Chapter 13: I/O Systems

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- I/O Hardware
- Application I/O Interface
- Kernel I/O Subsystem
- Transforming I/O Requests to Hardware Operations
- Performance

Objectives

- Explore the structure of an operating system's I/O subsystem
- Discuss the principles of I/O hardware and its complexity
- Provide details of the performance aspects of I/O hardware and software

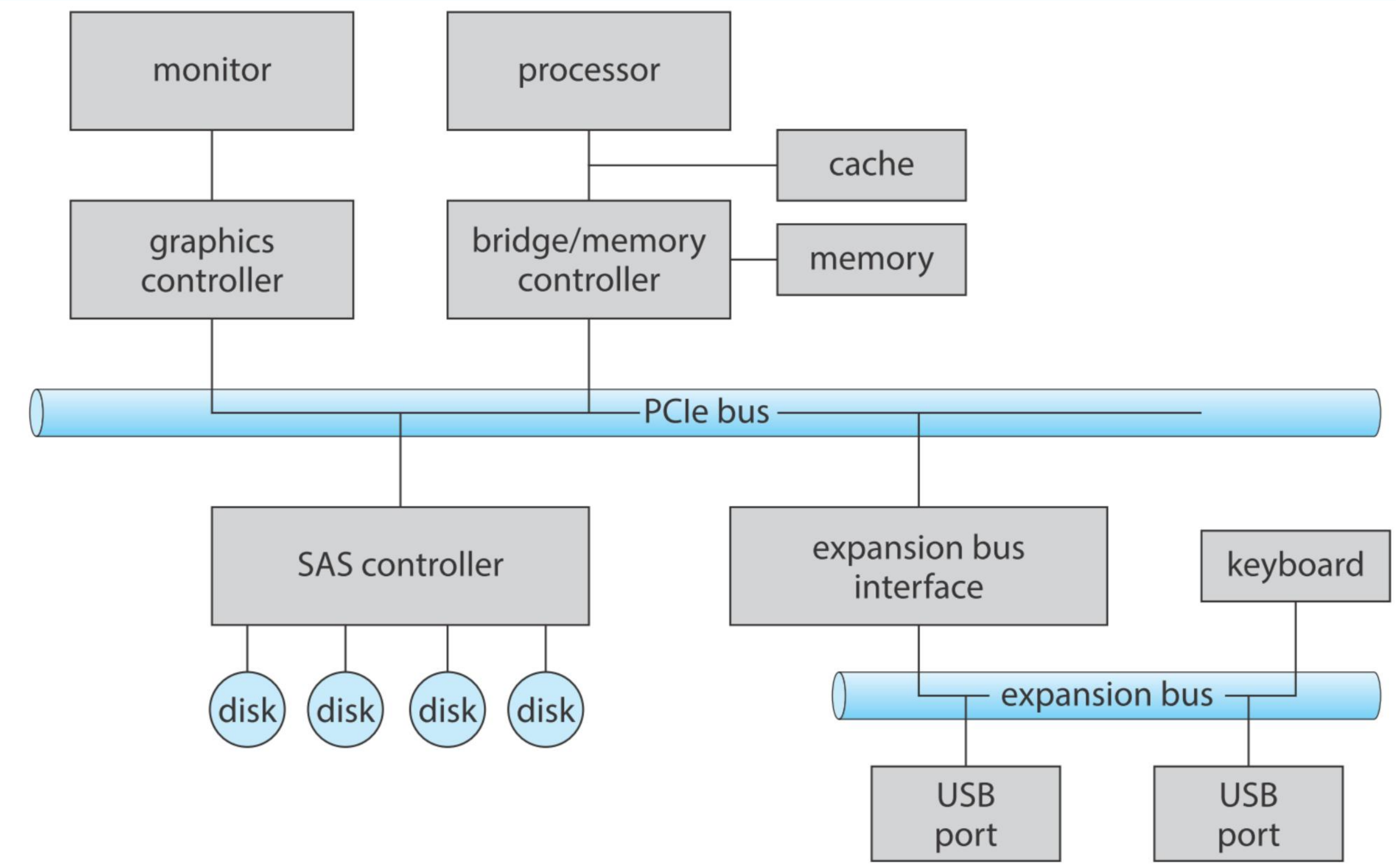
I/O Hardware

- Incredible variety of I/O devices
  - More than 200 harddisk manufacturers
- Common concepts
  - **Port**
  - **Bus** (**daisy chain** or shared direct access)
  - **Controller** (**host adapter**)
- I/O instructions control devices
- Devices have (port) addresses, used by
  - Special I/O instructions
  - **Memory-mapped** I/O

Device control registers mapped into processor address space.

