I/O Subsystem

COMS W4118
Prof. Kaustubh R. Joshi
krj@cs.columbia.edu

http://www.cs.columbia.edu/~krj/os

References: Operating Systems Concepts (9e), Linux Kernel Development, previous W4118s

I/O Subsystem

- Goals
- Architecture
- Device Characteristics
- OS Mechanisms
  - Transferring data
  - Notification
  - Buffering

The Requirements of I/O

- Without I/O, computers are not very useful
- But… thousands of devices, each slightly different
  - How to standardize the interface to all devices?
- Devices unpredictable and/or slow
  - How can we utilize them if we dont know what they will do or how they will perform?
- Devices unreliable: media failures, transmission errors
  - How to make them reliable?

Varied I/O Speeds

Some typical device, network, and bus data rates.

- 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

Device	Data rate
Keyboard	10 bytes/sec
Mouse	100 bytes/sec
56K modem	7 KB/sec
Scanner	400 KB/sec
Digital camcorder	3.5 MB/sec
802.11g Wireless	6.75 MB/sec
52x CD-ROM	7.8 MB/sec
Fast Ethernet	12.5 MB/sec
Compact flash card	40 MB/sec
FireWire (IEEE 1394)	50 MB/sec
USB 2.0	60 MB/sec
SONET OC-12 network	78 MB/sec
SCSI Ultra 2 disk	80 MB/sec
Gigabit Ethernet	125 MB/sec
SATA disk drive	300 MB/sec
Ultrium tape	320 MB/sec
PCI bus	528 MB/sec

Varied Device Characteristics

- Some operational parameters:
  - Byte/Block
    - Some devices provide single byte at a time (*e.g.* keyboard)
    - Others provide whole blocks (*e.g.* disks, tapes, etc)
  - Sequential/Random
    - Some devices must be accessed sequentially (*e.g.* tape)
    - Others can be accessed randomly (*e.g.* disk, cd, etc.)
  - Polling/Interrupts
    - Some devices require continual monitoring
    - Others generate interrupts when they need service

The Goal of the I/O Subsystem

- Provide uniform Interface for wide range of devices
  - This code works on many different devices:

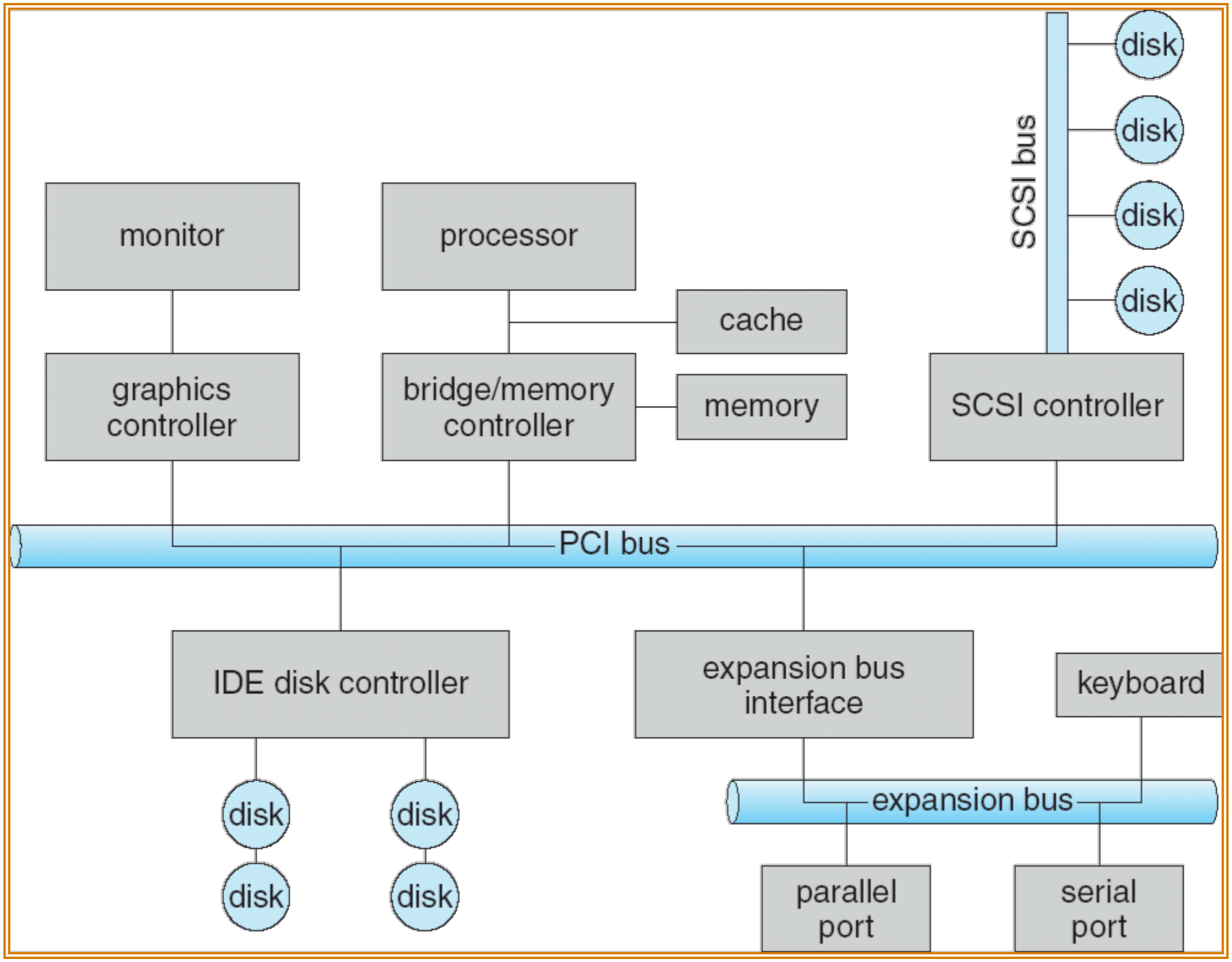
```
int fd = open("/dev/something");
for (int i = 0; i < 10; i++) {
    fprintf(fd,"Count %d\n",i);
}
close(fd);
```

  - Why? Because code that controls devices ("device driver") implements standard interface.

