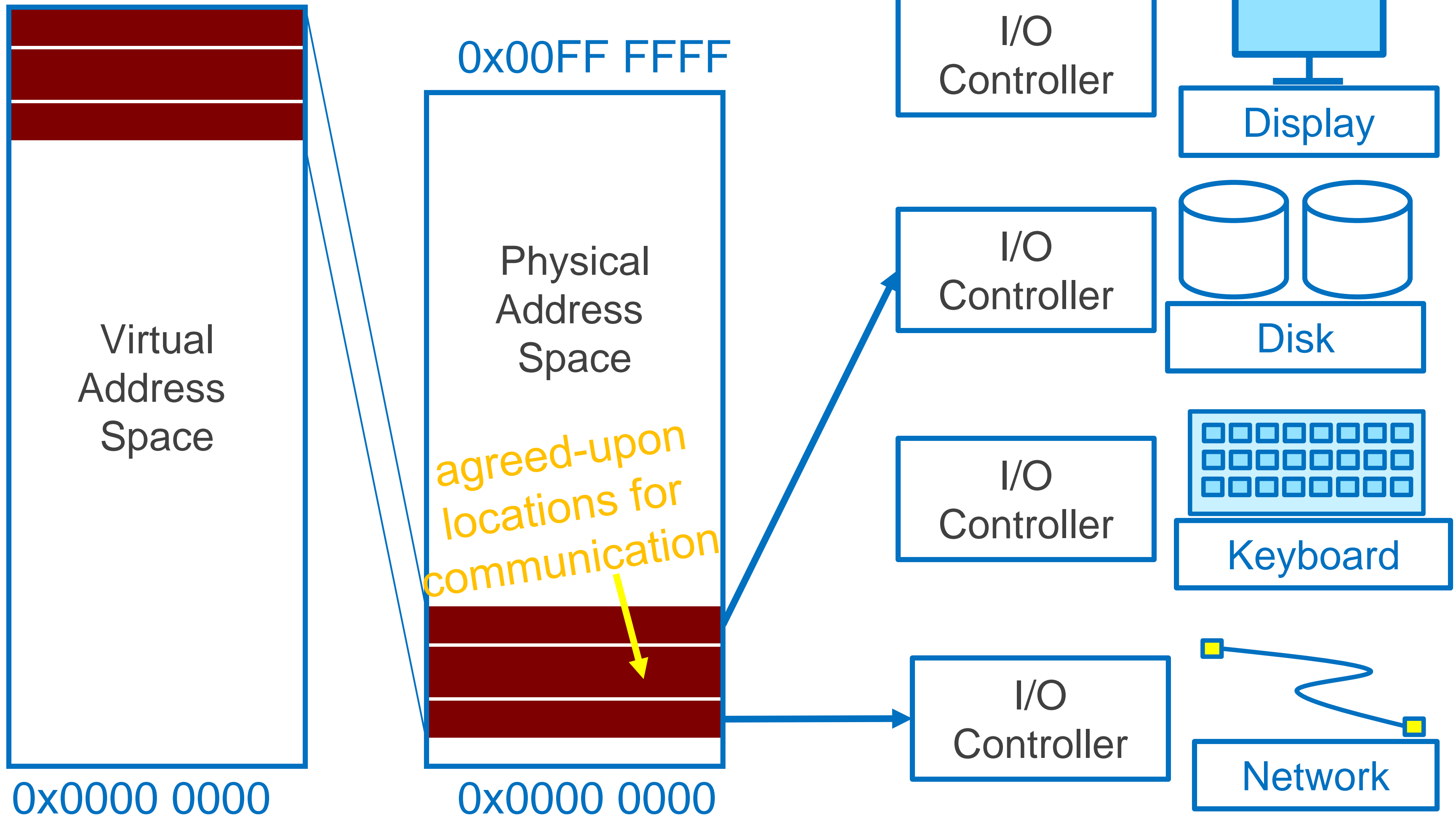
Q: How does ~~program~~ ~~OS~~ code talk to device?