Some systems use both.

A Typical PC Bus Structure



Device I/O Port Addresses 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)

I/O Port Registers

- **Data-in**: read by the host to get input
- **Data-out**: written by the host to send output
- **Status**: device status read by the host
- **Control**: written by the host to start a command or change the mode of a device

Polling

1. The host repeatedly reads the `busy` bit until that bit becomes clear.
2. The host sets the `write` bit in the `command` register and writes a byte into the `data-out` register.
3. The host sets the `command-ready` bit.
4. When the controller notices that the `command-ready` bit is set, it sets the `busy` bit.
5. The controller reads the command register and sees the `write` command. It reads the `data-out` register to get the byte and does the I/O to the device.
6. The controller clears the `command-ready` bit, clears the `error` bit in the status register to indicate that the device I/O succeeded, and clears the `busy` bit to indicate that it is finished.

- The above repeated for each byte.

Polling

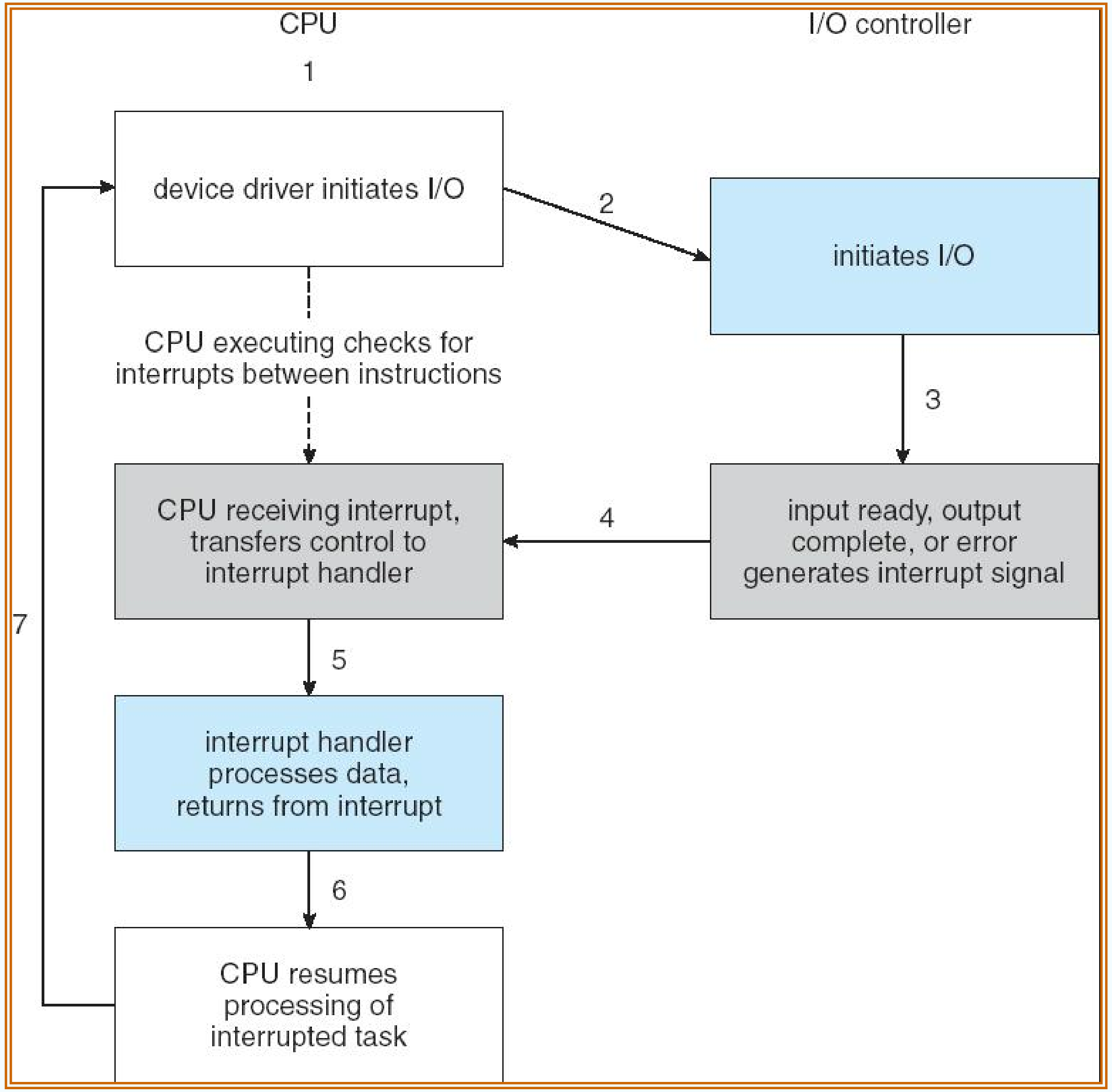
- Determines state of device
  - command-ready
  - busy
  - Error
- **Busy-wait** cycle in *Step 1* to wait for I/O from device