I/O Subsystem

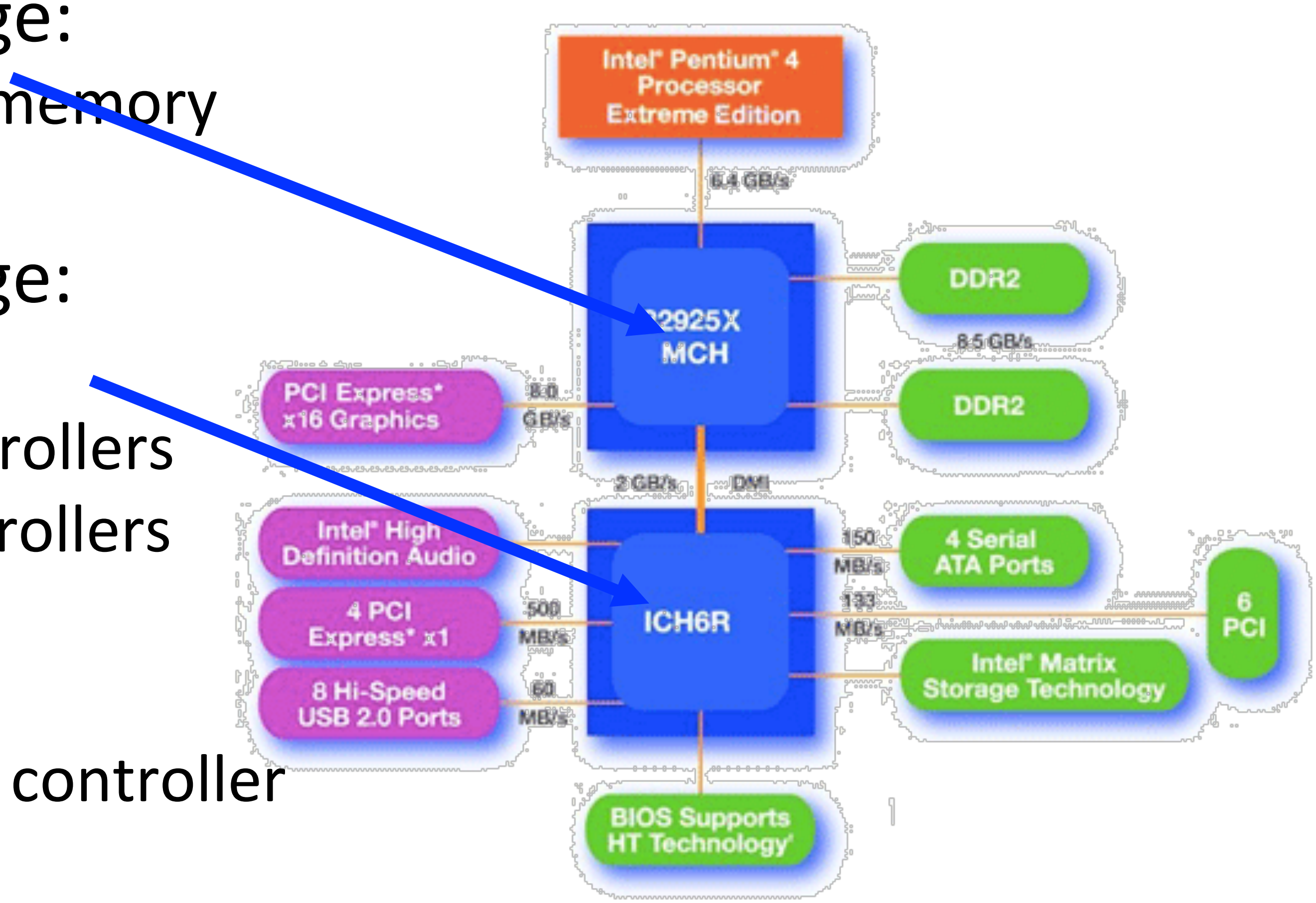
- Goals
- Architecture
- Device Characteristics
- OS Mechanisms
  - Transferring data
  - Notification
  - Buffering

Review: I/O Architecture

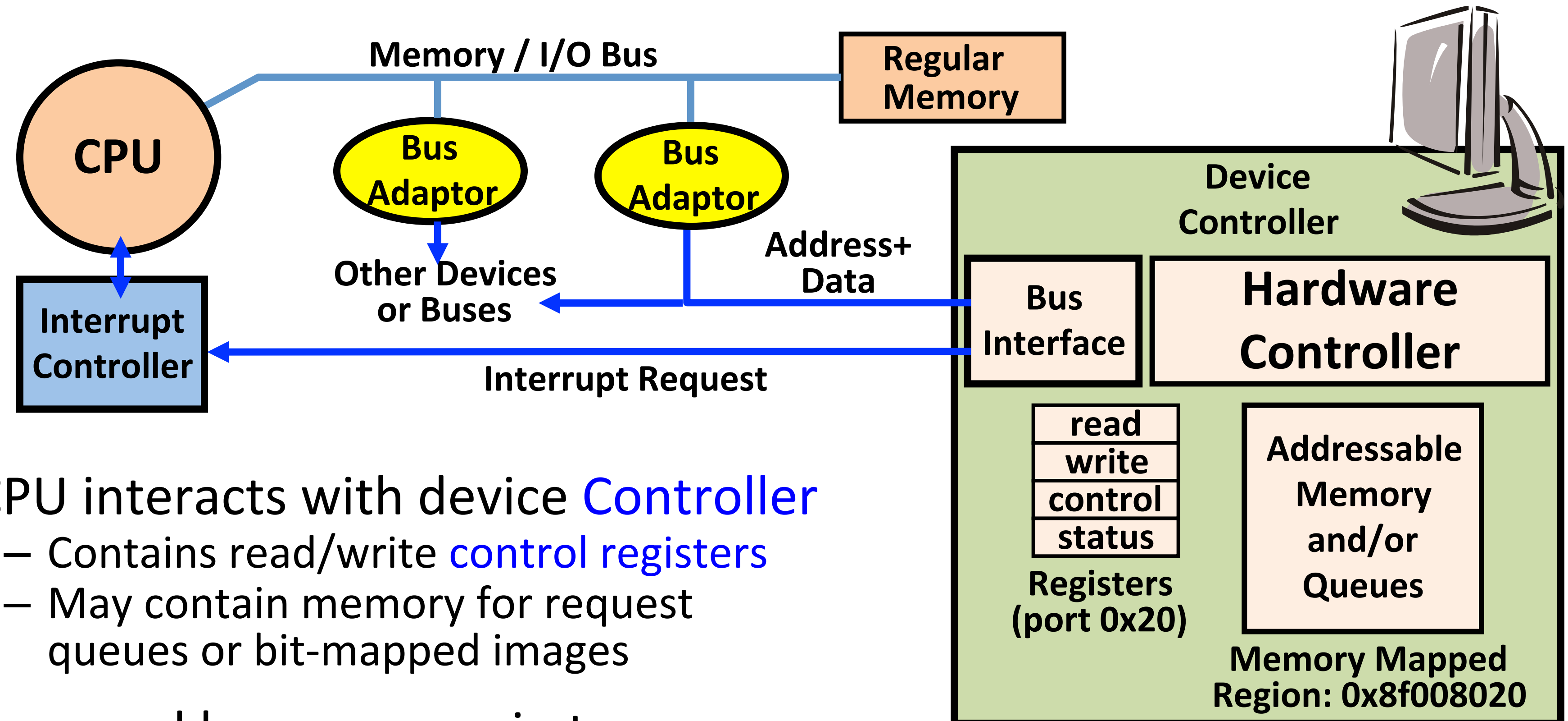


Intel Chipset Components

- Northbridge:
  - Handles memory
  - Graphics
- Southbridge:
  - PCI bus
  - Disk controllers
  - USB controllers
  - Audio
  - Serial I/O
  - Interrupt controller
  - Timers



