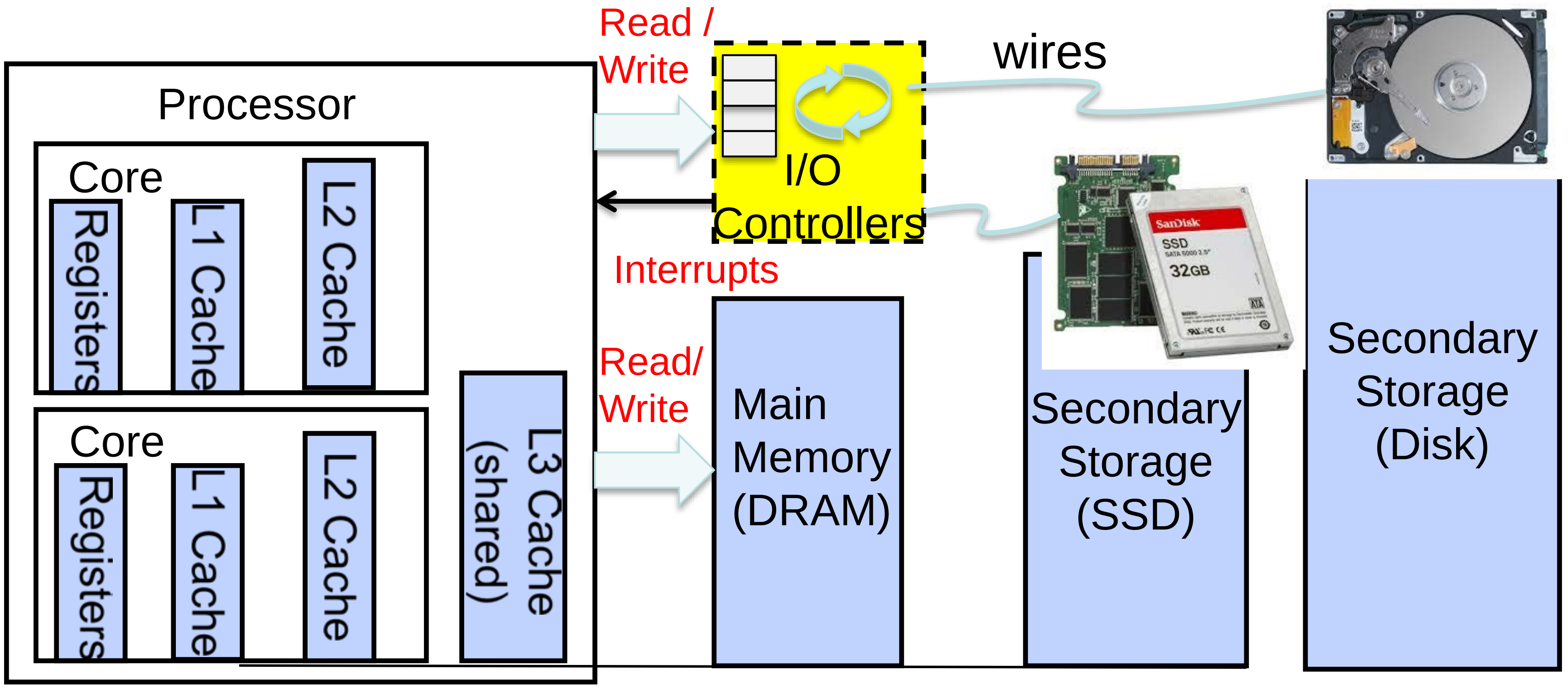
I/O Systems

Note: Some slides and/or pictures in the following are adapted from the text books on OS by Silberschatz, Galvin, and Gagne AND Andrew S. Tanenbaum and Albert S.Woodhull. Slides courtesy of Kubiatowicz, AJ Shankar, George Necula, Alex Aiken, Eric Brewer, Ras Bodik, Ion Stoica, Doug Tygar, David Wagner, Hakim Weatherspoon, etc.

The Requirements of I/O

- So far in this course:
  - We have learned how to manage CPU and Memory
- What about I/O?
  - Without I/O, computers are useless (disembodied brains?)
  - But… thousands of devices, each slightly different
    - How can we standardize the interfaces to these devices?
  - Devices unreliable: media failures and transmission errors
    - How can we make them reliable???
  - Devices unpredictable and/or slow
    - How can we manage them if we don’t know what they will do or how they will perform?

In a Picture



- I/O devices you recognize are supported by I/O Controllers
- Processors accesses them by reading/writing I/O registers as if they were memory
  - Write commands and arguments, read status and results

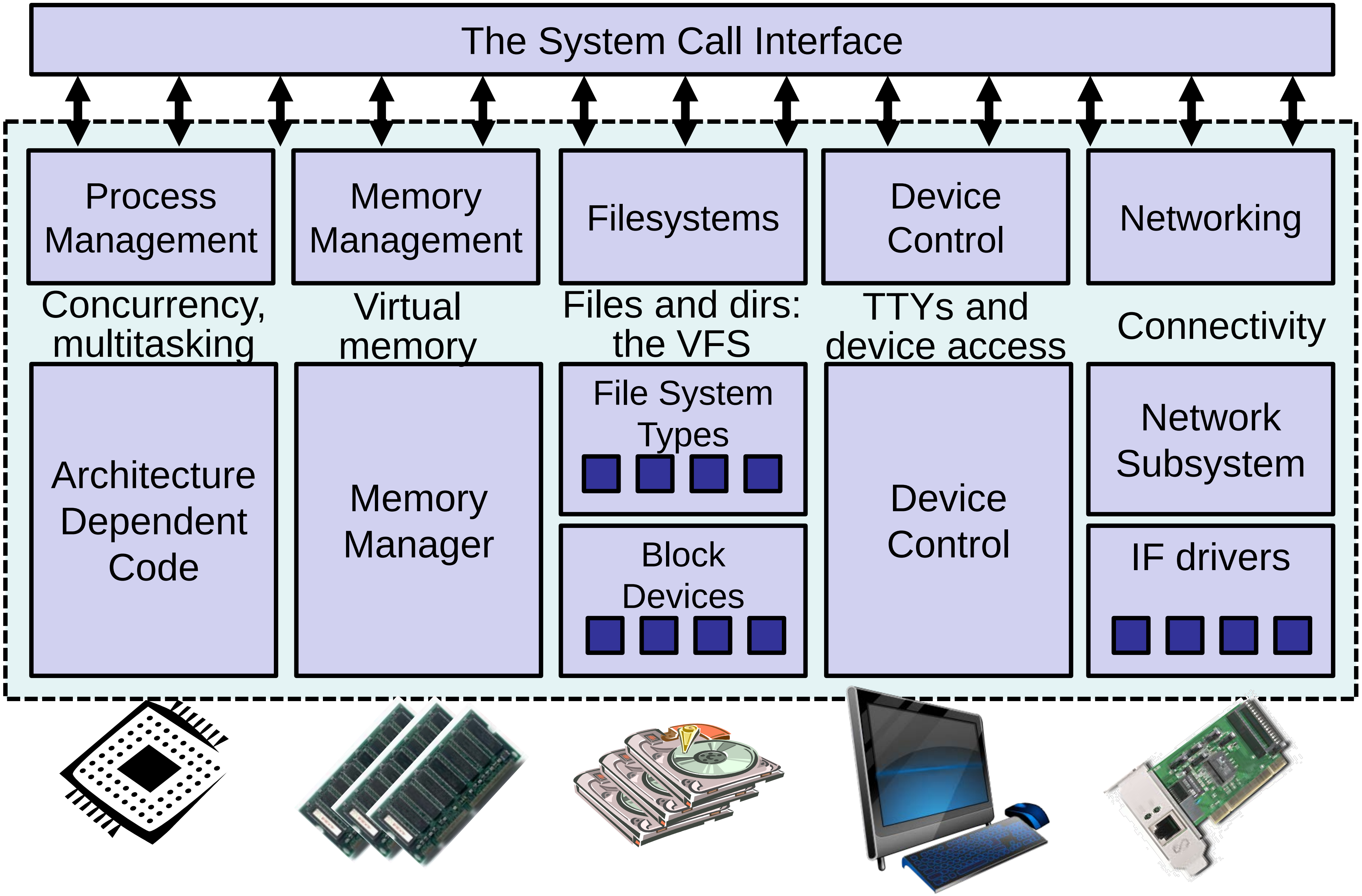
Operational Parameters for I/O

- Data granularity: Byte vs Block
  - Some devices provide single byte at a time (e.g., keyboard)
  - Others provide whole blocks (e.g., disks, networks, etc.)
- Access pattern: Sequential vs. Random
  - Some devices must be accessed sequentially (e.g., tape)
  - Others can be accessed “randomly” (e.g., disk, cd, etc.)
    - Fixed overhead to start transfers
  - Some devices require continual monitoring (polling)
  - Others generate interrupts when they need service
- Transfer Mechanism: Programmed I/O and DMA

Characteristics of I/O Devices

aspect	variation	example
data-transfer mode	character block	terminal disk
access method	sequential random	modem CD-ROM
transfer schedule	synchronous asynchronous	tape keyboard
sharing	dedicated sharable	tape keyboard
device speed	latency seek time transfer rate delay between operations	
I/O direction	read only write only read–write	CD-ROM graphics controller disk

Kernel Device Structure



The Goal of the I/O Subsystem

- Provide Uniform Interfaces, Despite Wide Range of Different Devices
  - This code works on many different devices:

```
int fd = open(“/dev/something”);
for (int i = 0; i < 10; i++) {
   fprintf(fd,”Count %d\n”,i);
}
close(fd);
```

  - Why? Because code that controls devices (“device driver”) implements standard interface.
- We will try to get a flavor for what is involved in actually controlling devices in rest of lecture
  - Can only scratch surface!