Repeatedly reading the **status** register until the busy bit becomes clear.
Can be inefficient!!

Interrupts

- CPU **Interrupt-request line** triggered by I/O device
- **Interrupt handler** receives interrupts
- **Maskable** to ignore or delay some interrupts
- Interrupt vector to dispatch interrupt to correct handler
  - Based on priority
  - Some **nonmaskable**
  - Interrupt chaining: To handle more devices than interrupt vector elements. Handlers on each list are called one by one.
- Interrupt mechanism also used for exceptions

Interrupt-Driven I/O Cycle



Intel Pentium Processor Event-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

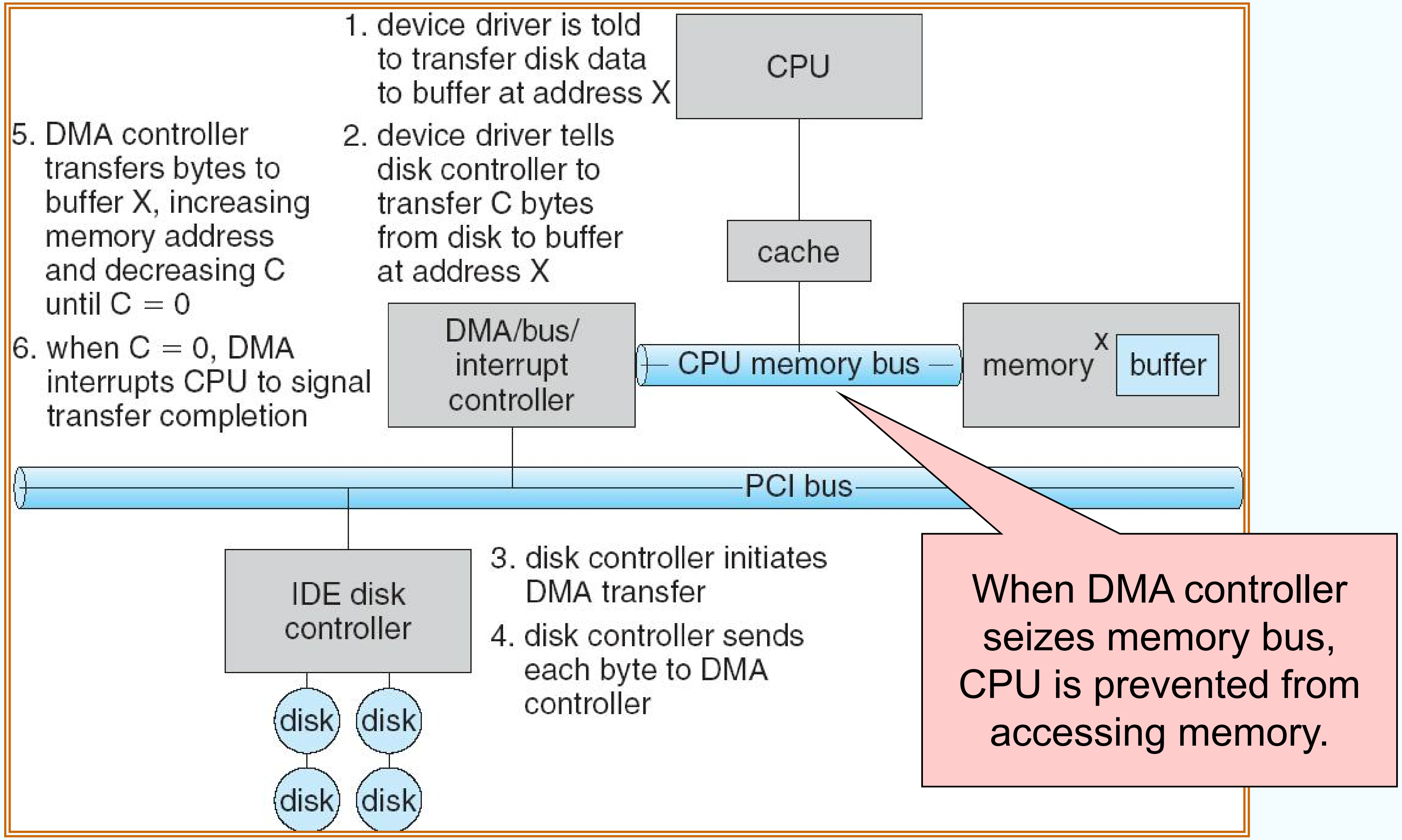
Various Interrupt Processing

- Page fault: saves the state of the process, moves it to the waiting queue, schedules another process to resume execution, then returns.
- Trap (s/w interrupt): saves the state of user code, switches to supervisor mode. Low priority
- Low priority interrupt can be preempted by high priority ones.
  - Example usage: high-priority handler
    - records the I/O status,
    - clears the device interrupt,
    - starts the next pending I/O, and
    - raises a low-priority interrupt to complete the work
  - Later, the low-priority handler
    - completes the user-level I/O by copying data from kernel buffers to the application space and
    - calling the scheduler to place the application on the ready queue