A: Map registers into virtual address space

Memory-mapped I/O ← Faster. Less boundary crossing

- Accesses to certain addresses redirected to I/O devices
- Data goes over the memory bus
- Protection: via bits in pagetable entries
- OS+MMU+devices configure mappings

Memory-Mapped I/O



Less-favored alternative = Programmed I/O:

- Syscall instructions that communicate with I/O
- Communicate via special device registers

Device Drivers

Programmed I/O

```
char read_kbd()
{
do {
    sleep();
    status = inb(0x64);
  } while(!(status & 1));

  return inb(0x60);
}
```

syscall

Memory Mapped I/O

```
struct kbd {
  char status, pad[3];
  char data, pad[3];
};
kbd *k = mmap(...);

char read_kbd()
{
  do {
    sleep();
    status = k->status;
  } while(!(status & 1));
  return k->data;
}
```

syscall

I/O Data Transfer

How to talk to device?

- Programmed I/O or Memory-Mapped I/O

How to get events?

- Polling or Interrupts

How to transfer lots of data?

```
disk->cmd = READ_4K_SECTOR;
disk->data = 12;
while (!(disk->status & 1) { }
for (i = 0..4k)
    buf[i] = disk->data;
```

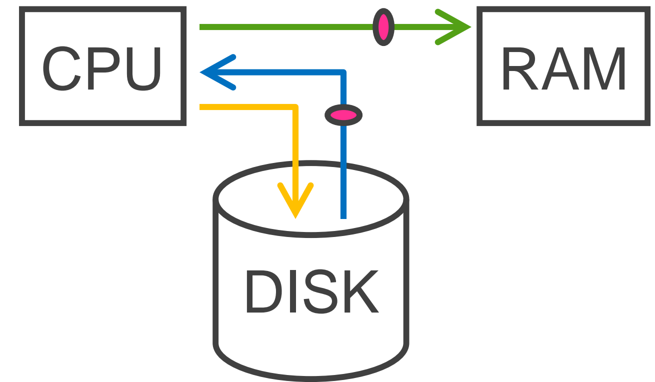
Very, ***Very,*** Expensive

Data Transfer

1. Programmed I/O: Device ←→ CPU ←→ RAM

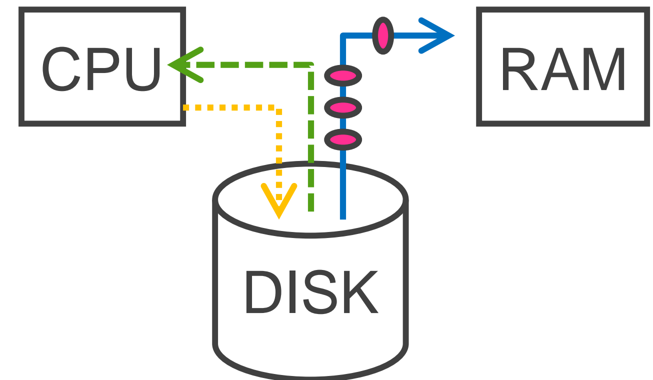
for (i = 1 .. n)

- CPU issues read request
- Device puts data on bus & CPU reads into registers
- CPU writes data to memory



2. Direct Memory Access (DMA): Device ←→ RAM

- CPU sets up DMA request
- for (i = 1 ... n)
  Device puts data on bus & RAM accepts it
- Device interrupts CPU after done



Which one is the winner? Which one is the loser?