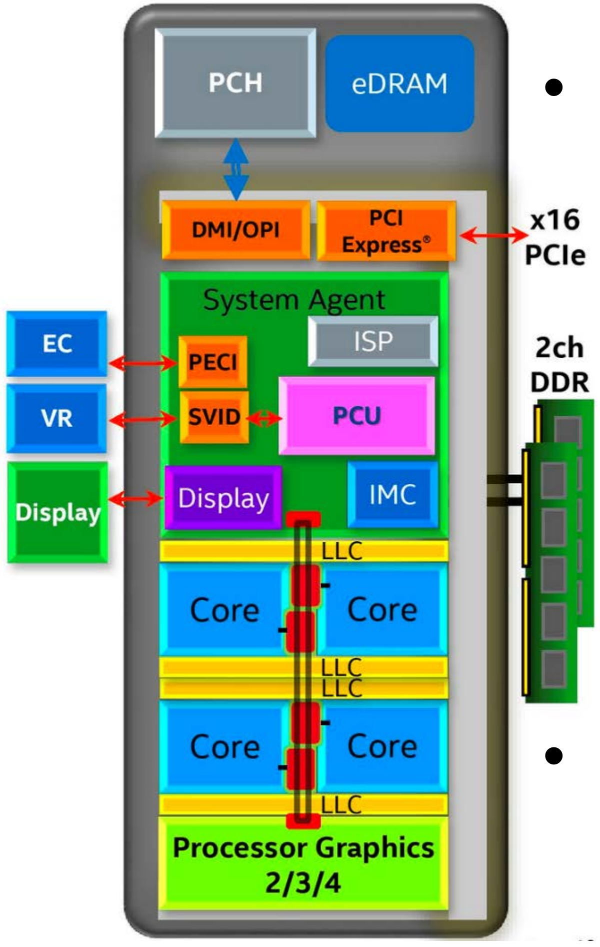
Want Standard Interfaces to Devices

- Block Devices: *e.g.* disk drives, tape drives, DVD-ROM
  - Access blocks of data
  - Commands include `open()`, `read()`, `write()`, `seek()`
  - Raw I/O or file-system access
  - Memory-mapped file access possible
- Character Devices: *e.g.* keyboards, mice, serial ports, some USB devices
  - Single characters at a time
  - Commands include `get()`, `put()`
  - Libraries layered on top allow line editing
- Network Devices: *e.g.* Ethernet, Wireless, Bluetooth
  - Different enough from block/character to have own interface
  - Unix and Windows include socket interface
    - Separates network protocol from network operation
    - Includes `select()` functionality
  - Usage: pipes, FIFOs, streams, queues, mailboxes

How Does User Deal with Timing?

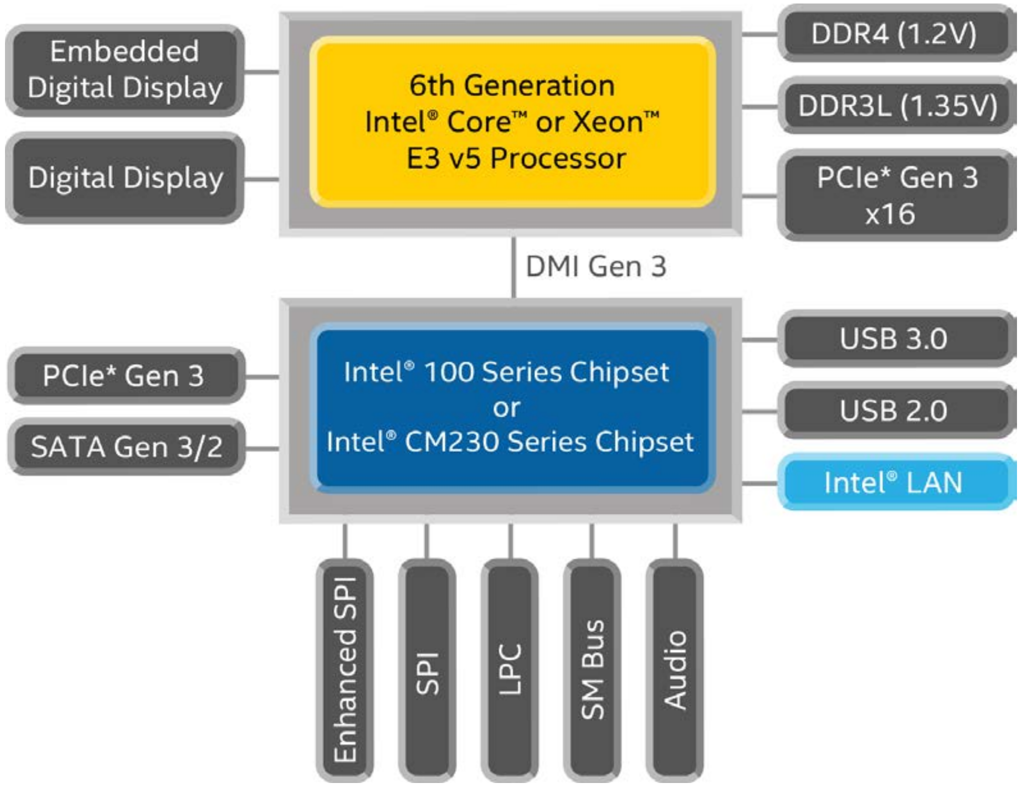
- Blocking Interface: "Wait"
  - When request data (e.g. `read()` system call), put process to sleep until data is ready
  - When write data (e.g. `write()` system call), put process to sleep until device is ready for data
- Non-blocking Interface: "Don't Wait"
  - Returns quickly from read or write request with count of bytes successfully transferred
  - Read may return nothing, write may write nothing
- Asynchronous Interface: "Tell Me Later"
  - When request data, take pointer to user's buffer, return immediately; later kernel fills buffer and notifies user
  - When send data, take pointer to user's buffer, return immediately; later kernel takes data and notifies user

Chip-scale Features of 2015 x86 (Sky Lake)



- Significant pieces:
  - Four OOO cores with deeper buffers
    - New Intel MPX (Memory Protection Extensions)
    - New Intel SGX (Software Guard Extensions)
    - Issue up to 6 μ-ops/cycle
  - Integrated GPU, System Agent (Mem, Fast I/O)
  - Large shared L3 cache with on-chip ring bus
    - 2 MB/core instead of 1.5 MB/core
    - High-BW access to L3 Cache
- Integrated I/O
  - Integrated memory controller (IMC)
    - Two independent channels of DRAM
  - High-speed PCI-Express (for Graphics cards)
  - Direct Media Interface (DMI) Connection to PCH (Platform Control Hub)