Direct Memory Access

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

Six Step Process to Perform DMA Transfer



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 Types in Linux

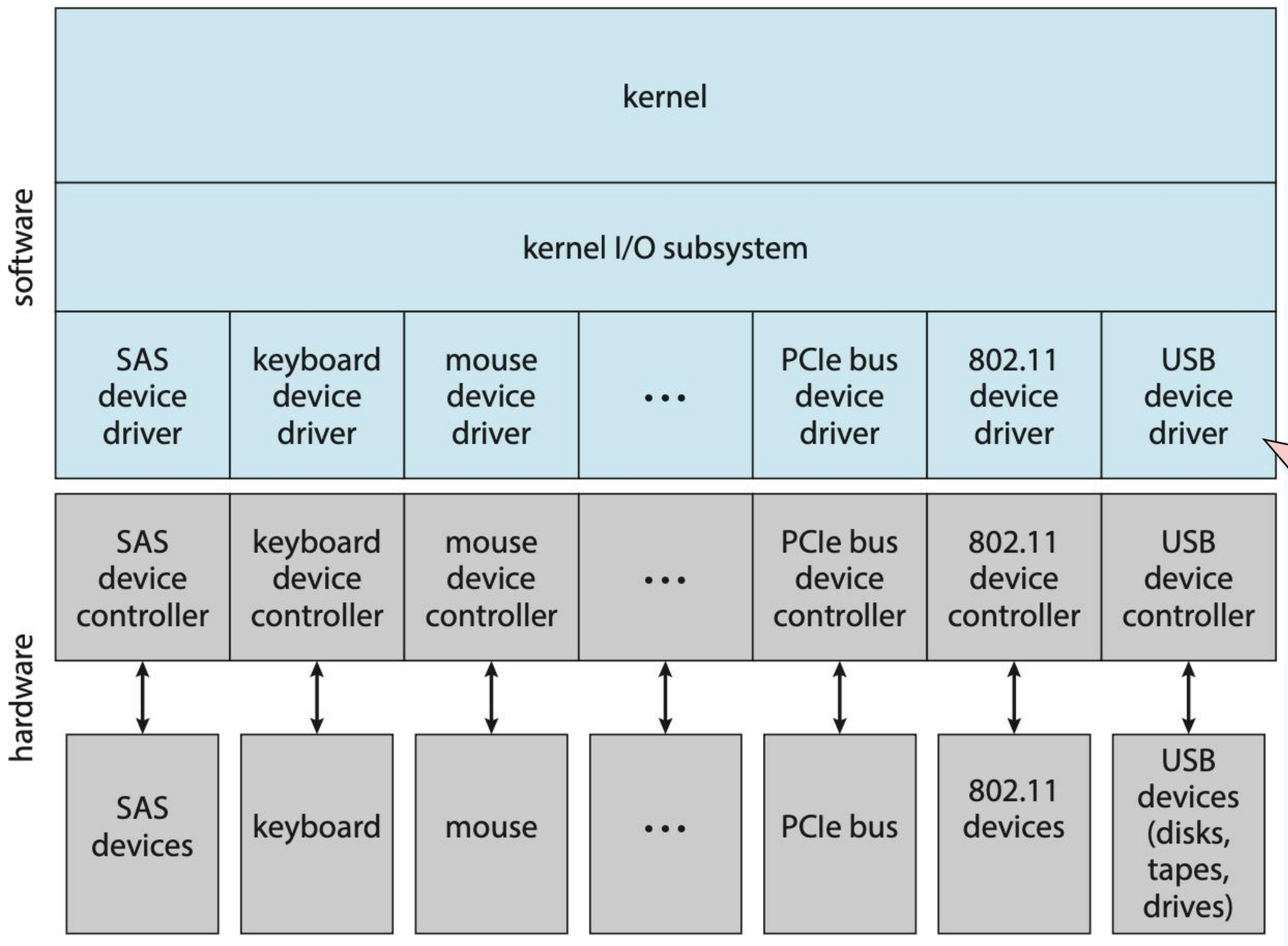
```
$ ls -l /dev
brw-rw---- 1 root disk 8, 0 Dec 20 20:13 sda
crw-rw-rw- 1 root root 1, 3 Dec 20 20:13 null
srw-rw-rw- 1 root root 0 Dec 20 20:13 log
prw-r--r-- 1 root root 0 Dec 20 20:13 fdata
```

- The columns are as follows from left to right:
  - Permissions
  - Owner
  - Group
  - Major Device Number
  - Minor Device Number
  - Timestamp
  - Device Name

- c – character
- b – block
- p – pipe
- s – socket

- SCSI devices
  - /dev/sda - First hard disk
  - /dev/sdb - Second hard disk
  - /dev/sda3 - Third partition on the first hard disk
- Older ATA HDD
  - /dev/hda - First hard disk
  - /dev/hdd2 - Second partition on 4th hard disk
- Pseudo devices
  - /dev/zero - accepts and discards all input, produces a continuous stream of NULL (zero value) bytes
  - /dev/null - accepts and discards all input, produces no output
  - /dev/random - produces random numbers

A Kernel I/O Structure



Device driver layer:
Hides differences among device controllers

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
  - Commands include `get, put`
  - Libraries layered on top allow line editing

Network Devices

- Varying 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 for servers
- Approaches vary widely (pipes, FIFOs, streams, queues, mailboxes)

