I/O Systems

Yajin Zhou (http://yajin.org)

Zhejiang University

Acknowledgement: some pages are based on the slides from Zhi Wang(fsu).

Review

- Disk: platter, cylinder, sector, track
- Time: positioning time = seek time + rotational latency
- SSD: read/write in page, but cannot overwrite in place
  - Flash translation layer, gc, over-provisioning area
- Disk structure, Disk attachment: host- ,network-, storage area network
- Disk scheduling: CFS, SSTF, SCAN, C-SCAN, C-LOOK
- Disk management: physical formatting, partition disk, logical formatting
- RAID: redundant array of inexpensive disk
  - RAID 0: split, RAID 1: mirror, RAID4/RAID 5/RAID 6: block with parity
- ZFS

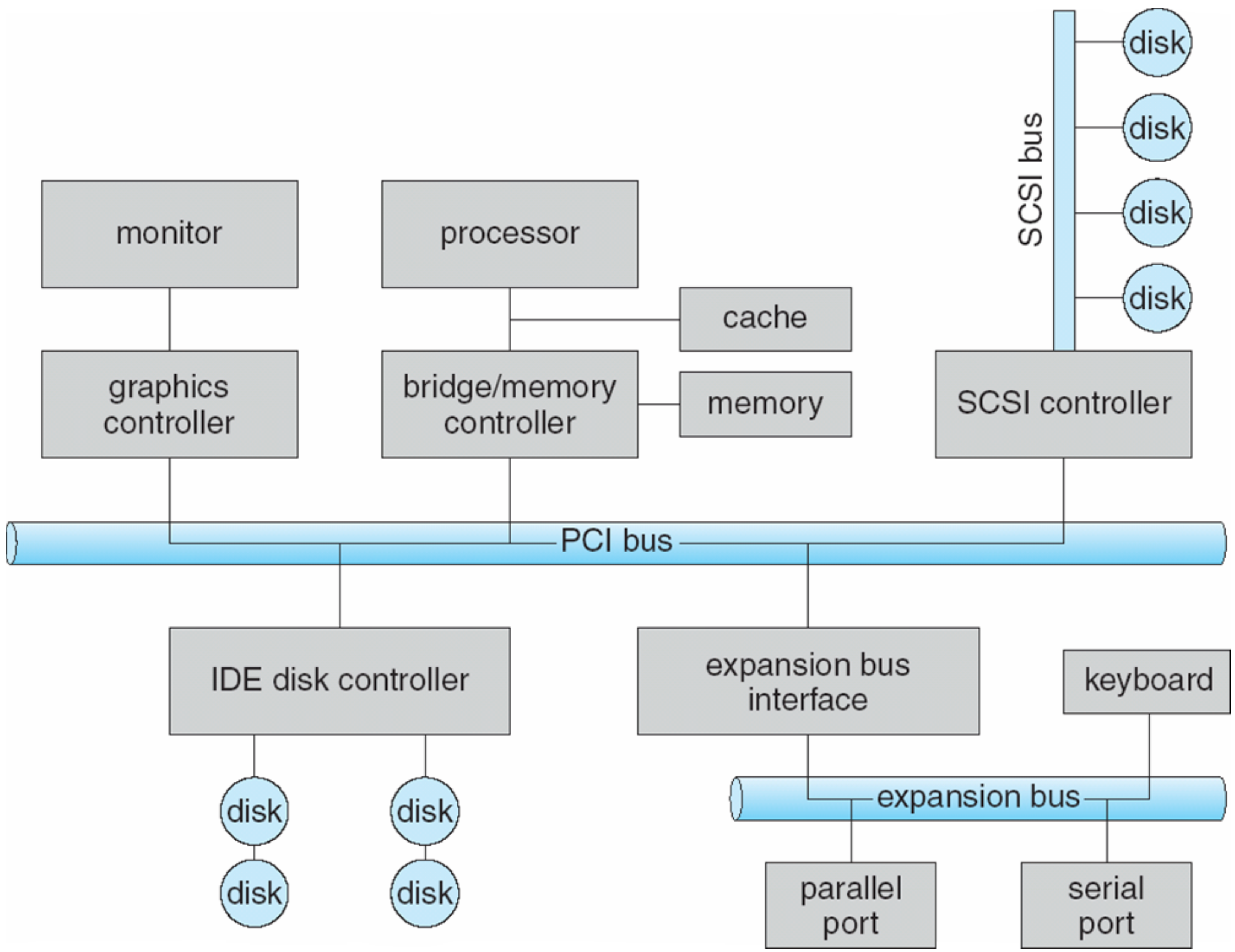
Overview

- I/O management is a major component of OS design and operation
  - important aspect of computer operation
    - I/O devices is the way computer to interact with user and other systems
  - I/O devices vary greatly
    - various methods to control them
    - performance varies
    - device drivers encapsulate device details; presents an uniform interface
  - new types of devices frequently emerges

I/O Hardware

- Incredible variety of I/O devices
  - storage, communication, human-interface
- Common concepts: signals from I/O devices interface with computer
  - **bus**: an interconnection between components (including CPU)
  - **port**: connection point for device
  - **controller**: component that control the device
    - can be integrated to device or separate circuit board
    - usually contains processor, microcode, private memory, bus controller, etc
- I/O access can use **polling** or **interrupt**

A Typical PC Bus Structure



I/O Hardware

- Some CPU architecture has **dedicated I/O instructions**
  - e.g., x86: in, out, ins, outs
- Devices usually provide registers for data and control I/O of device
  - device driver places (pointers to) commands and data to register
  - registers include **data-in**/**data-out**, **status**, **control** (or command) register
  - typically 1-4 bytes, or FIFO buffer
- Devices are assigned addresses for registers or on-device memory
  - **direct I/O instructions**
    - to access (mostly) registers
  - **memory-mapped I/O**
    - data and command registers mapped to processor address space
    - to access (large) on-device memory (graphics)

I/O Ports 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)