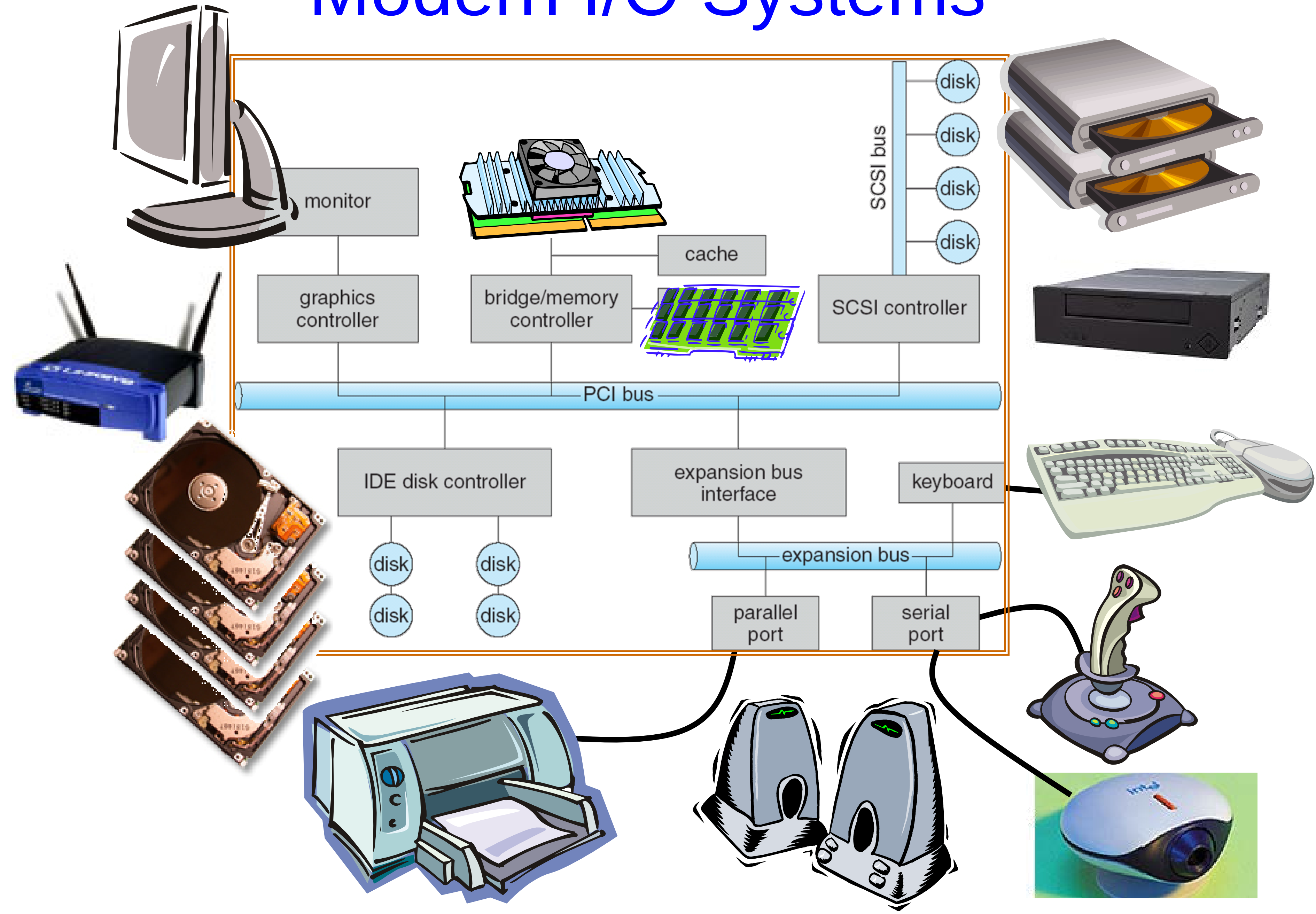
Sky Lake I/O: PCH



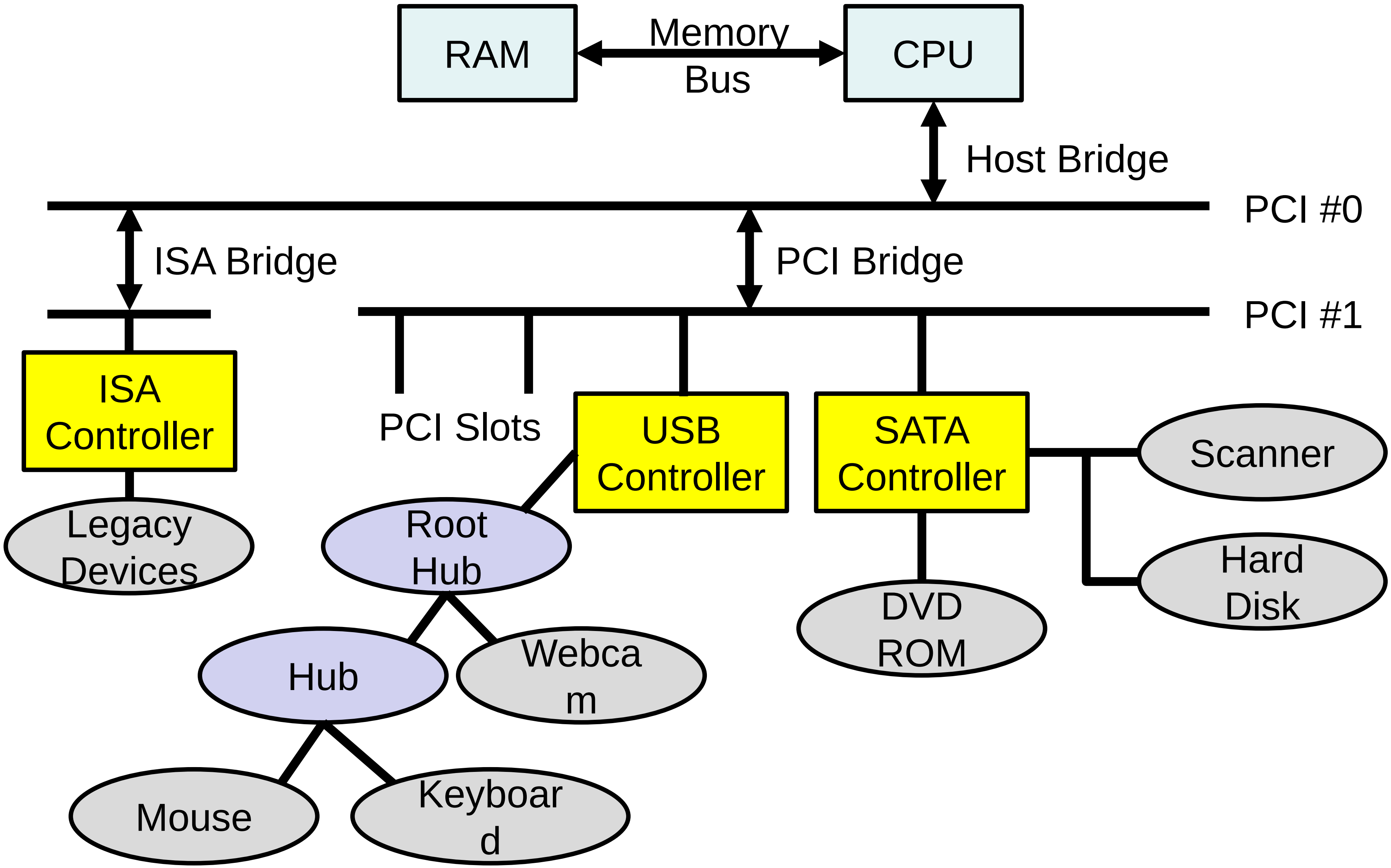
Sky Lake
System Configuration

- Platform Controller Hub
  - Connected to processor with proprietary bus
    - Direct Media Interface
- Types of I/O on PCH:
  - USB, Ethernet
  - Thunderbolt 3
  - Audio, BIOS support
  - More PCI Express (lower speed than on Processor)
  - SATA (for Disks)