Typical I/O Device Architecture



- CPU interacts with device Controller
  - Contains read/write control registers
  - May contain memory for request queues or bit-mapped images
- Accessed by processor in two ways:
  - I/O instructions: explicit in/out instructions
    - E.g., x86: out 0x21,AB
  - Memory mapped I/O: load/store instructions
    - Registers/memory appear in physical address space
    - I/O accomplished with load and store instructions

Memory-Mapped vs. Explicit I/O

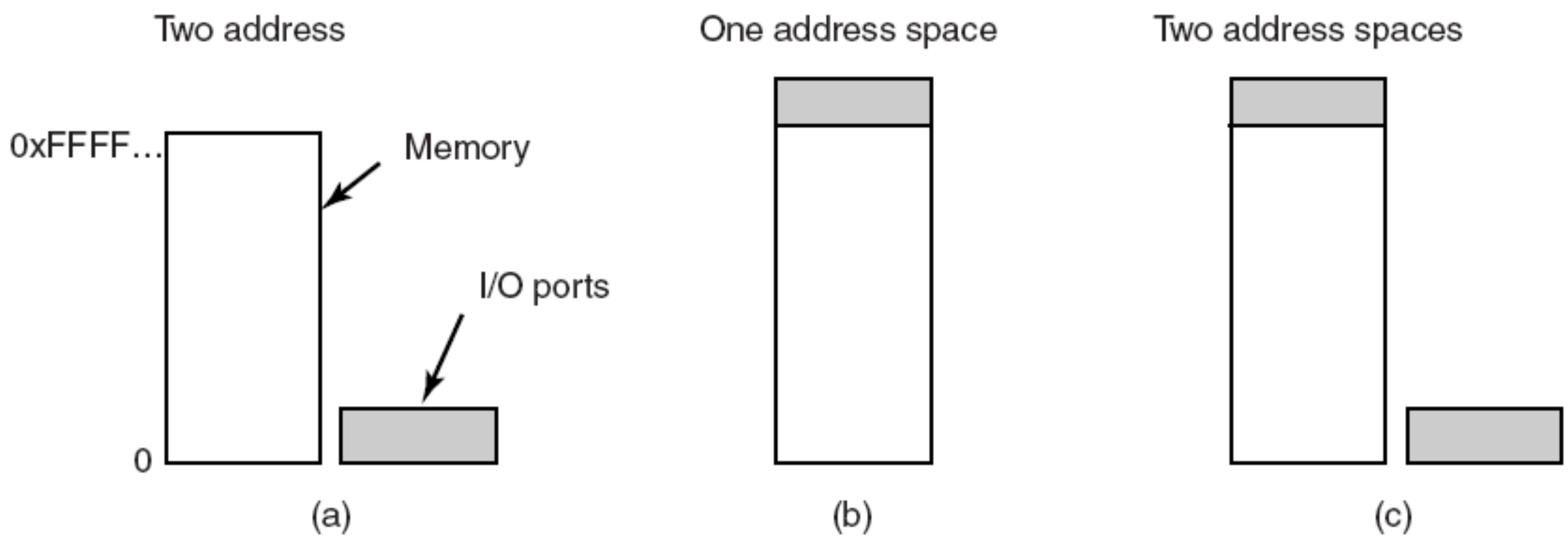
- Explicit I/O Instructions:
  - Must use assembly language
  - Prevents user-mode I/O

- Memory-Mapped I/O:
  - No need for special instructions (can use in C)
  - Allows user-based I/O
  - Caching addresses must be prevented

Device I/O Port Locations on PCs (partial)

I/O address range (hexadecimal)	device
000–00F	DMA controller
020–021	interrupt controller
040–043	timer
200–20F	game controller
2F8–2FF	serial port (secondary)
320–32F	hard-disk controller
378–37F	parallel port
3D0–3DF	graphics controller
3F0–3F7	diskette-drive controller
3F8–3FF	serial port (primary)

Memory-Mapped I/O

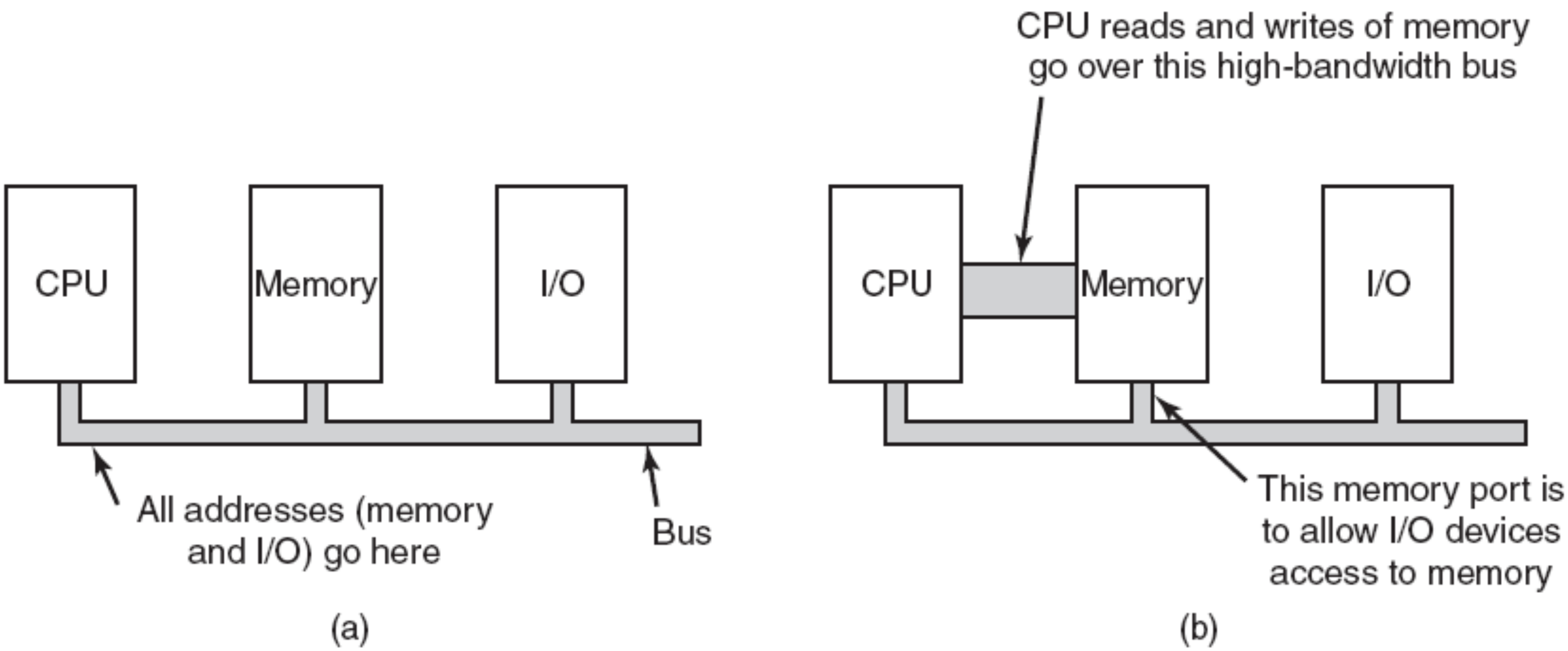


(a) Separate I/O and memory space.