DMA Example

DMA example: reading from audio (mic) input

- DMA engine on audio device… or I/O controller … or …

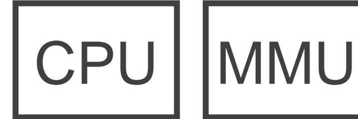
```
int dma_size = 4*PAGE_SIZE;
int *buf =           (dma_size);
...
dev->mic_dma_baseaddr = (int)buf;
dev->mic_dma_count = dma_len;
dev->cmd = DEV_MIC_INPUT |
DEV_INTERRUPT_ENABLE | DEV_DMA_ENABLE;
```

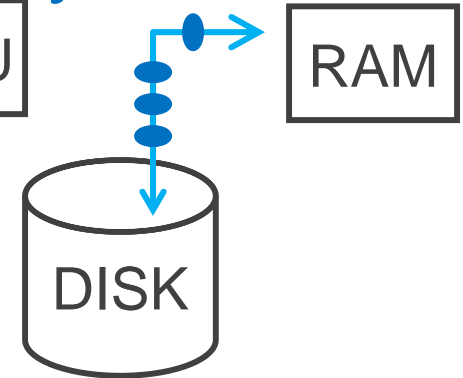
DMA Issues (1): Addressing

Issue #1: DMA meets Virtual Memory

RAM: physical addresses

Programs: virtual addresses





DMA Example

DMA example: reading from audio (mic) input

- DMA engine on audio device… or I/O controller … or …

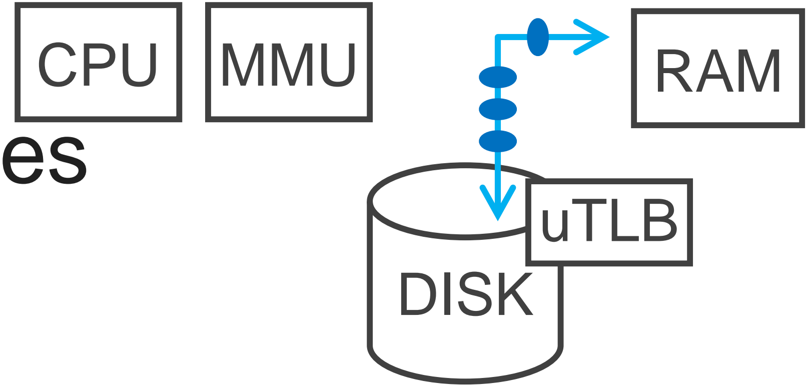
```
int dma_size = 4*PAGE_SIZE;
void *buf = alloc_dma(dma_size);
...
dev->mic_dma_baseaddr = virt_to_phys(buf);
dev->mic_dma_count = dma_len;
dev->cmd = DEV_MIC_INPUT |
DEV_INTERRUPT_ENABLE | DEV_DMA_ENABLE;
```