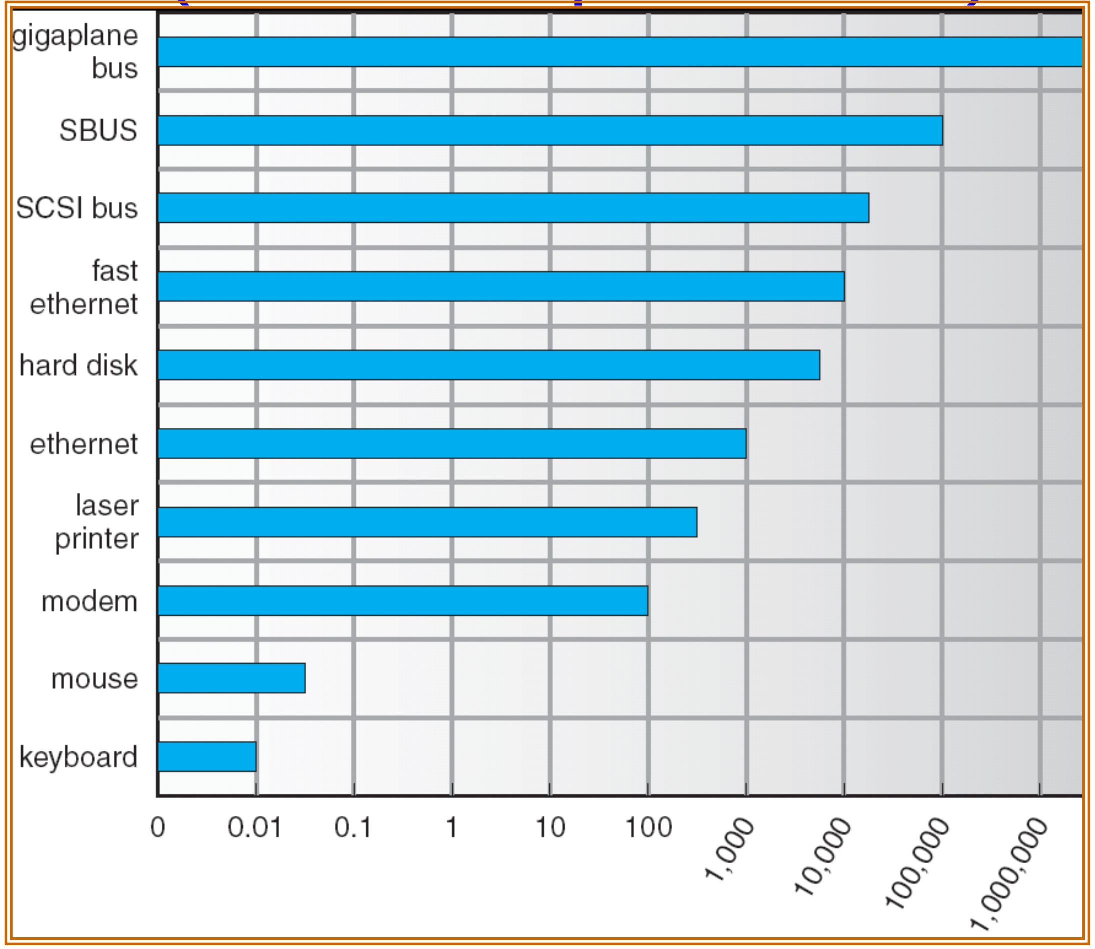
Modern I/O Systems



Example: PCI Architecture

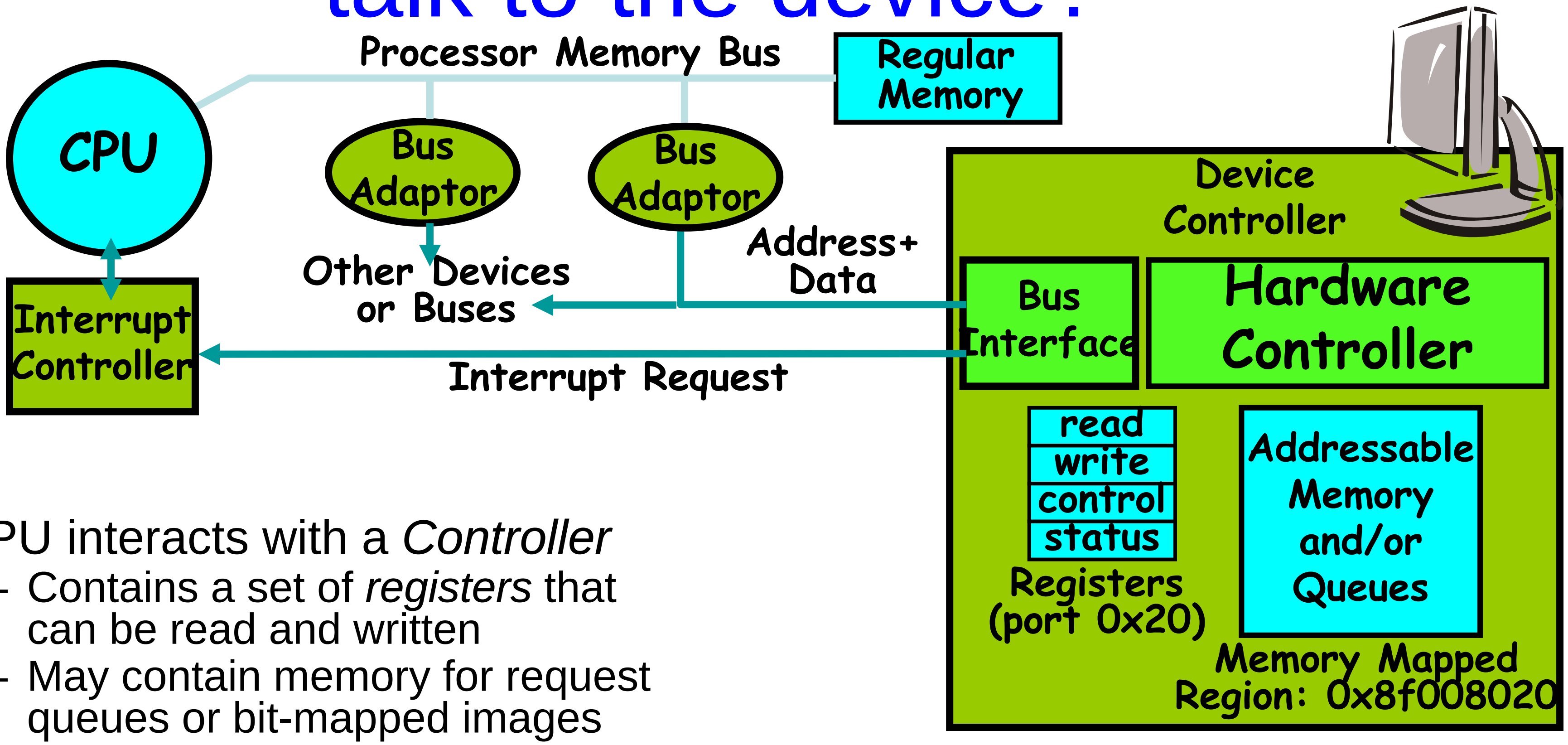


Example Device-Transfer Rates (Sun Enterprise 6000)



- Device rates vary over many orders of magnitude
  - System better be able to handle this wide range
  - Better not have high overhead/byte for fast devices!
  - Better not waste time waiting for slow devices

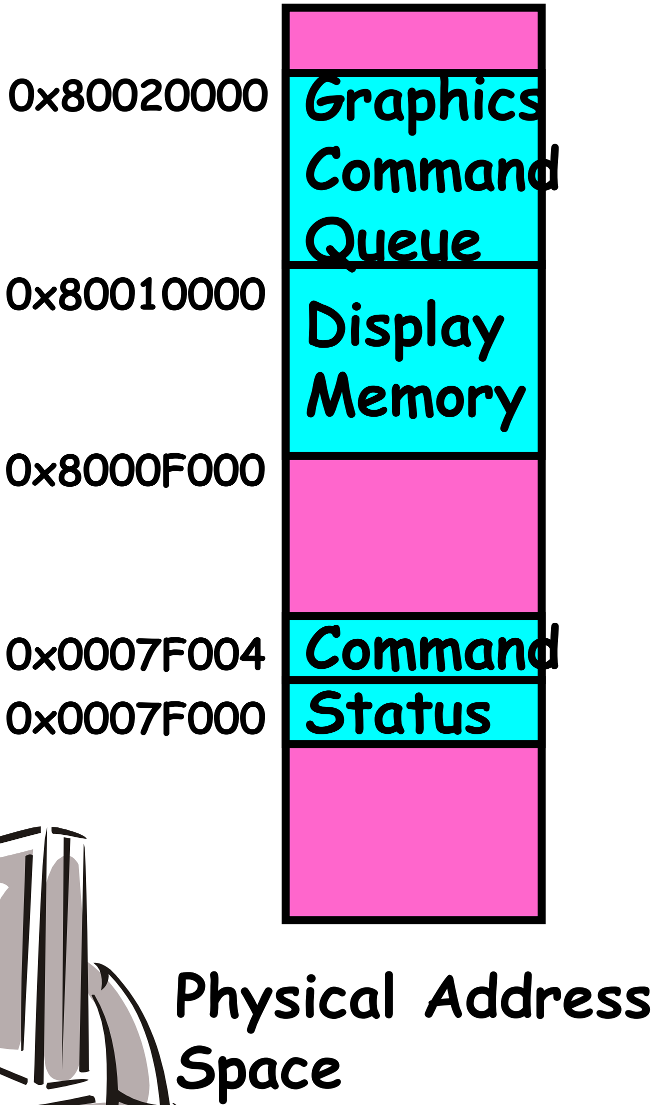
How does the processor actually talk to the device?