(b) Memory-mapped I/O.

(c) Hybrid: control in I/O address, data in memory

Memory-Mapped I/O



(a) A single-bus architecture.
(b) A dual-bus memory architecture.

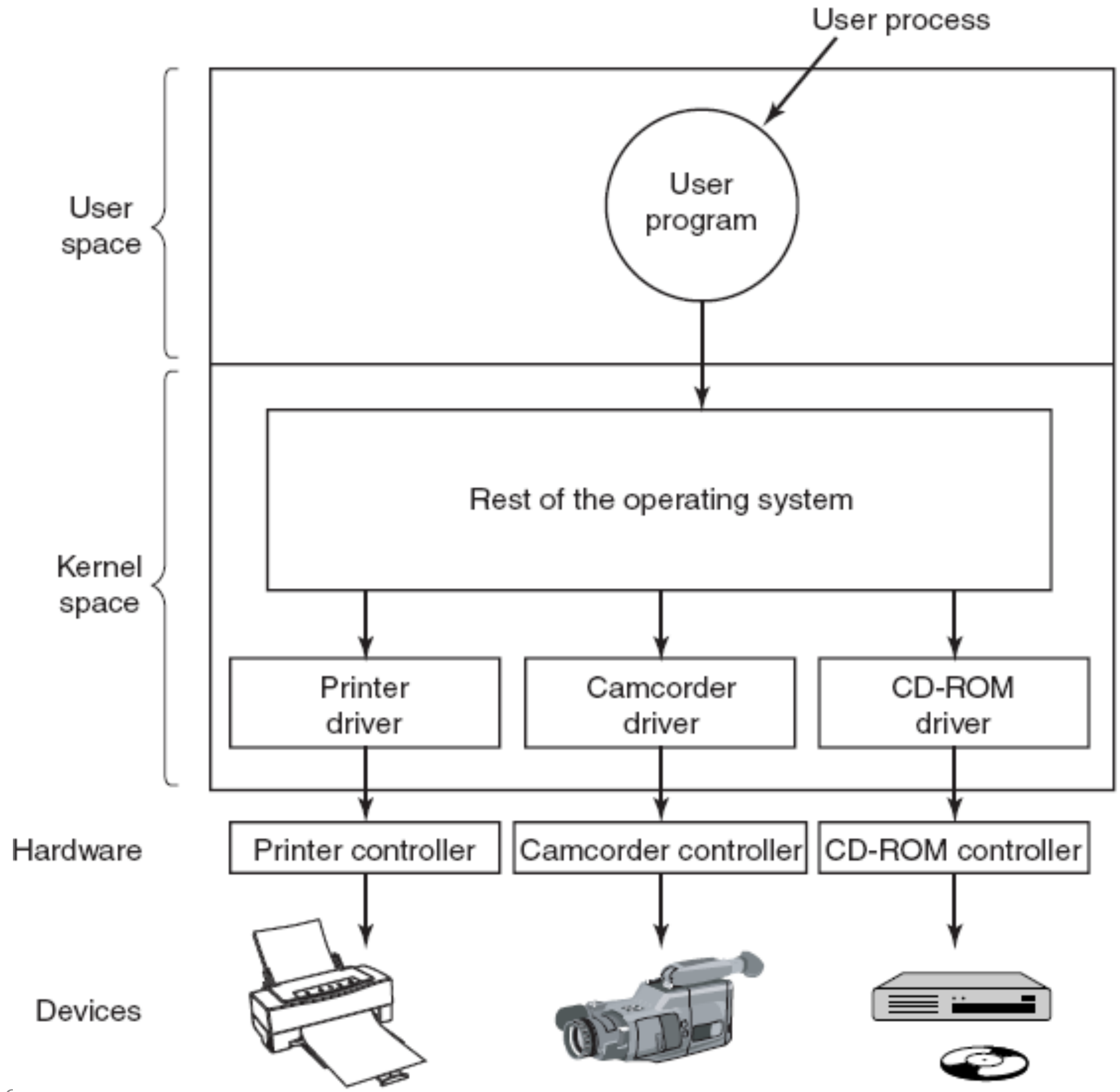
Application I/O Interface

- I/O system calls encapsulate device behaviors in generic classes
- Device-driver layer hides differences among I/O controllers from kernel
- Devices vary in many dimensions
  - Character-stream or block
  - Sequential or random-access
  - Sharable or dedicated
  - Speed of operation
  - read-write, read only, or write only

Device Drivers

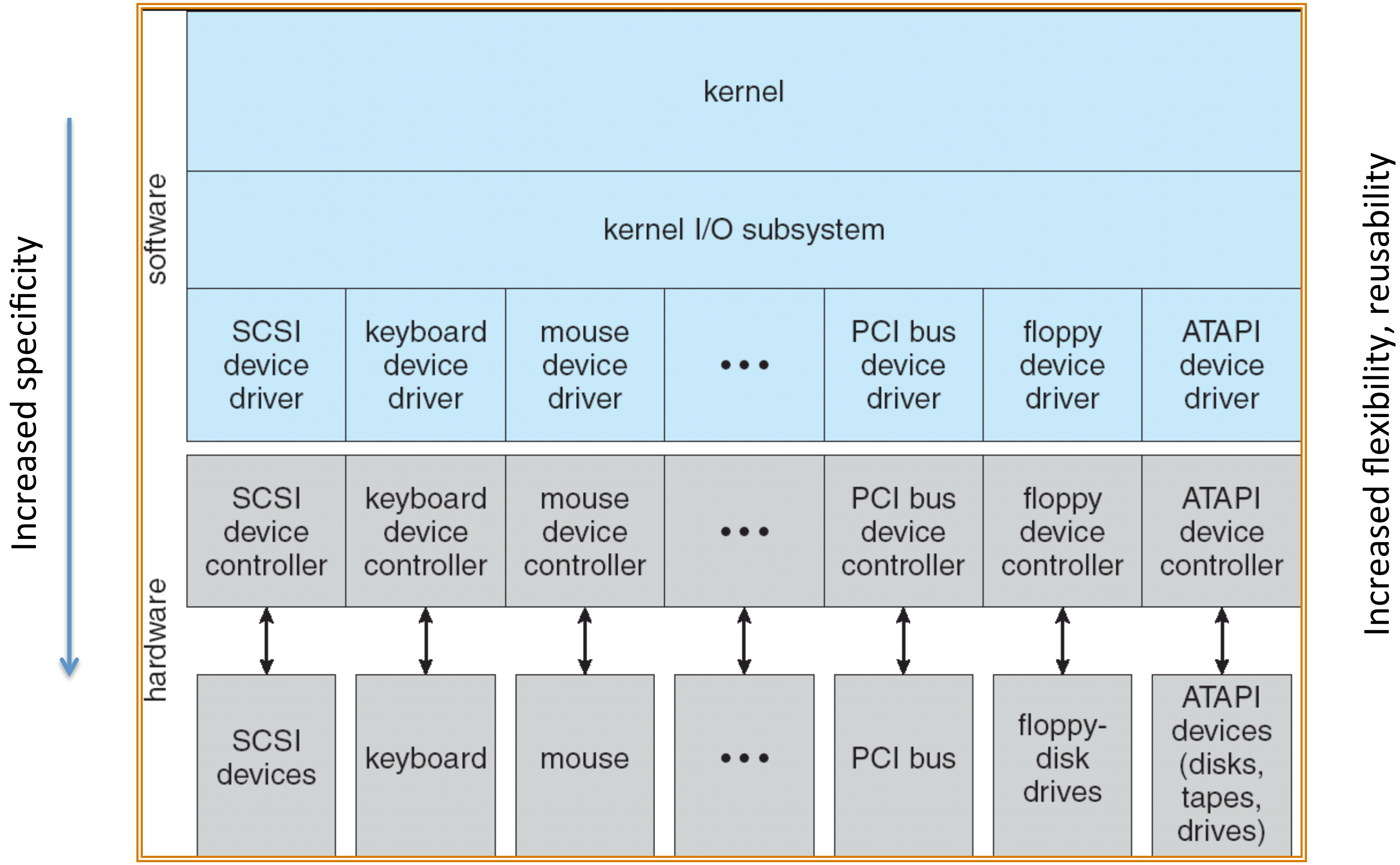
Device-specific code in the kernel that interacts directly with the device hardware