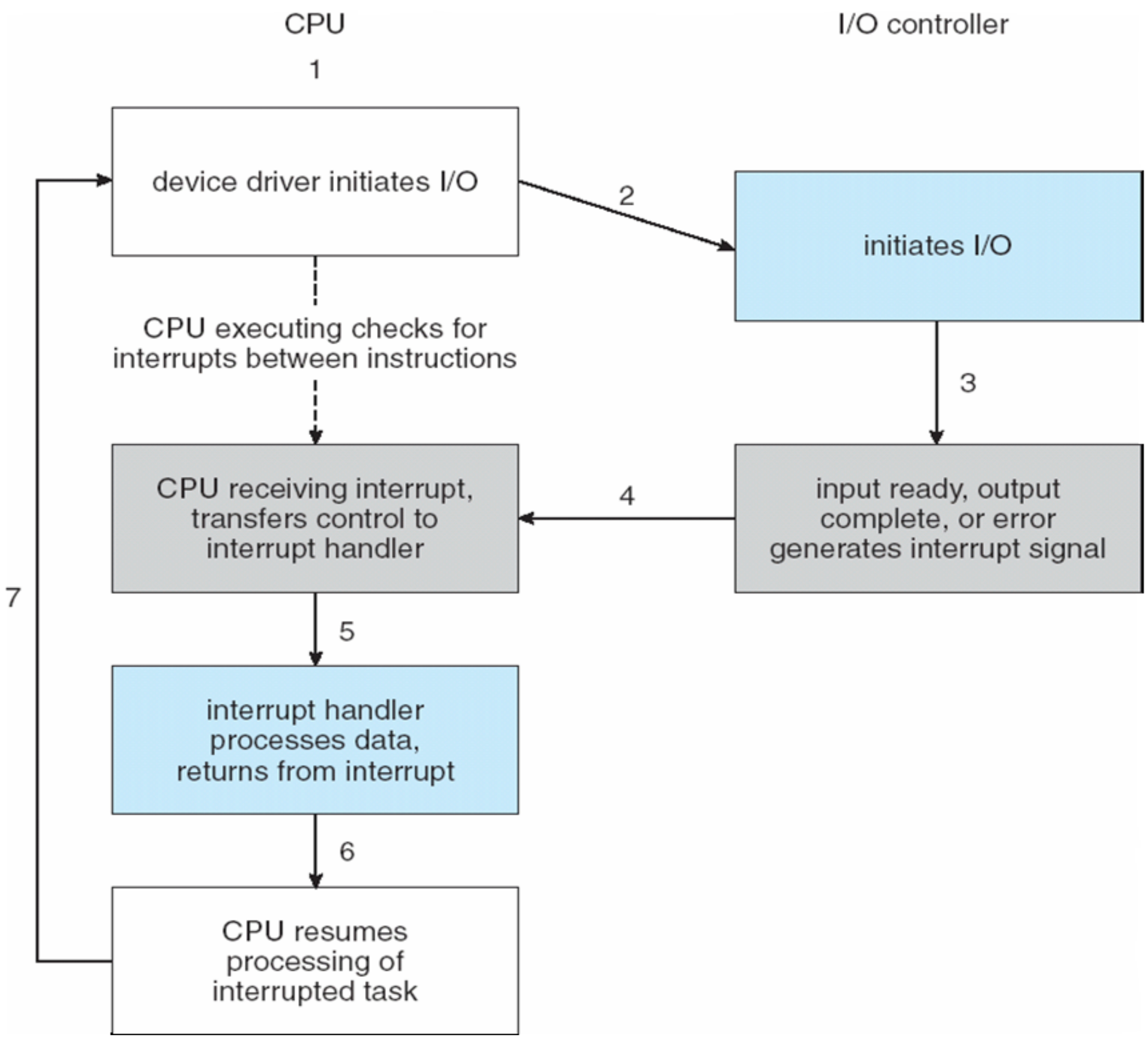
Polling

- For each I/O operation:
  - busy-wait if device is busy (status register)
  - send the command to the device controller (command register)
  - read status register until it indicates command has been executed
  - read execution status, and possibly reset device status
- Polling requires busy wait
  - reasonable if device is fast; inefficient if device slow

Interrupts

- Polling requires **busy-wait**, inefficient use of CPU resource
- Interrupts can avoid busy-wait
  - device driver send a command to the controller, and return
  - OS can schedule other activities
  - device will interrupt the processor when command has been executed
  - OS retrieves the result by handling the interrupt
- Interrupt-based I/O requires **context switch** at start and end
  - if interrupt frequency is extremely high, context switch wastes CPU time
  - solution: use polling instead
    - example: **NAPI** in Linux enables polling under very high network load

Interrupt-Driven I/O Cycle



Intel Pentium Interrupt Vector Table

vector number	description
0	divide error
1	debug exception
2	null interrupt
3	breakpoint
4	INTO-detected overflow
5	bound range exception
6	invalid opcode
7	device not available
8	double fault
9	coprocessor segment overrun (reserved)
10	invalid task state segment
11	segment not present
12	stack fault
13	general protection
14	page fault
15	(Intel reserved, do not use)
16	floating-point error
17	alignment check
18	machine check
19–31	(Intel reserved, do not use)
32–255	maskable interrupts

Interrupts

- Interrupt is also used for exceptions
  - **protection error** for access violation
  - **page fault** for memory access error
  - software interrupt for **system calls**
- Multi-CPU systems can process interrupts concurrently
  - sometimes a CPU may be dedicated to handle interrupts
  - interrupts can also have **CPU affinity**