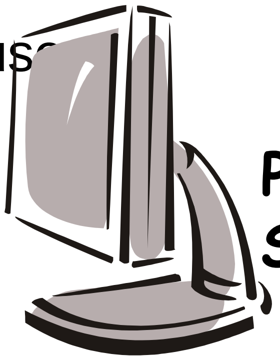


- CPU interacts with a *Controller*
  - Contains a set of *registers* that can be read and written
  - May contain memory for request queues or bit-mapped images
- Regardless of the complexity of the connections and buses, processor accesses registers in two ways:
  - I/O instructions: in/out instructions
    - Example from the Intel architecture: `out 0x21,AL`
  - Memory mapped I/O: load/store instructions
    - Registers/memory appear in physical address space
    - I/O accomplished with load and store instructions

Example: Memory-Mapped Display Controller

- Memory-Mapped:
  - Hardware maps control registers and display memory into physical address space
    - Addresses set by hardware jumpers or programming at boot time
  - Simply writing to display memory (also called the “frame buffer”) changes image on screen
    - Addr: 0x8000F000—0x8000FFFF
  - Writing graphics description to command-queue area
    - Say enter a set of triangles that describe some scene
    - Addr: 0x80010000—0x8001FFFF
  - Writing to the command register may caus on-board graphics hardware to do something
    - Say render the above scene
    - Addr: 0x0007F004
- Can protect with page tables



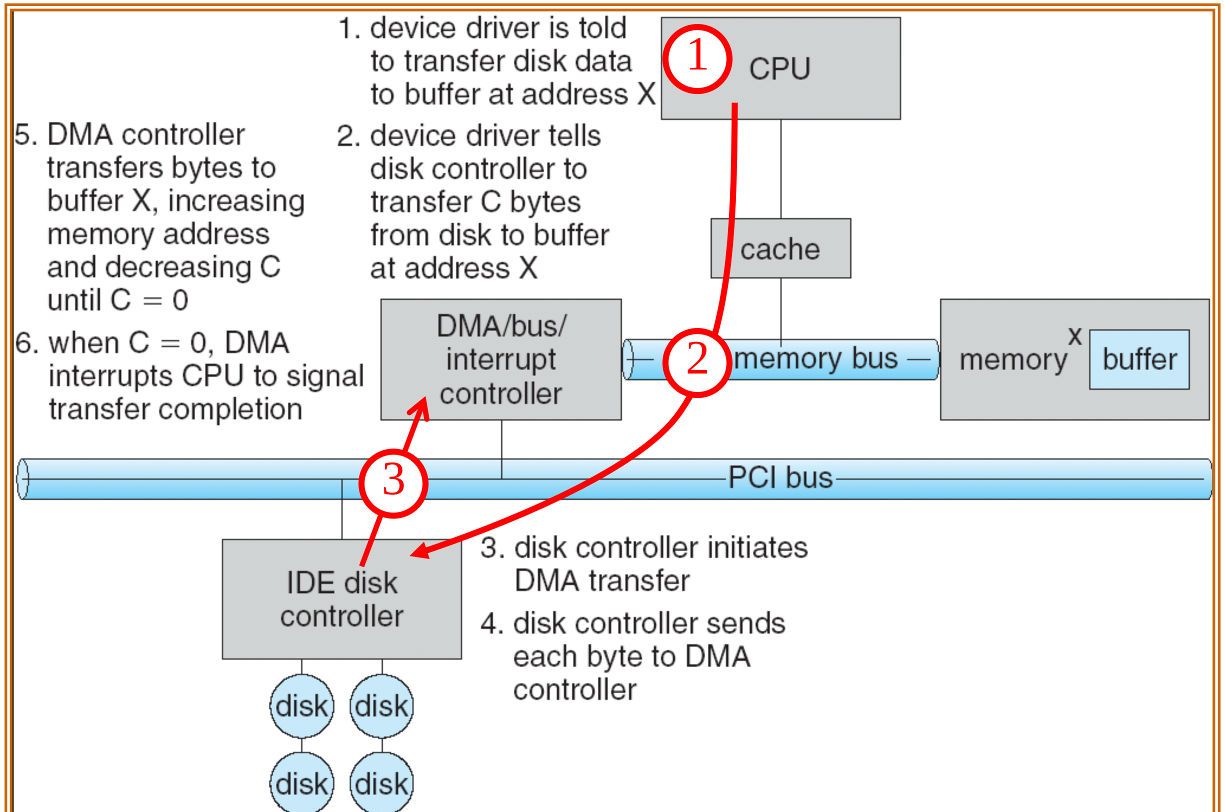


Transferring Data To/From Controller

- Programmed I/O:
  - Each byte transferred via processor in/out or load/store
  - Pro: Simple hardware, easy to program
  - Con: Consumes processor cycles proportional to data size

- Direct Memory Access:
  - Give **a special controller** access to memory bus for large data tx
  - Ask it to transfer data blocks to/from memory directly
  - Bypasses CPU

- Sample interaction with DMA controller (from OSC book):


1. device driver is told to transfer disk data to buffer at address X
CPU
1
5. DMA controller transfers bytes to buffer X, increasing memory address and decreasing C until C = 0
2. device driver tells disk controller to transfer C bytes from disk to buffer at address X
cache
6. when C = 0, DMA interrupts CPU to signal transfer completion
DMA/bus/interrupt controller
2
memory bus
memory
x
buffer
3
PCI bus
3. disk controller initiates DMA transfer
4. disk controller sends each byte to DMA controller
IDE disk controller
disk
disk
disk
disk

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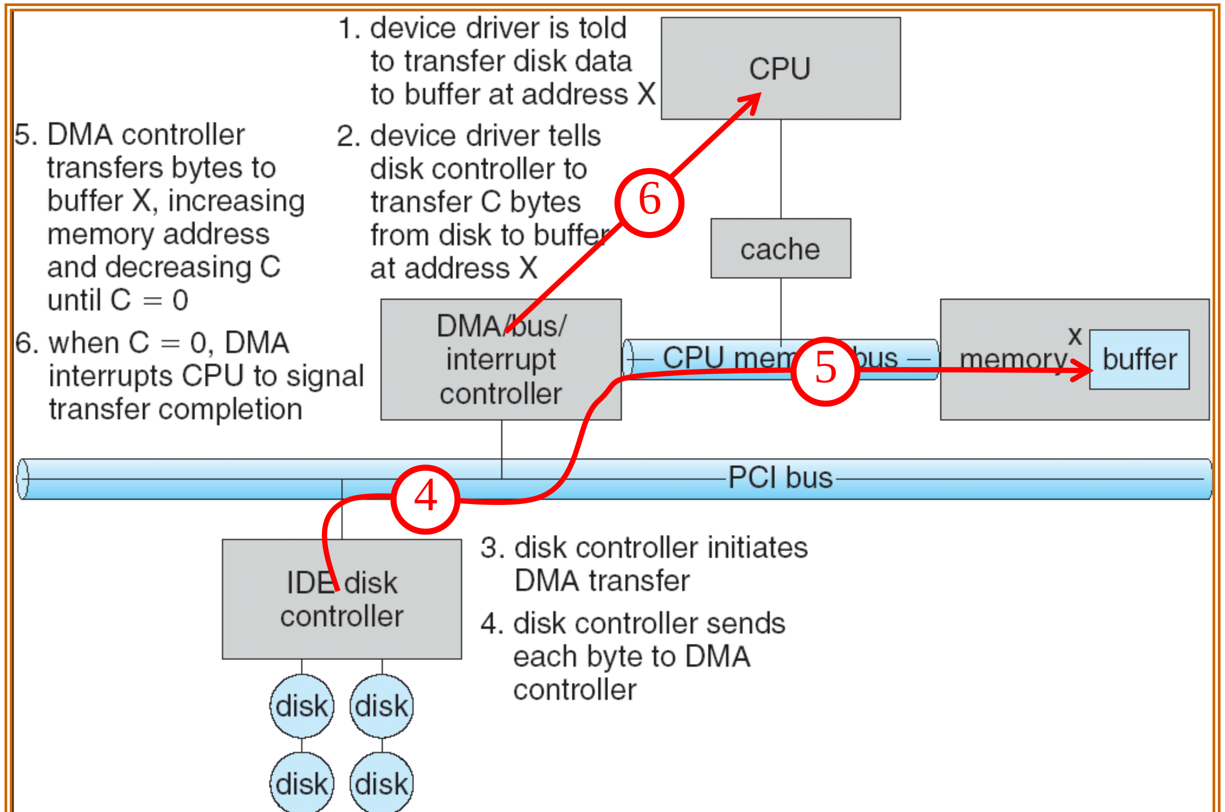
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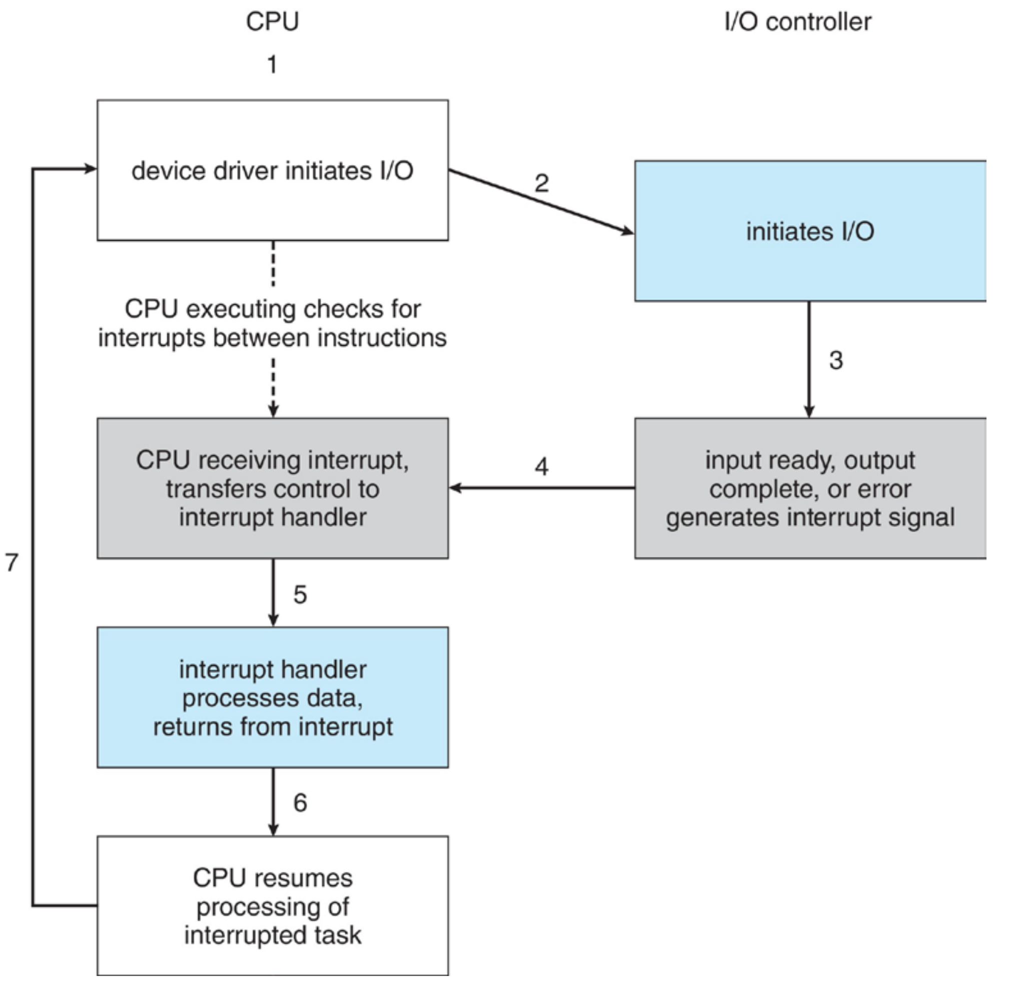
CPU
cache
DMA/bus/interrupt controller
CPU memory bus
memory
x
buffer
PCI bus
IDE disk controller
disk
disk
disk
disk
4
5
6