- 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



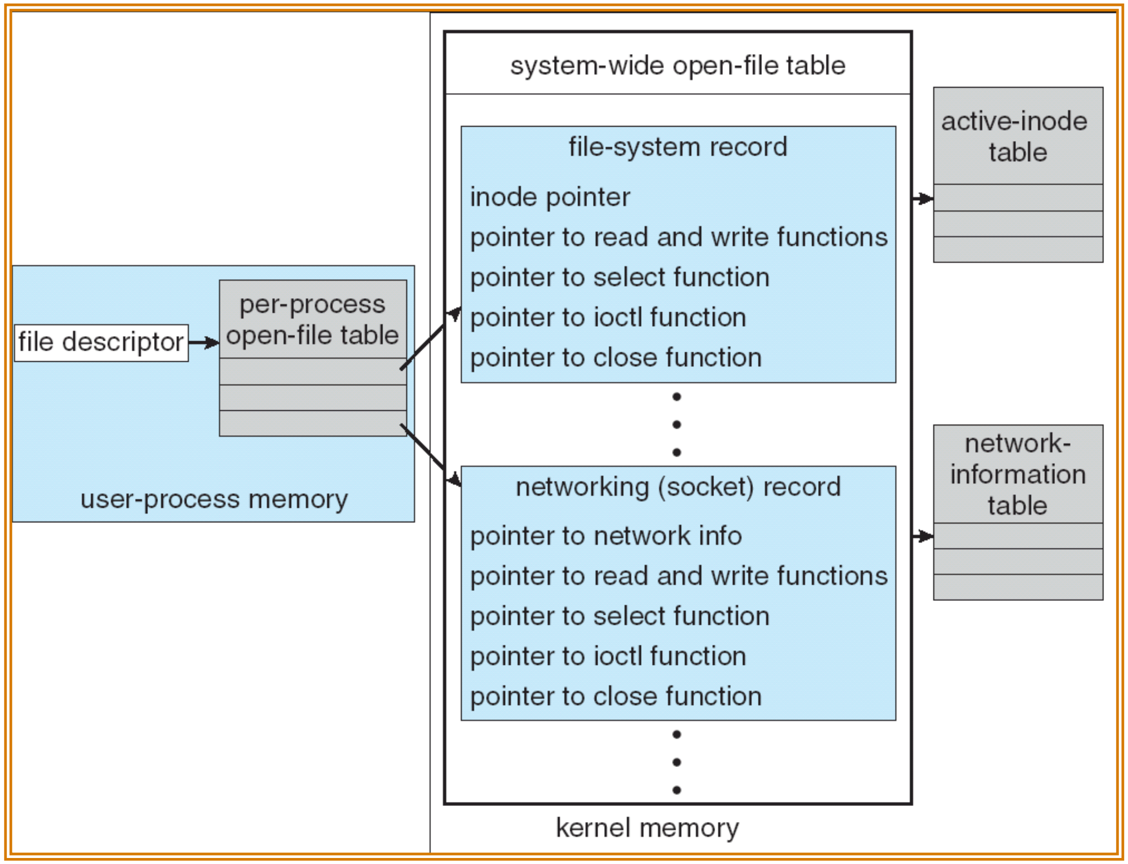
Picture from Tanenbaum, Modern Operating S

A Kernel I/O Structure



UNIX I/O Kernel Structure

Kernel keeps state for I/O components, including open file tables, network connections, character device state



Device Driver Structure

- 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()
    - Implement special VMAs to support mmap() based I/O
    - 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
    - May use deferred processing (softirq, tasklet, kernel threads)

Life Cycle of An I/O Request

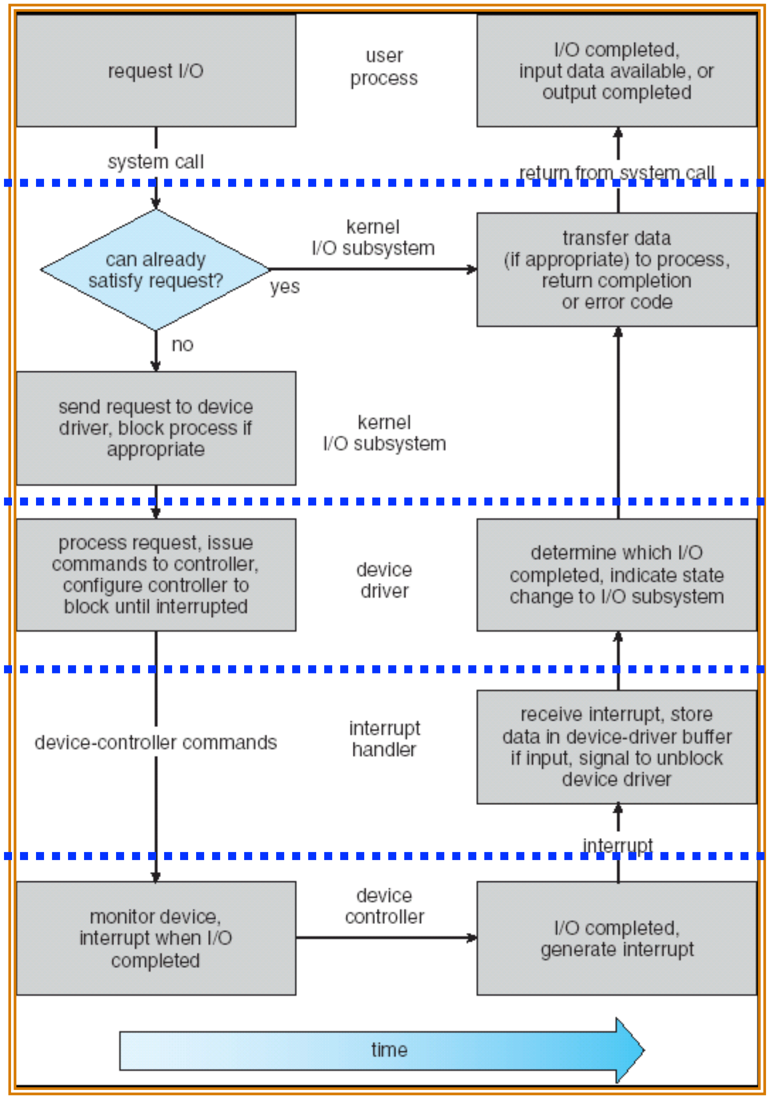
User Program

Kernel I/O or memory Subsystem

Device Driver Top Half

Device Driver Bottom Half

Device Hardware



I/O Subsystem

- Goals
- Architecture
- Device Characteristics
- OS Mechanisms
  - Transferring data
  - Notification
  - Buffering