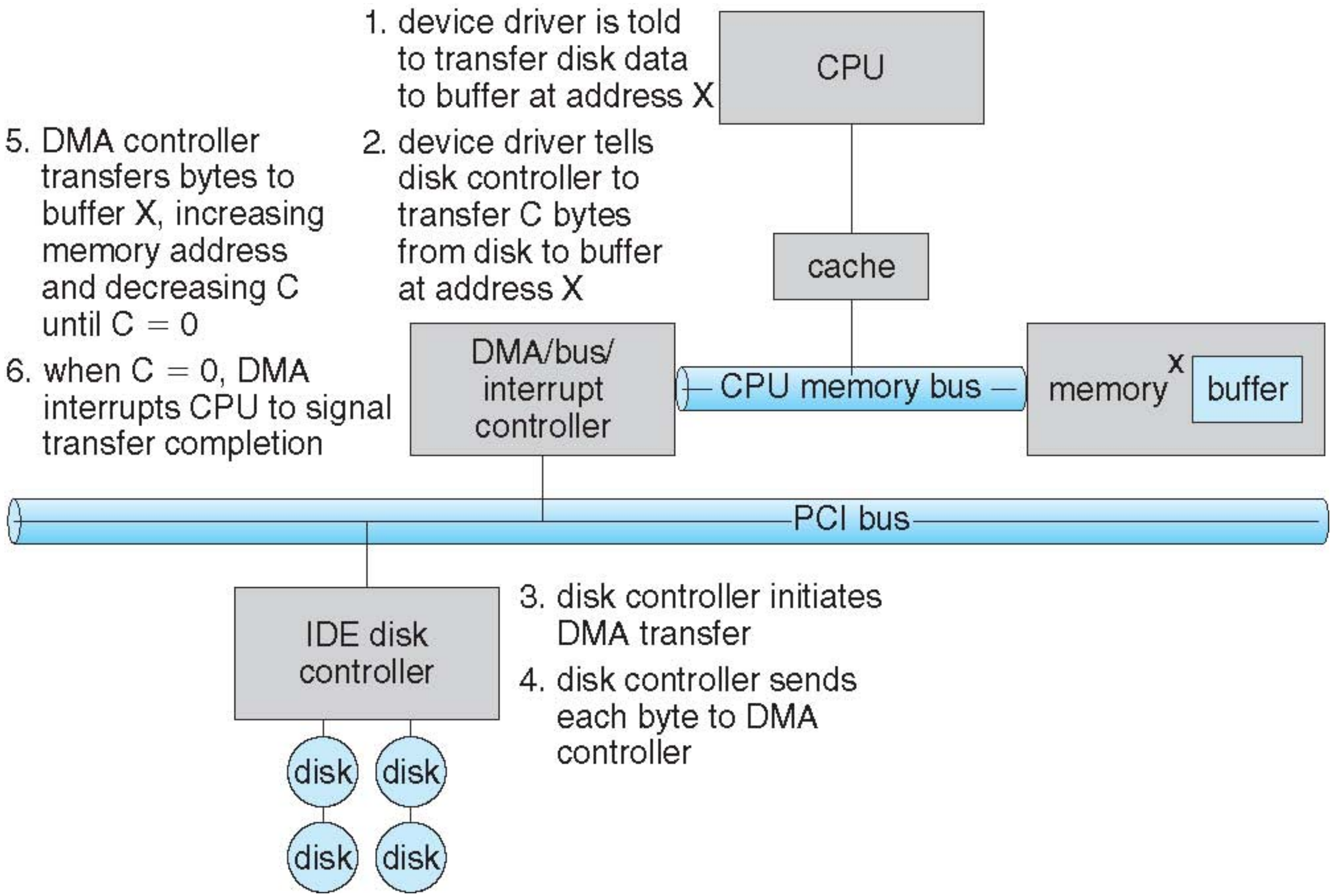
SMP IRQ Affinity

- Starting with the 2.4 kernel, Linux has gained the ability to assign certain IRQs to specific processors (or groups of processors). This is known as SMP IRQ affinity, and it allows you control how your system will respond to various hardware events. It allows you to restrict or repartition the work load that you server must do so that it can more efficiently do it's job.
  - "balance" out multiple NICs in a multi-processor machine. By tying a single NIC to a single CPU, you should be able to scale the amount of traffic your server can handle nicely.
  - database servers (or servers with lots of disk storage) that also have heavy network loads can dedicate a CPU to their disk controller and assign another to deal with the NIC to help improve response times.

Direct Memory Access

- DMA transfer data directly between I/O device and memory
  - OS only need to issue commands, data transfers bypass the CPU
  - no programmed I/O (one byte at a time), data transferred in large blocks
  - it requires DMA controller in the device or system
- OS issues commands to the DMA controller
  - a command includes: operation, memory address for data, count of bytes…
  - usually it is the pointer of the command written into the command register
  - when done, device interrupts CPU to signal completion