DMA Issues (1): Addressing

Issue #1: DMA meets Virtual Memory

RAM: physical addresses

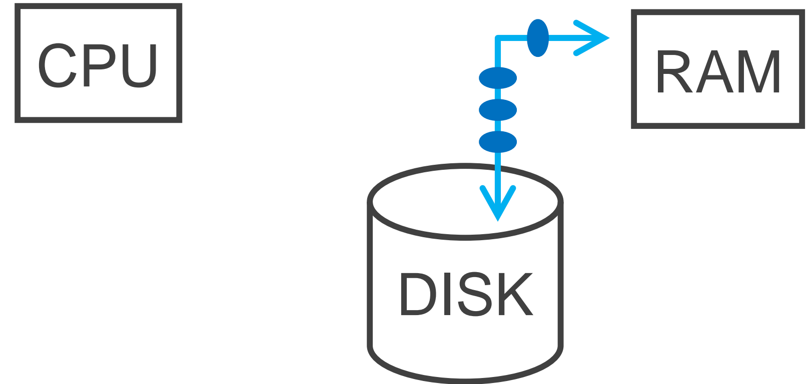
Programs: virtual addresses



DMA Issues (2): Virtual Mem

Issue #2: DMA meets *Paged* Virtual Memory

DMA destination page may get swapped out

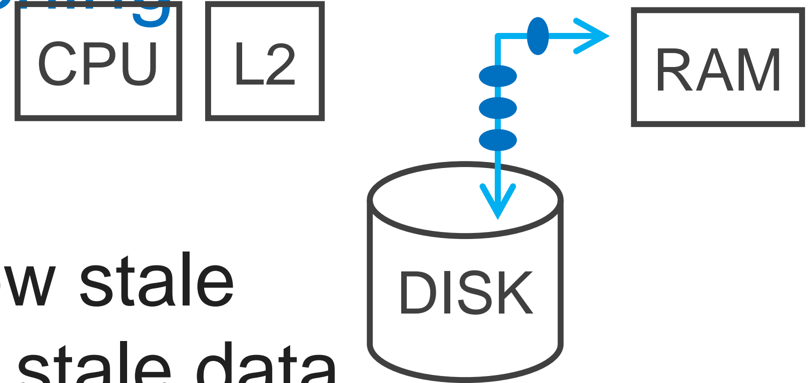


DMA Issues (4): Caches

Issue #4: DMA meets Caching

DMA-related data could be cached in L1/L2

- DMA to Mem: cache is now stale
- DMA from Mem: dev gets stale data

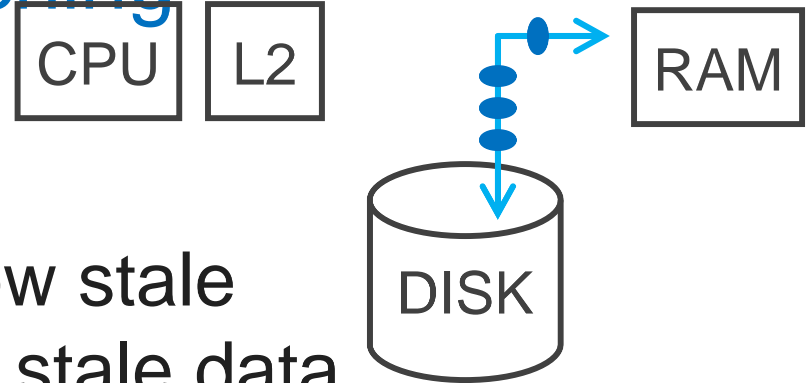


DMA Issues (4): Caches

Issue #4: DMA meets Caching

DMA-related data could be cached in L1/L2

- DMA to Mem: cache is now stale
- DMA from Mem: dev gets stale data



Programmed I/O vs Memory Mapped I/O

Programmed I/O

- Requires special instructions
- Can require dedicated hardware interface to devices
- Protection enforced via kernel mode access to instructions
- Virtualization can be difficult

Memory-Mapped I/O

- Re-uses standard load/store instructions
- Re-uses standard memory hardware interface
- Protection enforced with normal memory protection scheme
- Virtualization enabled with normal memory virtualization scheme

Polling vs. Interrupts

How does program learn device is ready/done?

1. Polling: Periodically check I/O status register
   - Common in small, cheap, or real-time embedded systems
   - \+ Predictable timing, inexpensive
   - – Wastes CPU cycles
2. Interrupts: Device sends interrupt to CPU
   - Cause register identifies the interrupting device
   - Interrupt handler examines device, decides what to do
   - \+ Only interrupt when device ready/done
   - – Forced to save CPU context (PC, SP, registers, *etc.*)
   - – Unpredictable, event arrival depends on other devices' activity

Clicker Question: Which is better?

(A) Polling (B) Interrupts (C) Both equally good/bad

I/O Takeaways

Diverse I/O devices require hierarchical interconnect which is more recently transitioning to point-to-point topologies.

Memory-mapped I/O is an elegant technique to read/write device registers with standard load/stores.

Interrupt-based I/O avoids the wasted work in polling-based I/O and is usually more efficient.

Modern systems combine memory-mapped I/O, interrupt-based I/O, and direct-memory access to create sophisticated I/O device subsystems.