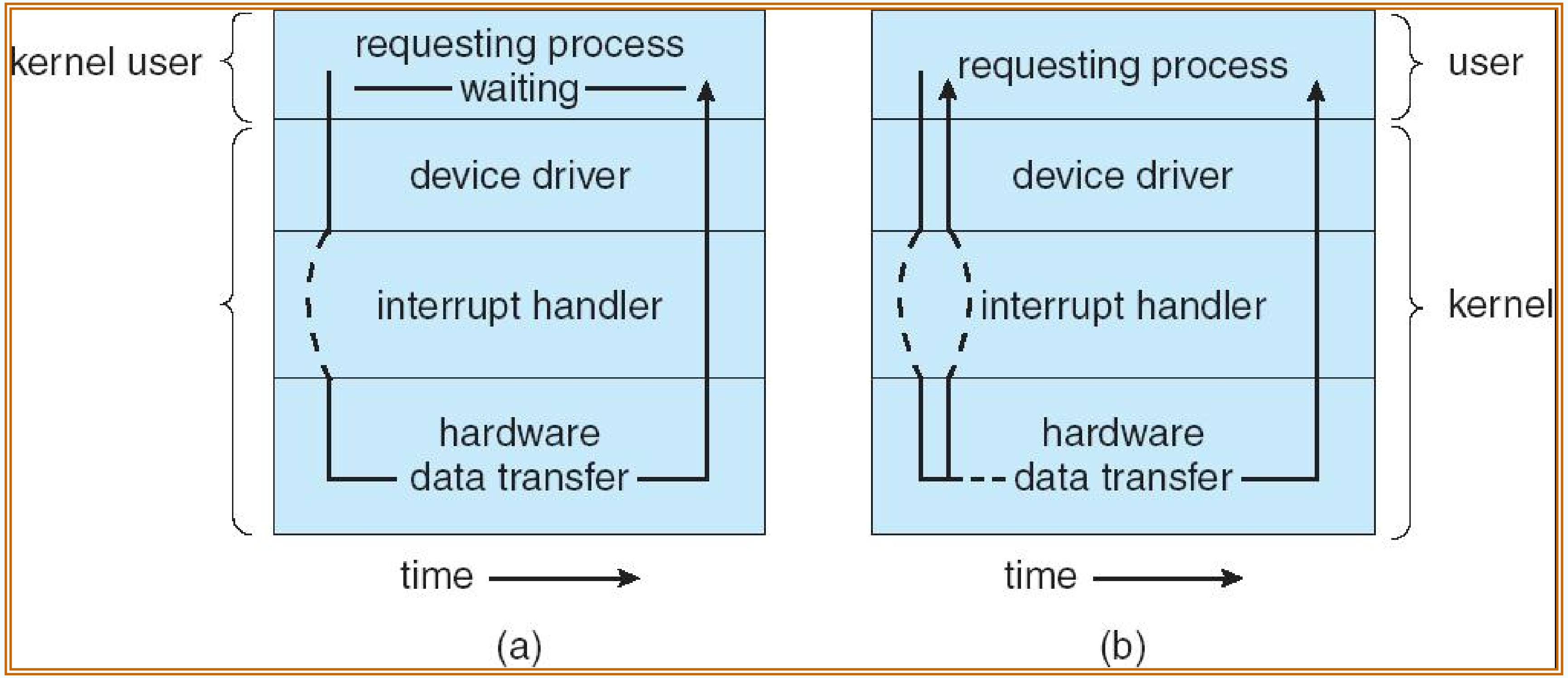
Clocks and Timers

- Provide current time, elapsed time, timer
- **Programmable interval timer** used for timings, to generate periodic interrupts
- `ioctl` (on UNIX) covers odd aspects of I/O such as clocks and timers

Blocking and Nonblocking I/O

- **Blocking** - process suspended until I/O completed
  - Easy to use and understand
  - Insufficient for some needs
- **Nonblocking** - I/O call returns as much as available
  - User interface, data copy (buffered I/O)
  - Implemented via multi-threading
  - Returns quickly with count of bytes read or written
- **Asynchronous** - process runs while I/O executes
  - Difficult to use
  - I/O subsystem signals process when I/O completed