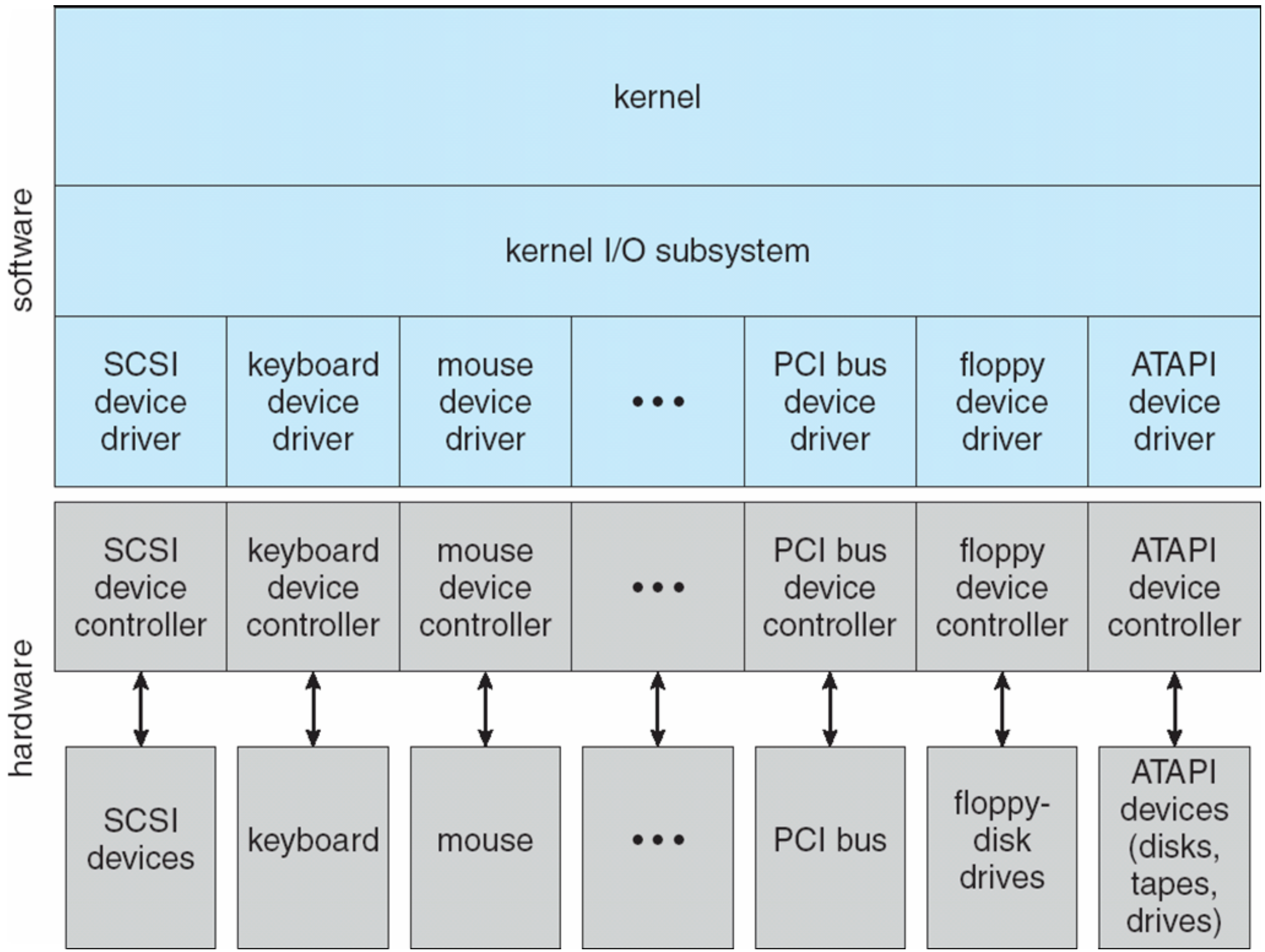
Six Steps of DMA Transfer



Application I/O Interface

- I/O system calls encapsulate device behaviors in generic classes
  - in Linux, devices can be accessed **as files**; low-level **access with ioctl**
- Device-driver layer hides differences among I/O controllers from kernel
  - each OS has its own I/O subsystem and device driver frameworks
  - new devices talking already-implemented protocols need no extra work

Kernel I/O Structure



Characteristics of I/O Devices

- 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

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

Characteristics of I/O Devices

- Broadly, I/O devices can be grouped by the OS into
  - **block I/O: read, write, seek**
  - **character I/O** (Stream)
  - **memory-mapped file access**
  - **network sockets**
- Direct manipulation of I/O device usually an escape / back door
  - Linux's **ioctl** call to send commands to a device driver

Block and Character Devices

- Block devices access data in blocks, such as disk drives…
  - commands include **read, write, seek**
  - raw I/O, direct I/O, or file-system access
  - memory-mapped file access possible (e.g., memory-mapped files)
  - DMA
- Character devices include keyboards, mice, serial ports…
  - very diverse types of devices

Network Devices

- Varying enough from block and character to have own interface
  - very different from pipe, mailbox…
- Popular interface for network access is the **socket** interface
  - it separates network protocol from detailed network operation
  - some non-network operations are implemented as sockets
    - e.g., Unix socket

Clocks and Timers

- Clocks and timers can be considered as character devices
  - very important devices as they provide current time, elapsed time, timer
- Normal resolution about 1/60 second, some OS provides higher-resolution ones

Synchronous/Asynchronous I/O

- **Synchronous I/O** includes blocking and non-blocking I/O
  - **blocking I/O**: process suspended until I/O completed
    - easy to use and understand, but may be less efficient
    - insufficient for some needs
  - **non-blocking I/O**: I/O calls return **as much data as available**
    - process does not block, returns whatever existing data (read or write)
    - use select to find if data is ready, then use read or write to transfer data
- **Asynchronous I/O**: process runs while I/O executes,
  - I/O subsystem signals process when I/O completed via signal or callback
  - difficult to use but very efficient

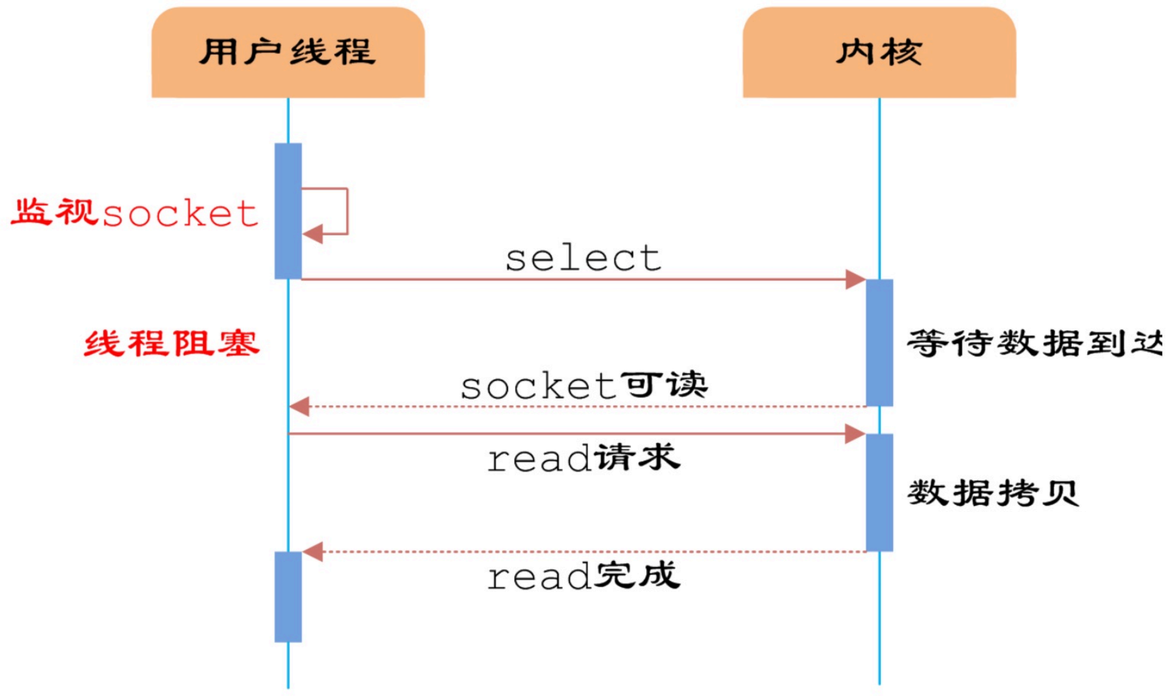
select()