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

Block and Character Devices

- Block devices include disk drives
  - Commands include read, write, seek
  - Raw I/O or file-system access
  - Memory-mapped file access possible
- Character devices include keyboards, mice, serial ports
  - Single character at a time
  - Commands include get, put
  - Libraries layered on top allow line editing

Network Devices

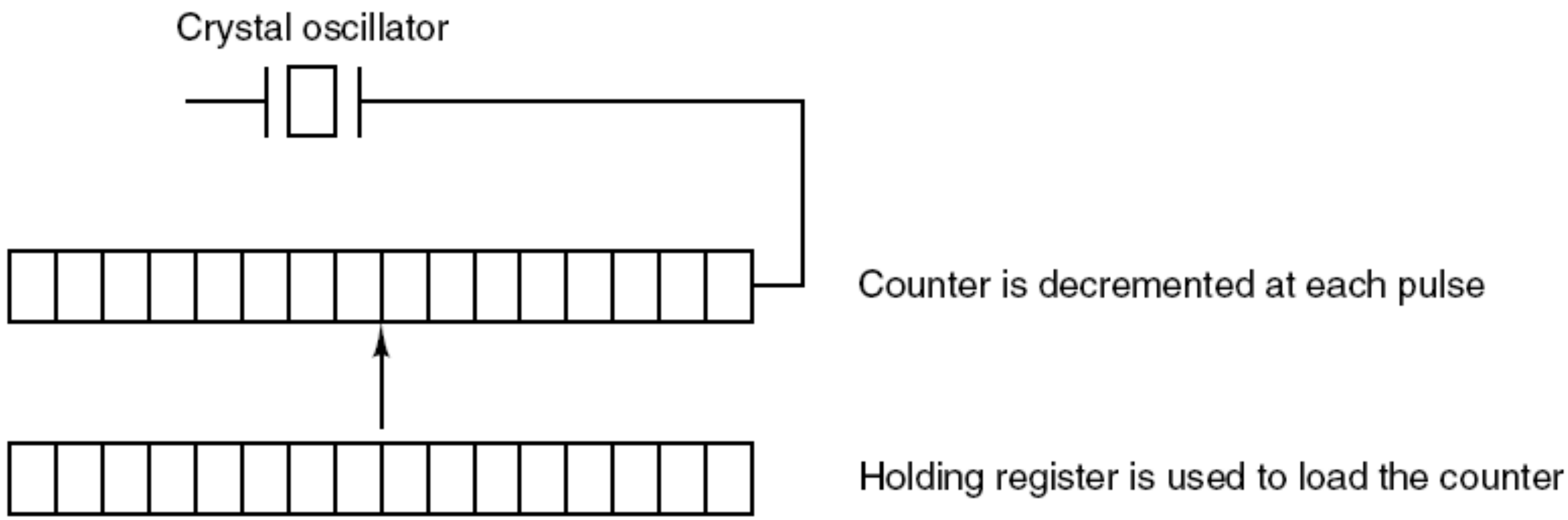
- Different enough from block and character to have own interface
- Unix and Windows NT/9*x*/2000 include socket interface
  - Separates network protocol from network operation
  - Includes select functionality
- Approaches vary widely (pipes, FIFOs, streams, queues, mailboxes)

Clock Devices and Timers

- Maintaining the time of day
- Accounting for CPU usage
- Preventing processes from running longer than they are allowed to
- Handling alarm system call made by user processes
- Providing watchdog timers for parts of the system itself.
- Doing profiling, monitoring, statistics gathering

Clock Hardware

A programmable clock.



I/O Subsystem

- Goals
- Architecture
- Device Characteristics
- OS Mechanisms
  – Transferring data
  – Notification
  – Buffering

Transferring Data to/from Controller

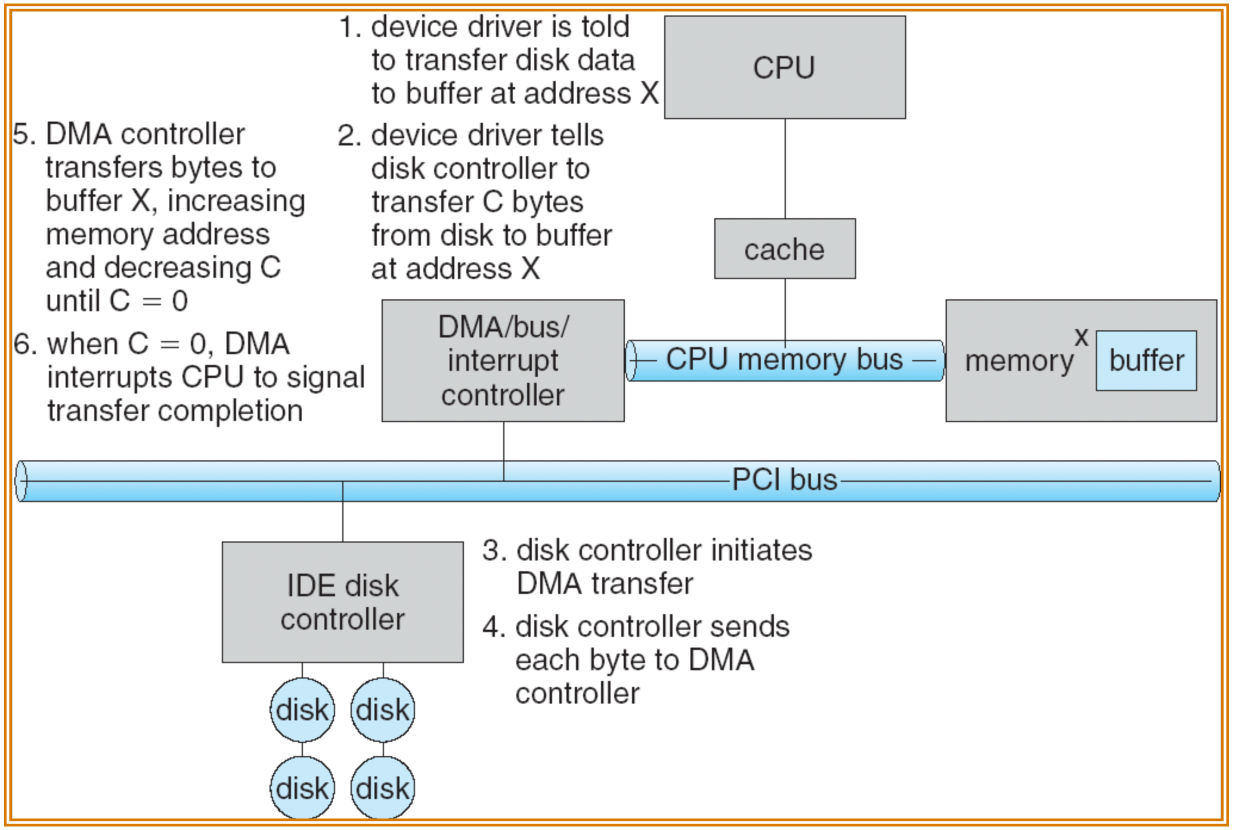
- Programmed I/O:
  - Each byte transferred via processor in/out or load/store
  - Pro: Simple hardware, easy to program
  - Con: Consumes processor cycles proportional to data size
- Direct Memory Access:
  - Give controller access to memory bus
  - Ask it to transfer data to/from memory directly