I/O Device Notifying the OS

- The OS needs to know when:
  - The I/O device has completed an operation
  - The I/O operation has encountered an error
- I/O Interrupt:
  - Device generates an interrupt whenever it needs service
  - Interrupt handler in Kernel receives interrupts
  - Pro: handles unpredictable events well
  - Con: interrupts cause relatively high overhead
    - E.g., a quiet macOS desktop generated 23,000 interrupts over 10 seconds!


CPU
I/O controller
1
device driver initiates I/O
2
initiates I/O
CPU executing checks for interrupts between instructions
3
CPU receiving interrupt, transfers control to interrupt handler
4
input ready, output complete, or error generates interrupt signal
5
interrupt handler processes data, returns from interrupt
6
CPU resumes processing of interrupted task
7

I/O Device Notifying the OS

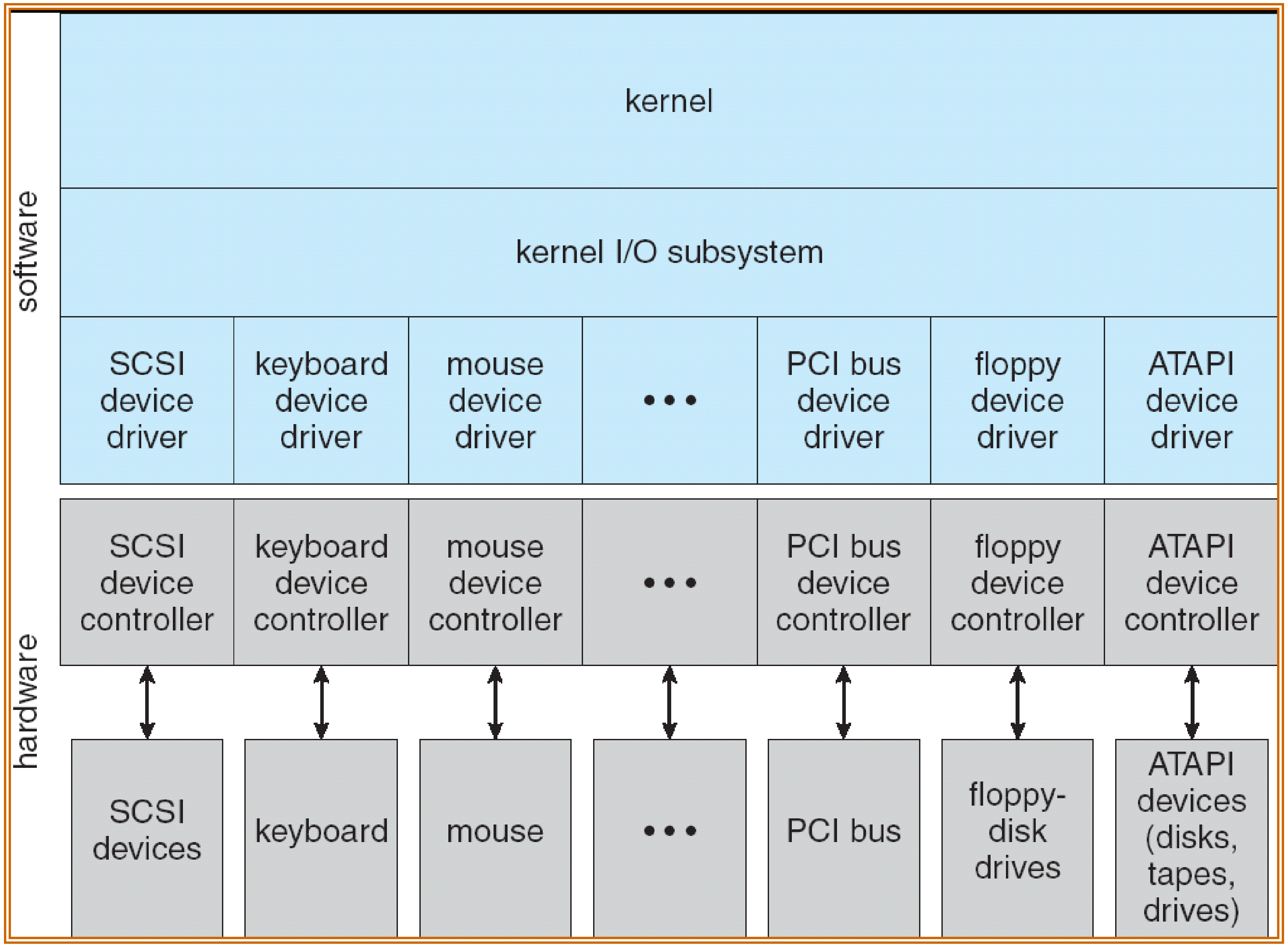
- I/O Interrupt

- Polling:
  - OS periodically checks a device-specific status register
    - I/O device puts completion information in status register
    - Could use timer to invoke lower half of drivers occasionally

  - Pro: low overhead
  - Con: may waste many cycles on polling if infrequent or unpredictable I/O operations

- Some devices combine both polling and interrupts
  - For instance: High-bandwidth network device:
    - Interrupt for first incoming packet
    - Poll for following packets until hardware empty

A Kernel I/O Structure



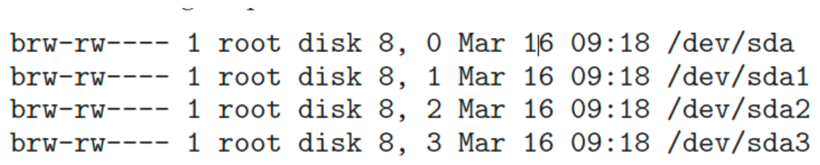
Application I/O Interface

- I/O system calls encapsulate device behaviors in generic classes
- Device-driver layer hides differences among I/O controllers from kernel
- New devices talking already-implemented protocols need no extra work
- Each OS has its own I/O subsystem structures and device driver frameworks
- Devices vary in many dimensions
  - **Character-stream** or **block**
  - **Sequential** or **random-access**
  - **Synchronous** or **asynchronous** (or both)
  - **Sharable** or **dedicated**
  - **Speed of operation**
  - **read-write**, **read only**, or **write only**