- Blocking

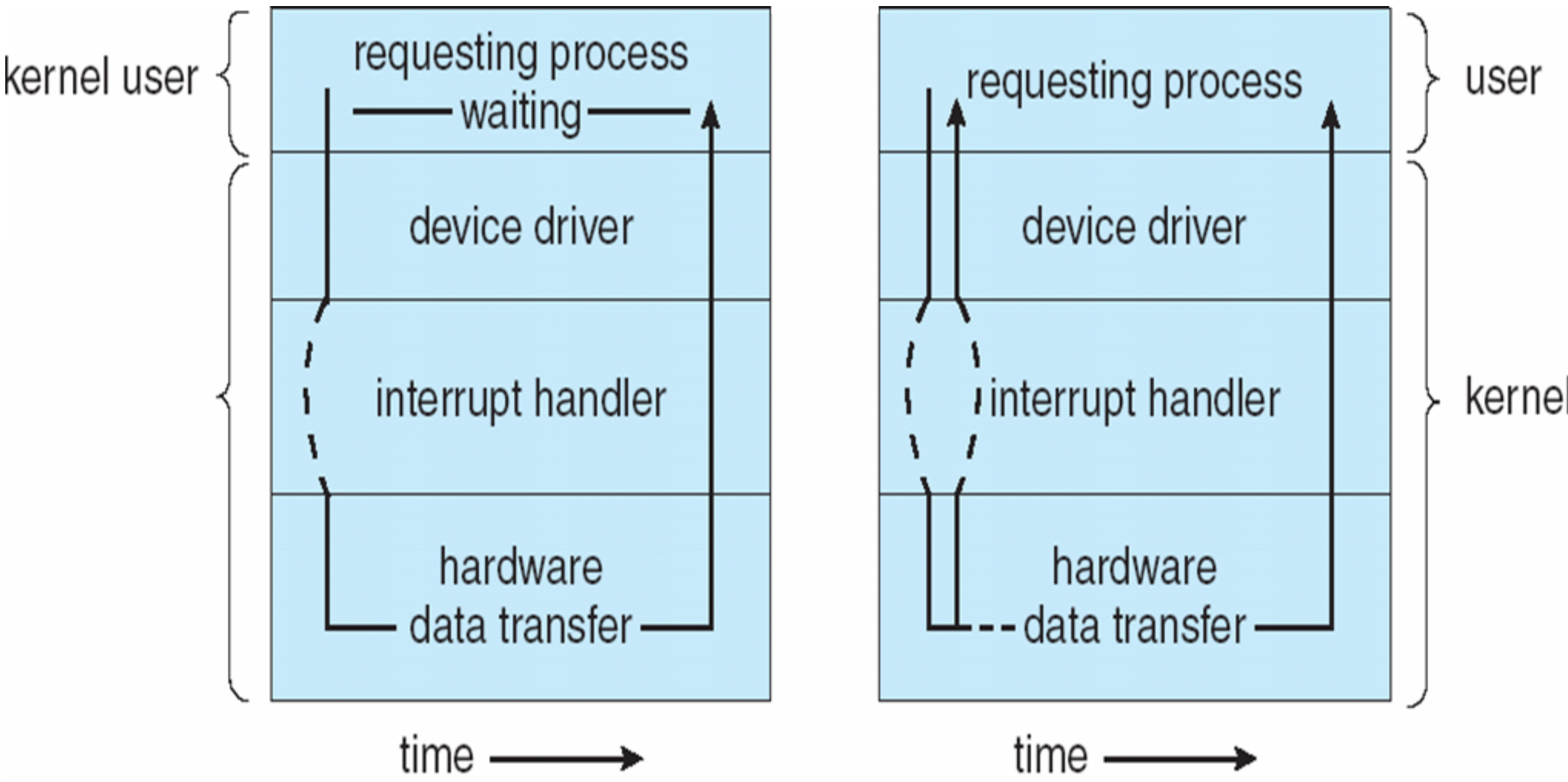
```
int iResult = recv(s, buffer,1024);
```

- Nonblocking

```
int iResult = ioctlsocket(s, FIOBIO, (unsigned long *)&ul);
iResult = recv(s, buffer,1024);
```