Programmed I/O

Writing a string to the printer using programmed I/O.

```
copy_from_user(buffer, p, count);                /* p is the kernel buffer */
for (i = 0; i < count; i++) {                    /* loop on every character */
    while (*printer_status_reg != READY) ;       /* loop until ready */
    *printer_data_register = p[i];               /* output one character */
}
return_to_user( );
```

Direct Memory Access (DMA)



- Used to avoid **programmed I/O** for large data movement
- Requires **DMA** controller
- Bypasses CPU to transfer data directly between I/O device and memory

Notifying the OS: Polling

- The OS needs to know when:
  - The I/O device has completed an operation
  - The I/O operation has encountered an error
- One way is to ***Poll***:
  - OS periodically checks a device-specific status register
  - I/O device puts completion information in status register
  - **Busy-wait** cycle to wait for I/O from device
  - Pro: simple, potentially low overhead
  - Con: may waste many cycles on polling if infrequent, expensive, or unpredictable I/O operations

Notifying the OS: Interrupts

- I/O Interrupt:
  - Device generates an interrupt whenever it needs service
  - Pro: handles unpredictable events well
  - Con: interrupts relatively high overhead
- Some devices combine ***both*** polling and interrupts
  - Example: Intel E1000 Gigabit Ethernet Adapter:
    - Interrupt for first incoming packet
    - Poll for subsequent packets until hardware packet arrival queue is empty

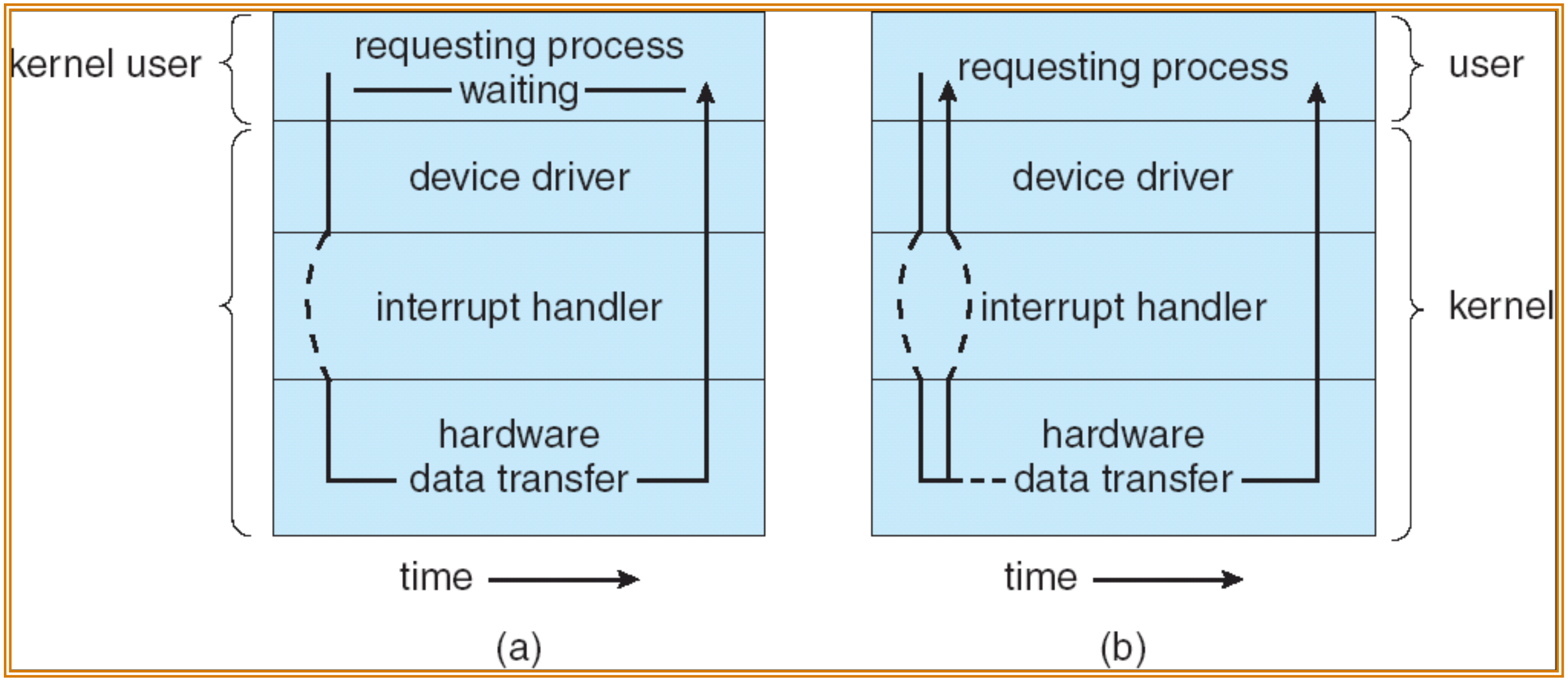
I/O Performance

- 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 performance:
  - Use DMA
  - Reduce/eliminate data copying
  - Reduce number of context switches
  - Reduce interrupts by using large transfers, smart controllers, polling

Blocking and Nonblocking I/O

- Blocking Interface: "Wait"
  - Put process to sleep until data is ready (for read) or written (for write)
- 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