Classification of I/O Devices

- Subtleties of devices handled by device drivers
- Broadly I/O devices can be grouped by the OS into
  - Block I/O
  - Character I/O (Stream)
  - Memory-mapped file access
  - Network sockets
- For direct manipulation of I/O device specific characteristics, usually an escape / back door
  - Unix **`ioctl()`** call to send arbitrary bits to a device control register and data to device data register
- UNIX and Linux use tuple of “major” and “minor” device numbers to identify type and instance of devices (here major 8 and minors 0-4)

```
% ls -l /dev/sda*
```



```
brw-rw---- 1 root disk 8, 0 Mar 16 09:18 /dev/sda
brw-rw---- 1 root disk 8, 1 Mar 16 09:18 /dev/sda1
brw-rw---- 1 root disk 8, 2 Mar 16 09:18 /dev/sda2
brw-rw---- 1 root disk 8, 3 Mar 16 09:18 /dev/sda3
```

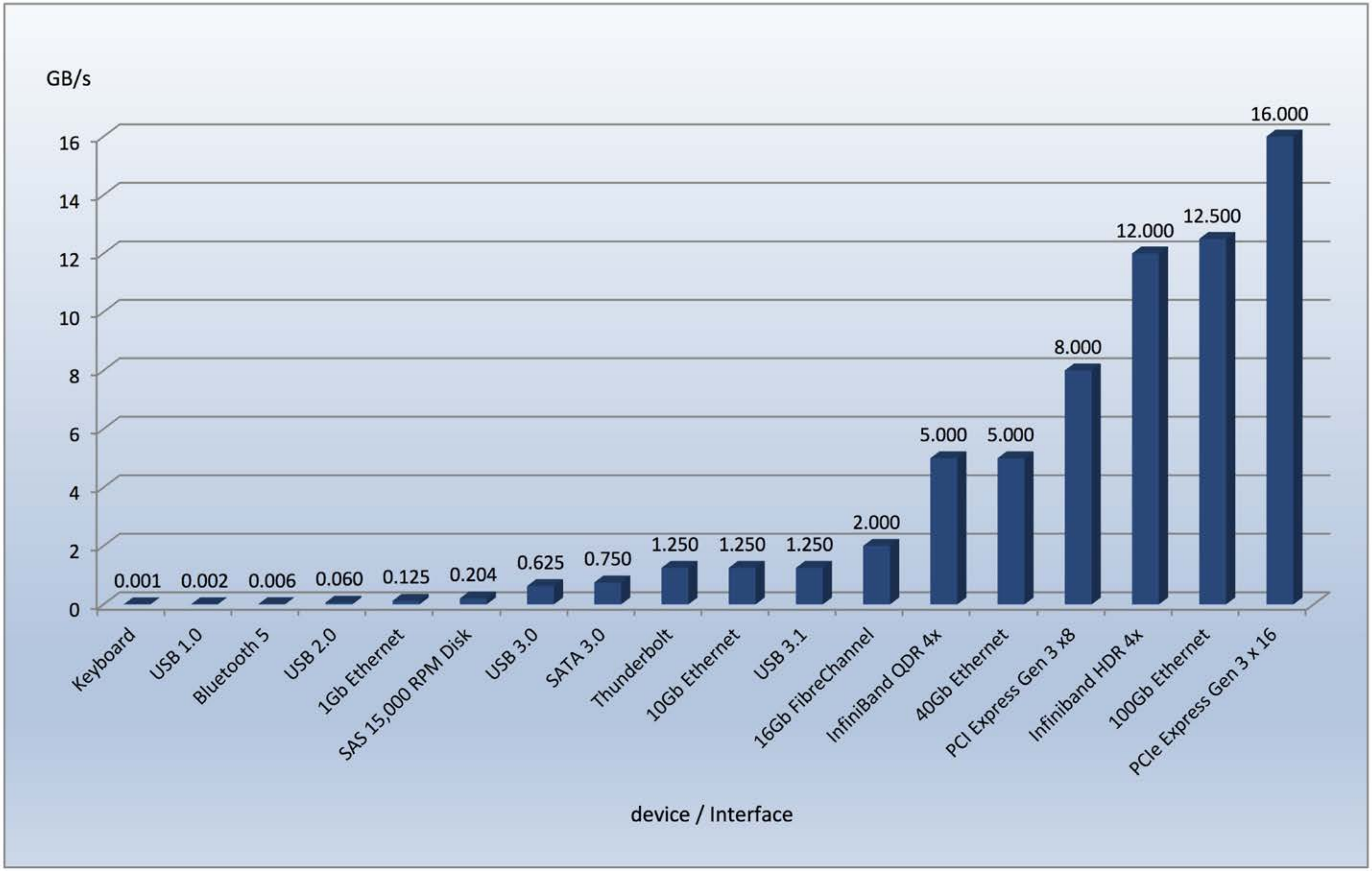
Device Drivers

- Device Driver: Device-specific code in the kernel that interacts directly with the device hardware
  - Supports a standard, internal interface
  - Same kernel I/O system can interact easily with different device drivers
  - Special device-specific configuration supported with the `ioctl()` system call
- Device Drivers typically divided into two pieces:
  - Top half: accessed in call path from system calls
    - Implements a set of standard, cross-device calls like `open()`, `close()`, `read()`, `write()`, `ioctl()`, `strategy()`
    - This is the kernel's interface to the device driver
    - Top half will *start* I/O to device, may put thread to sleep until finished
  - Bottom half: run as interrupt routine
    - Gets input or transfers next block of output
    - May wake sleeping threads if I/O now complete

Kernel I/O Subsystem

- Scheduling
  - Some I/O request ordering via per-device queue
  - Some OSs try fairness
  - Some implement Quality Of Service
- **Buffering** - store data in memory while transferring between devices
  - To cope with device speed mismatch
  - To cope with device transfer size mismatch
  - To maintain “copy semantics”
  - **Double buffering** – two copies of the data
    - Kernel and user
    - Varying sizes
    - Full / being processed and not-full / being used
    - Copy-on-write can be used for efficiency in some cases

Common PC and Data-center I/O devices and Interface Speeds



Kernel I/O Subsystem

- **Caching** - faster device holding copy of data
  - Always just a copy
  - Key to performance
  - Sometimes combined with buffering
- **Spooling** - hold output for a device
  - If device can serve only one request at a time
  - i.e., Printing
- **Device reservation** - provides exclusive access to a device
  - System calls for allocation and de-allocation
  - Watch out for deadlock!
- **Error Handling**
  - OS can recover from disk read, device unavailable, transient write failures
    - Retry a read/write, for example
    - Most return an error number or code when I/O request fails

I/O Protection

- User process may accidentally or purposefully attempt to disrupt normal operation via illegal I/O instructions
  - All I/O instructions defined to be privileged
  - I/O must be performed via system calls
    - Memory-mapped and I/O port memory locations must be protected too

Kernel I/O Subsystem Summary

- In summary, the I/O subsystem coordinates an extensive collection of services that are available to applications and to other parts of the kernel
  - Management of the name space for files and devices
  - Access control to files and devices
  - Operation control (for example, a modem cannot seek())
  - File-system space allocation
  - Device allocation
  - Buffering, caching, and spooling
  - I/O scheduling
  - Device-status monitoring, error handling, and failure recovery
  - Device-driver configuration and initialization
  - Power management of I/O devices
- The upper levels of the I/O subsystem access devices via the uniform interface provided by the device drivers

Transforming I/O Requests to Hardware Operations

- Consider reading a file from disk for a process:
  - Determine device holding file
  - Translate name to device representation
  - Physically read data from disk into buffer
  - Make data available to requesting process
  - Return control to process