Two I/O Methods



(a)
synchronous

(b)
asynchronous

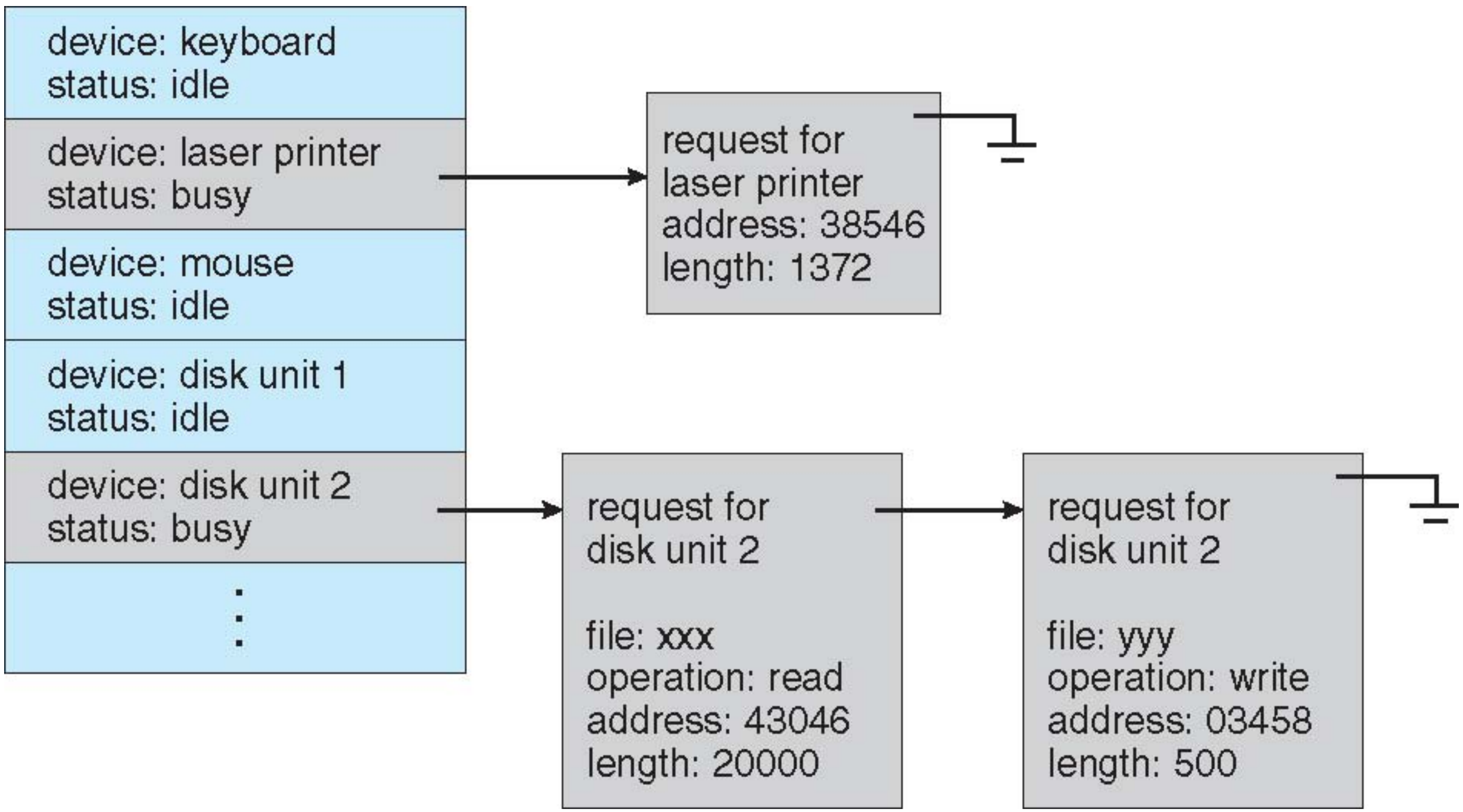
Kernel I/O Subsystem

- **I/O scheduling**
  - to queue I/O requests via per-device queue
  - to schedule I/O for fairness and quality of service
- **Buffering** - store data in memory while transferring between devices
  - to cope with device speed mismatch: receive from network and write to ssd, double buffering
  - to cope with device transfer size mismatch: network buffer reassembly of message
  - to maintain “copy semantics”: write()

Kernel I/O Subsystem

- **Caching**: hold **a copy of data for fast access**
  - key to performance
  - sometimes combined with buffering
    - Buffer in memory is also used as caching for file operations
- **Spooling**: hold output 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

Device-status Table



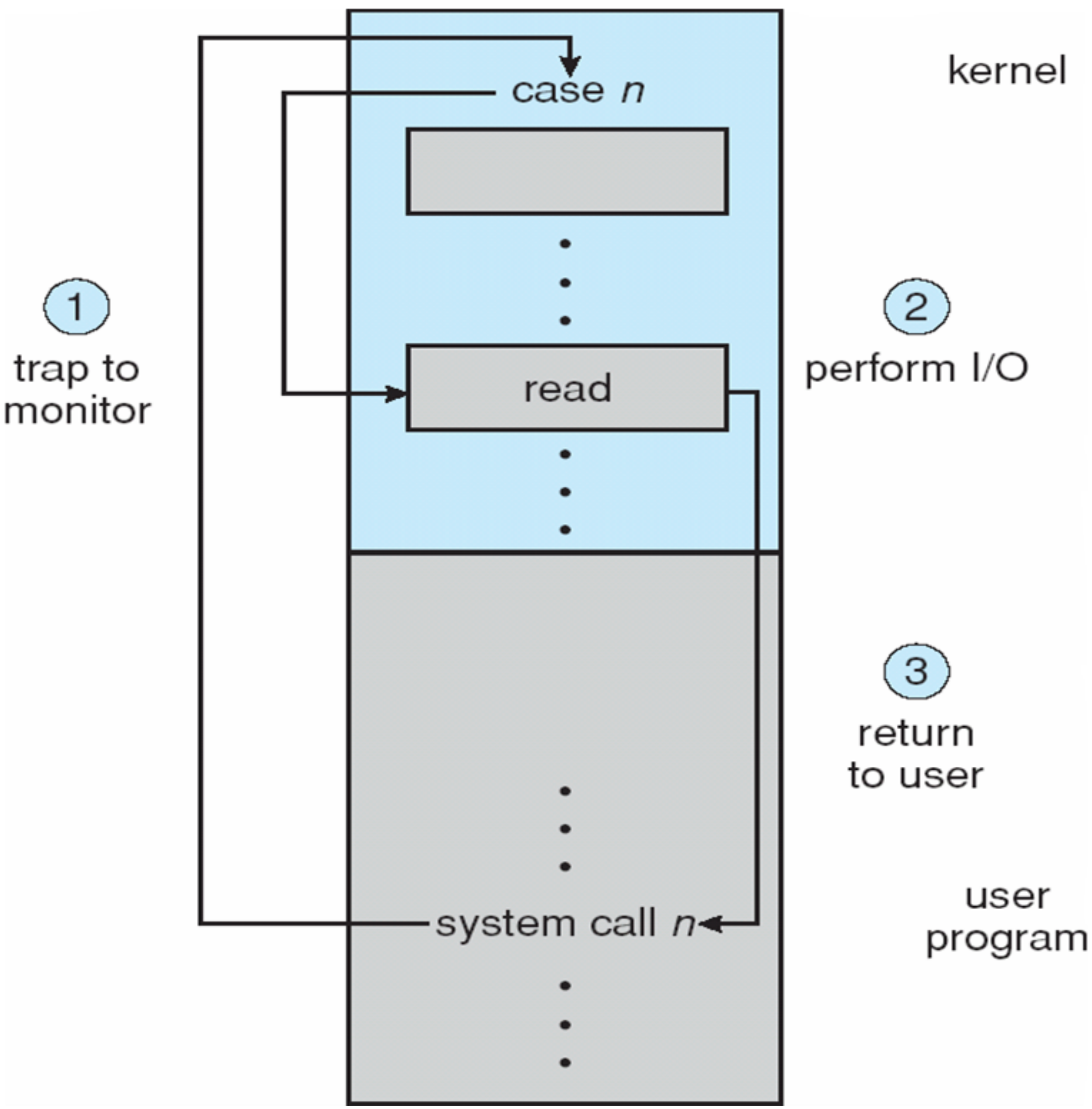
Error Handling

- Some OSes try to recover from errors
    - e.g., device unavailable, transient write failures
    - sometimes via retrying the read or write
    - some systems have more advanced error handling
        - track error frequencies, stop using device with high error frequency
- Some OSes just return an error number or code when I/O request fails
    - system error logs hold problem reports

I/O Protection

- OS need to protect I/O devices
  - e.g., keystrokes can be stolen by a **keylogger** if keyboard is not protected
  - always assume user may attempt to obtain illegal I/O access
- To protect I/O devices:
  - define all I/O instructions to be privileged
    - I/O must be performed via system calls
  - memory-mapped I/O and I/O ports must be protected too