Asynchronous I/O



Synchronous

Asynchronous

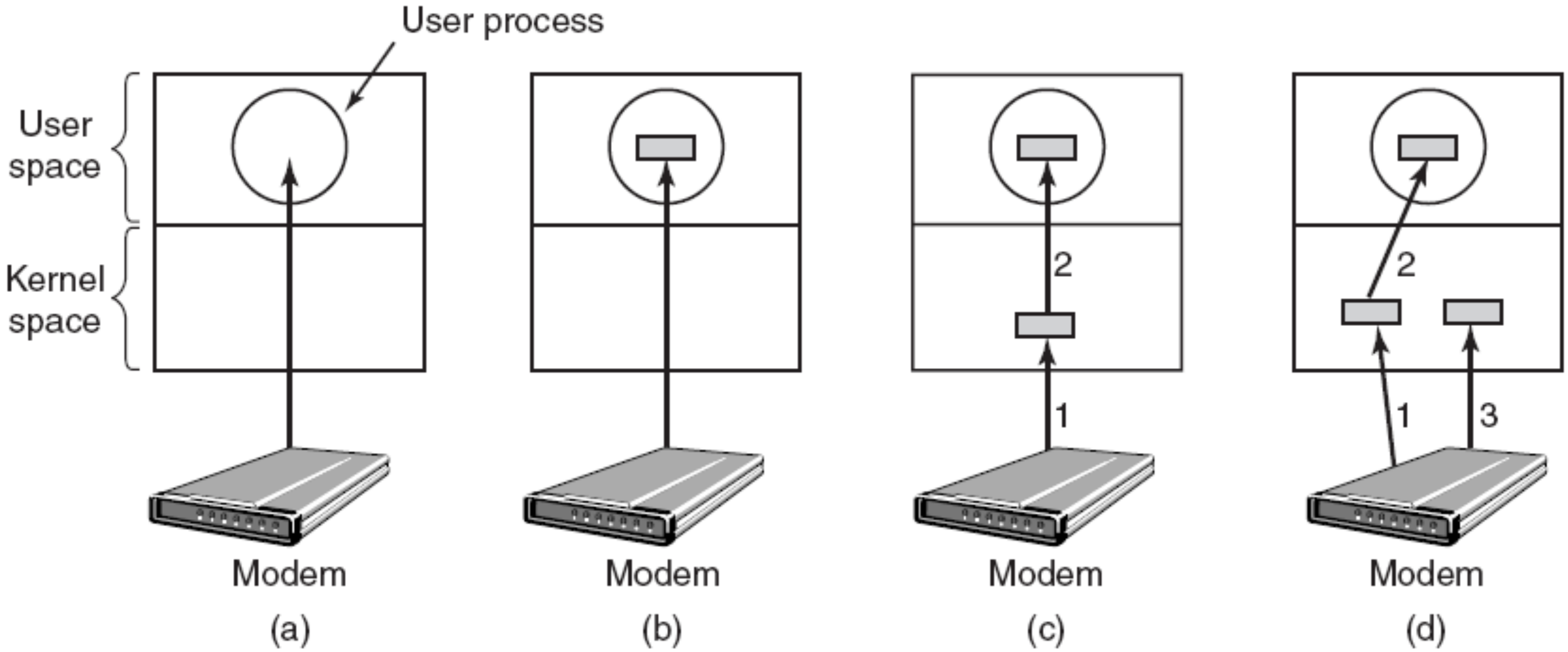
Kernel I/O Subsystem

- Common Interfaces for
  - **Device reservation** - exclusive access to a device
    - System calls for allocation and deallocation
    - Watch out for deadlock
  - **Caching** - fast memory holding copy of data
    - Always just a copy
    - Key to performance
  - **Scheduling** – I/O request reordering
    - Via per-device queue, goal: fairness
  - **Spooling** - hold a copy of output for a device
    - If device can serve one request at a time, e.g., printing

Buffering

- 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"

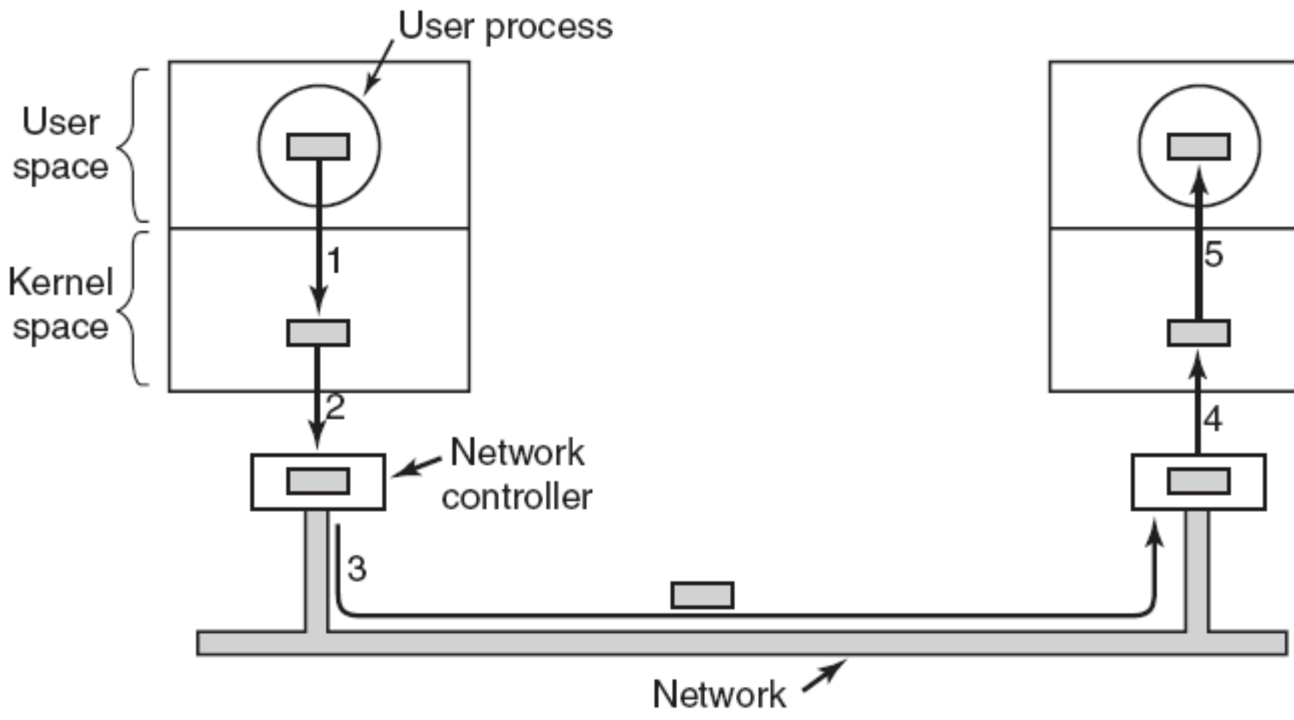
Buffering



- Unbuffered input
- Buffering in user space
- Buffering in the kernel followed by copying to user space
- Double buffering in the kernel.

Buffering

Networking may involve many copies of a packet. May reduce performance.



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

Interaction of I/O and VM

- The kernel deals with (kernel) virtual addresses
- These do not necessarily correspond to physical addresses
- Contiguous virtual addresses are probably not contiguous in physical memory
- Some systems have an I/O map — the I/O bus manager has a (version of) the virtual memory map
- More often, the kernel has to translate the virtual addresses itself

Other I/O Issues

- Scatter/Gather I/O
  - Suppose we're reading a single packet or disk block into two or more non-contiguous pages
  - The I/O transfer has to use more than one (address, length) pair for that transfer to scatter the data around memory
  - The same applies on output, where it has to be gathered from different physical pages

- Direct I/O
  - For efficiency, we may want to avoid copying data to/from user space
  - Sometimes possible to do direct I/O
  - Must consult user virtual memory map for translation
  - Must lock pages in physical memory during I/O

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