Life Cycle of An I/O Request

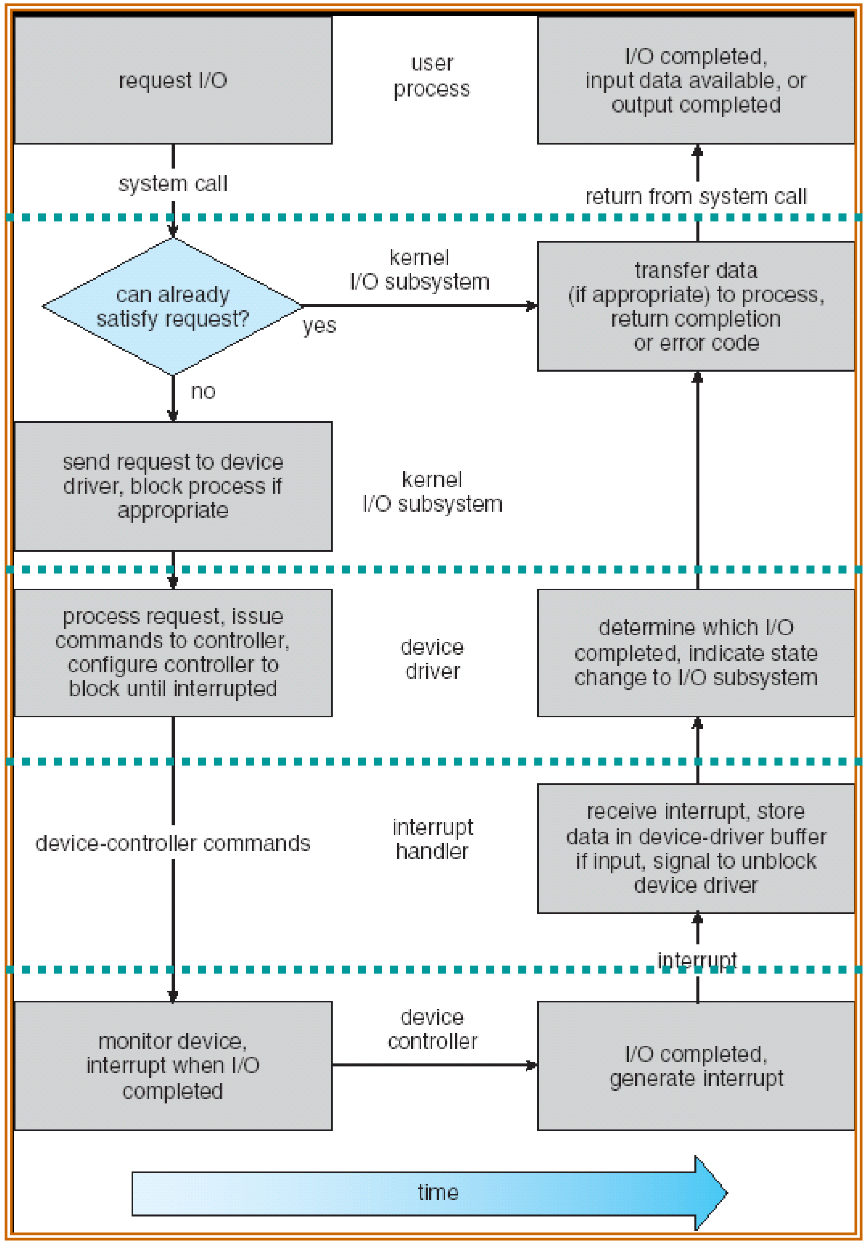
User Program

Kernel I/O Subsystem

Device Driver Top Half

Device Driver Bottom Half

Device Hardware

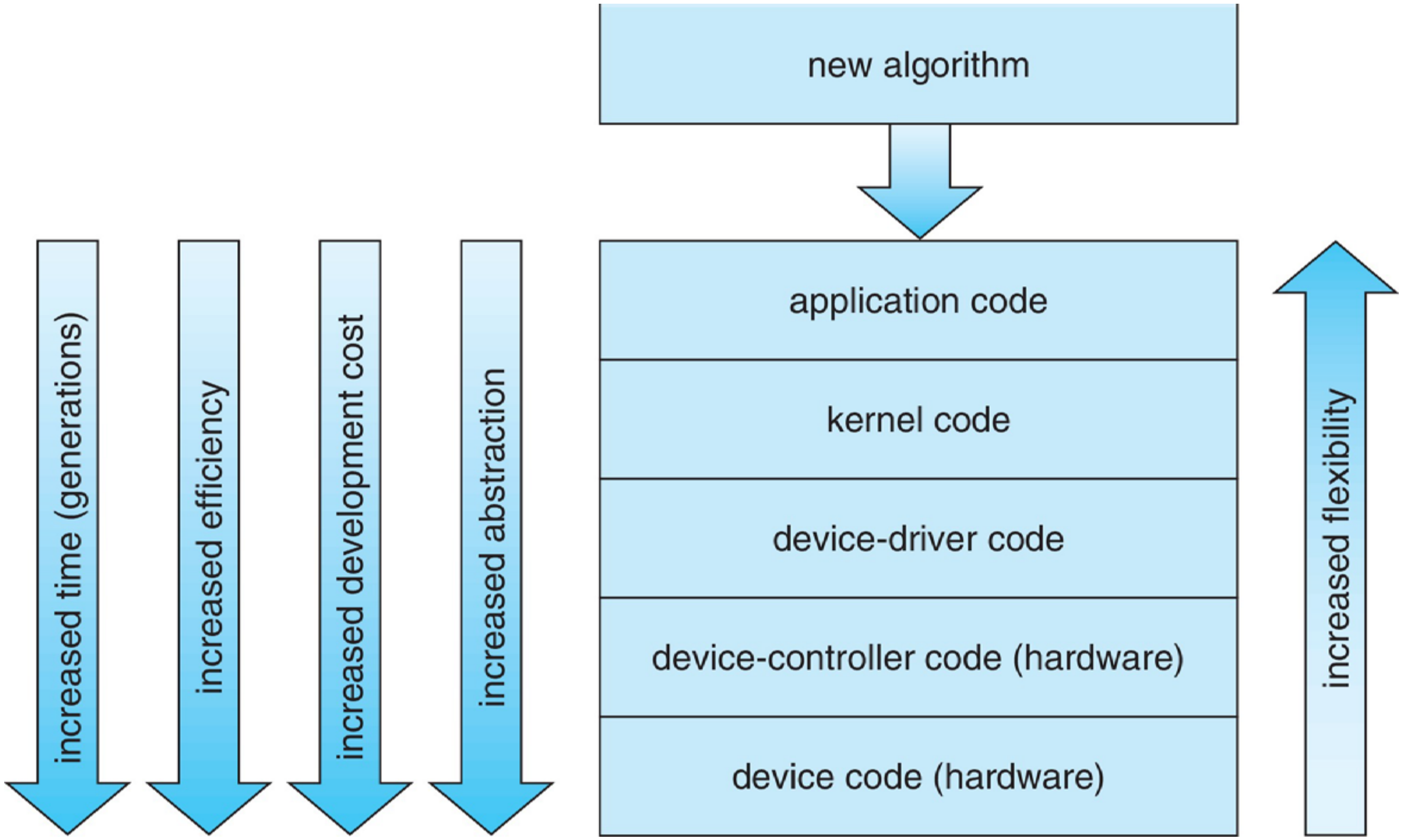


request I/O
user process
I/O completed, input data available, or output completed
system call
return from system call
can already satisfy request?
kernel I/O subsystem
yes
transfer data (if appropriate) to process, return completion or error code
no
send request to device driver, block process if appropriate
kernel I/O subsystem
process request, issue commands to controller, configure controller to block until interrupted
device driver
determine which I/O completed, indicate state change to I/O subsystem
device-controller commands
interrupt handler
receive interrupt, store data in device-driver buffer if input, signal to unblock device driver
interrupt
monitor device, interrupt when I/O completed
device controller
I/O completed, generate interrupt
time

System Performance

- I/O a major factor in system performance:
  - Demands CPU to execute device driver, kernel I/O code
  - Context switches due to interrupts
  - Data copying
  - Network traffic especially stressful
- Improving I/O performance
  - Reduce number of context switches
  - Reduce data copying
  - Reduce interrupts by using large transfers, smart controllers, polling
  - Use DMA
  - Use smarter hardware devices
  - Balance CPU, memory, bus, and I/O performance for highest throughput
  - Move user-mode processes / daemons to kernel threads

Device-Functionality Progression



Summary

- I/O Devices Types:
  - Many different speeds (0.1 bytes/sec to GBytes/sec)
  - Different Access Patterns:
    - Block Devices, Character Devices, Network Devices
  - Different Access Timing:
    - Blocking, Non-blocking, Asynchronous
- I/O Controllers: Hardware that controls actual device
  - Processor Accesses through I/O instructions, load/store to special physical memory
  - Report their results through either interrupts or a status register that processor looks at occasionally (polling)
- Notification mechanisms
  - Interrupts
  - Polling: Report results through status register that processor looks at periodically
- Device Driver: Device-specific code in kernel for interfacing to I/O devices
  - Provide clean Read/Write interface to OS above
  - Manipulate devices through PIO, DMA & interrupt handling
  - Three types: block, character, and network

References

- Chapter 13 in Galvin et al 9th Edition