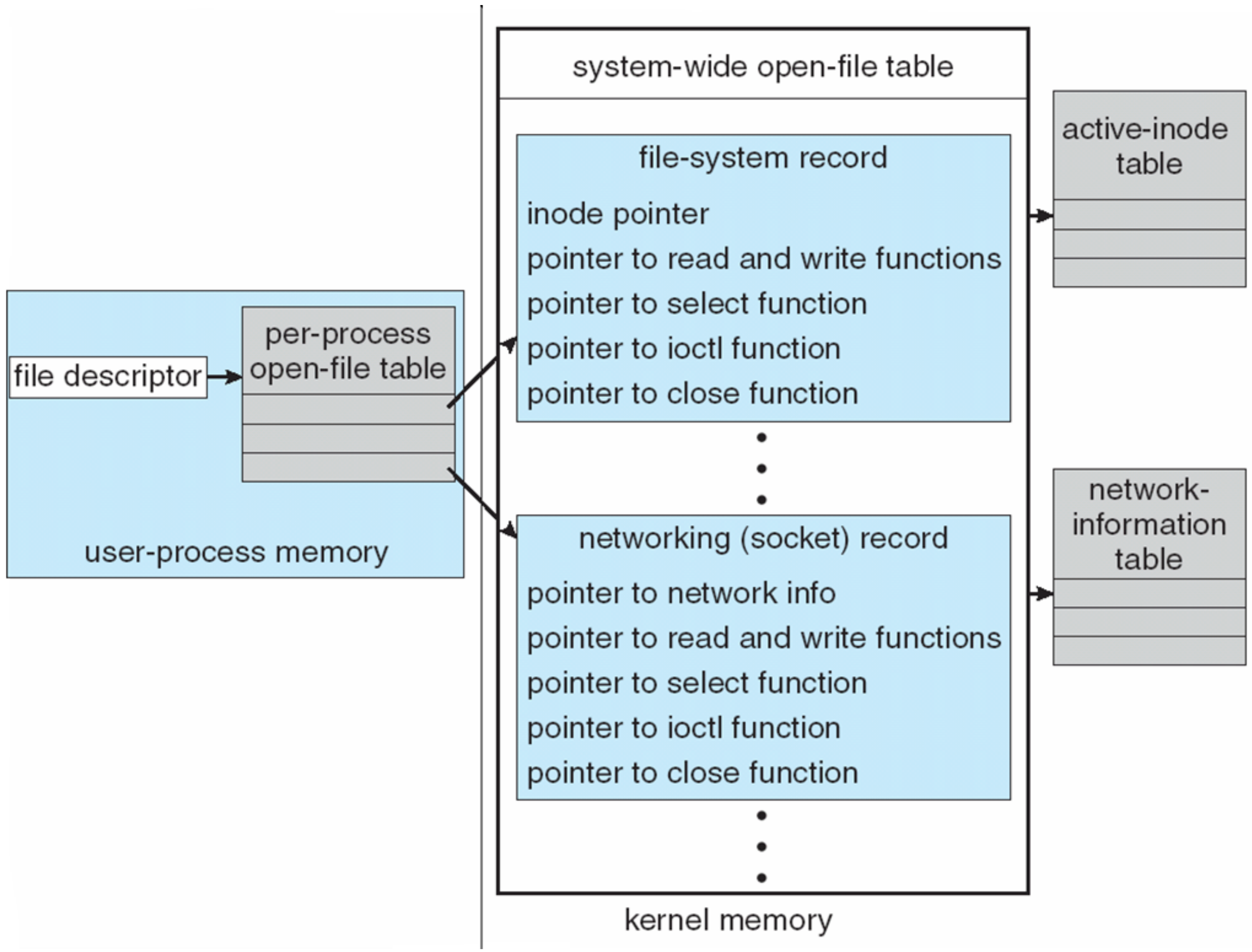
Use System Call to Perform I/O



Kernel Data Structures

- Kernel keeps state info for I/O components
  - e.g., open file tables, network connections, character device state
  - many data structures to track buffers, memory allocation, “dirty” blocks
    - sometimes very complicated
- Some OS uses message passing to implement I/O, e.g., Windows
  - message with I/O information passed from user mode into kernel
  - message modified as it flows through to device driver and back to process

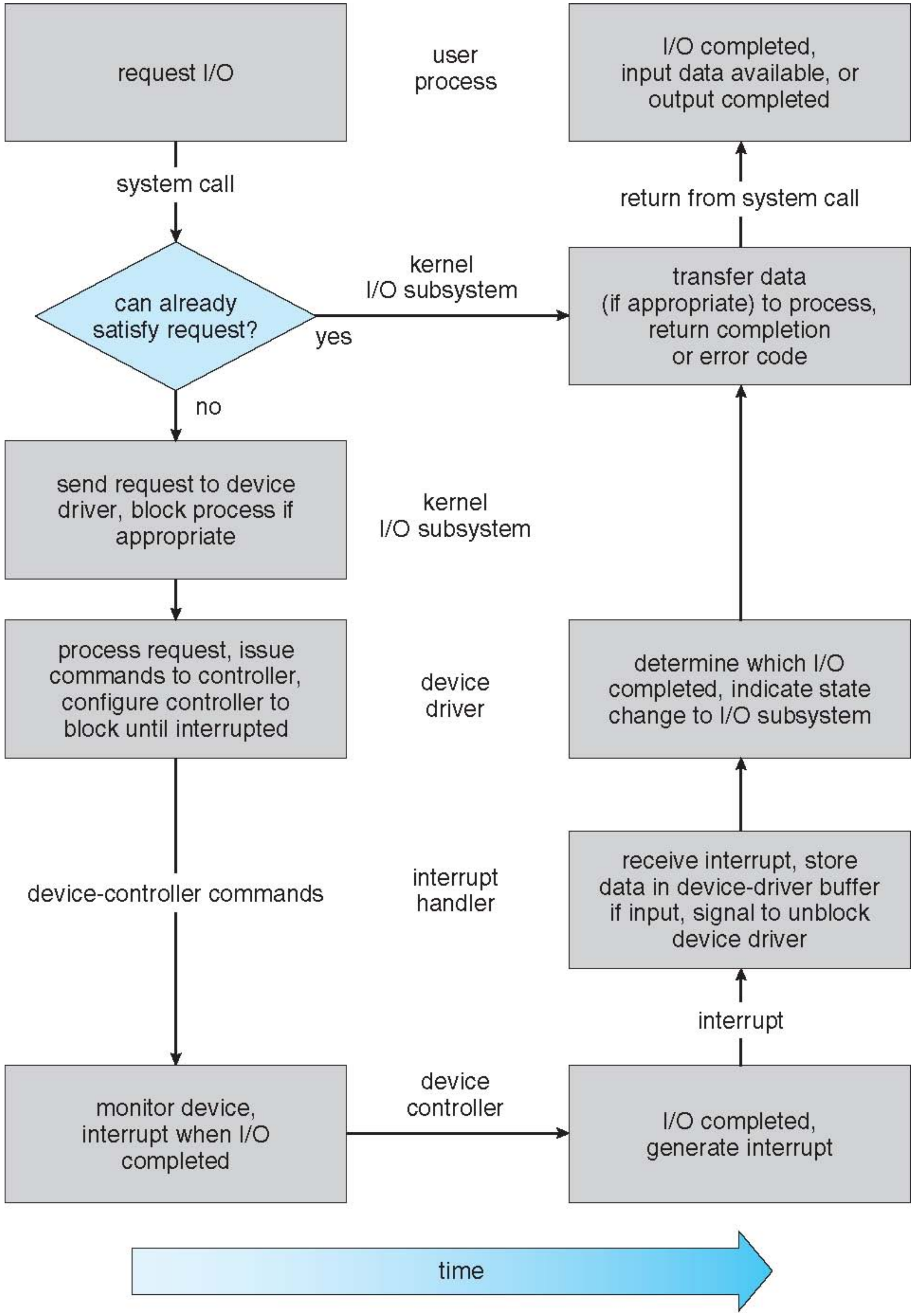
UNIX I/O Kernel Structure



I/O Requests to Hardware

- **System resource** access needs to be mapped to hardware
- Consider reading a file from disk for a process:
  - determine device holding file
  - translate name to **device representation**
    - FAT, UNIX: major/minor
  - physically read data from disk into buffer
  - make data available to requesting process
  - return control to process

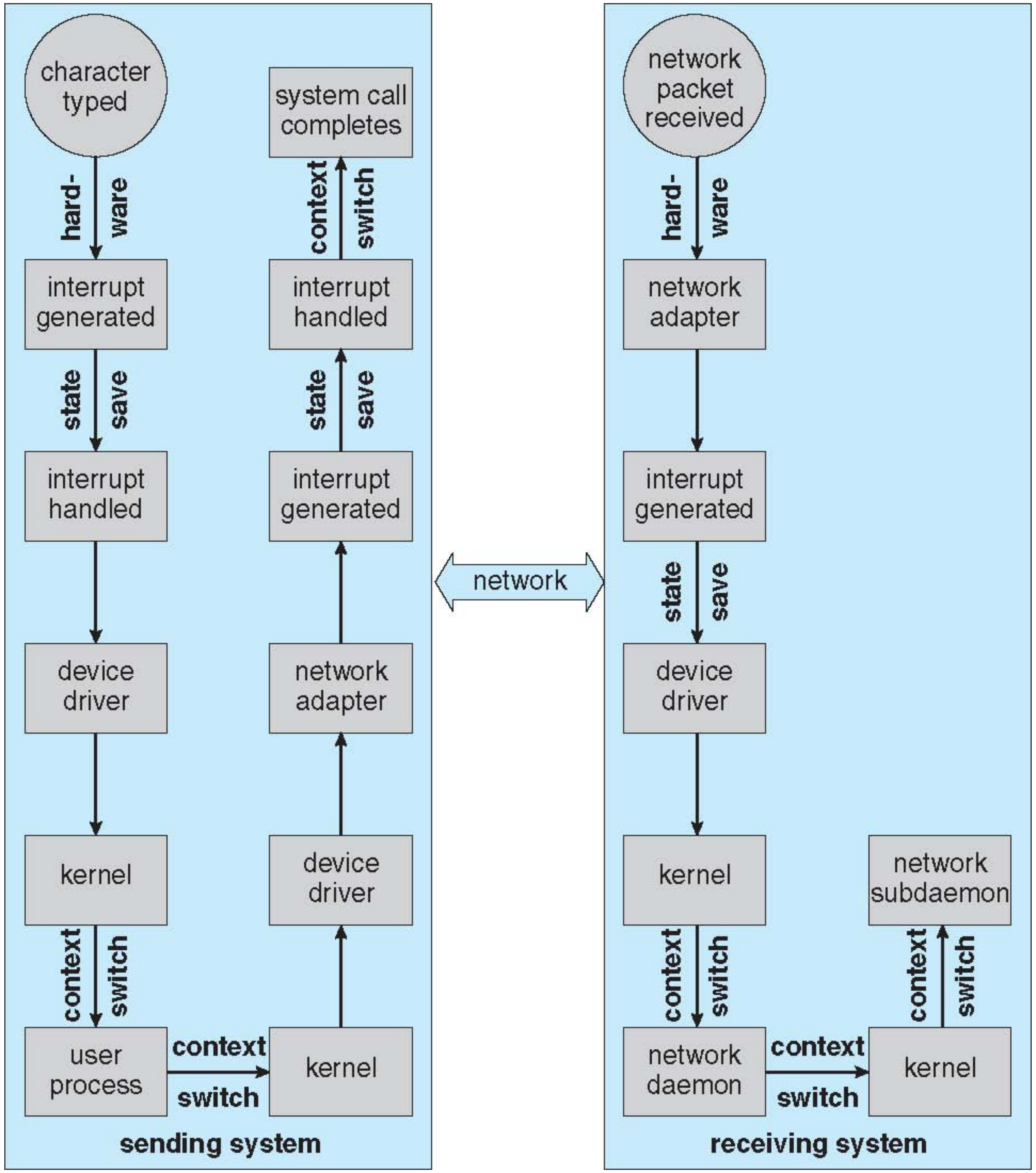
Life Cycle of An I/O Request



Performance

- I/O is a major factor in system performance:
  - CPU to execute device driver, kernel I/O code
  - context switches due to interrupts
  - data buffering and copying
    - network traffic especially stressful

Network Communications: high context switch



Improve 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