Two I/O Methods



Synchronous

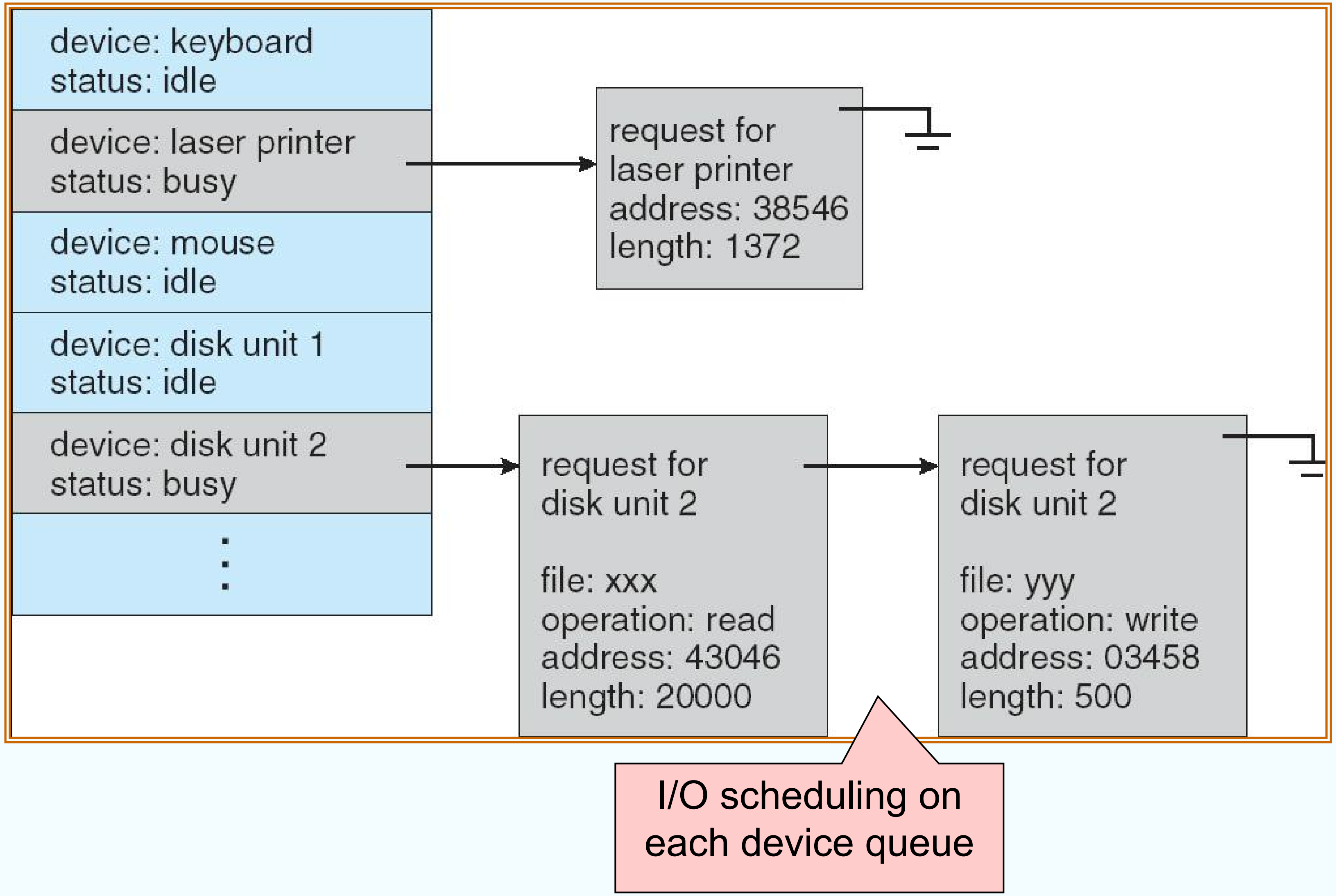
Asynchronous

Kernel I/O Subsystem

- **Scheduling**
  - Some I/O request ordering via per-device queue
    - E.g. disk scheduling
  - Some OSs try fairness
- **Buffering** - store data in memory while transferring between devices
  - To cope with device speed mismatch, e.g. receiving data from modem to disk.
    - Double buffering
  - To cope with device transfer size mismatch, e.g. network packet
  - To maintain “copy semantics” (when a write() system call specifies a buffer for storing the data, and modifies its contents after the system call)

Device-status Table

Aka “device-control table”



Kernel I/O Subsystem

- **Caching** - fast memory holding copy of data
  - Always just a copy
  - Key to performance
- **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 deallocation
  - Watch out for deadlock

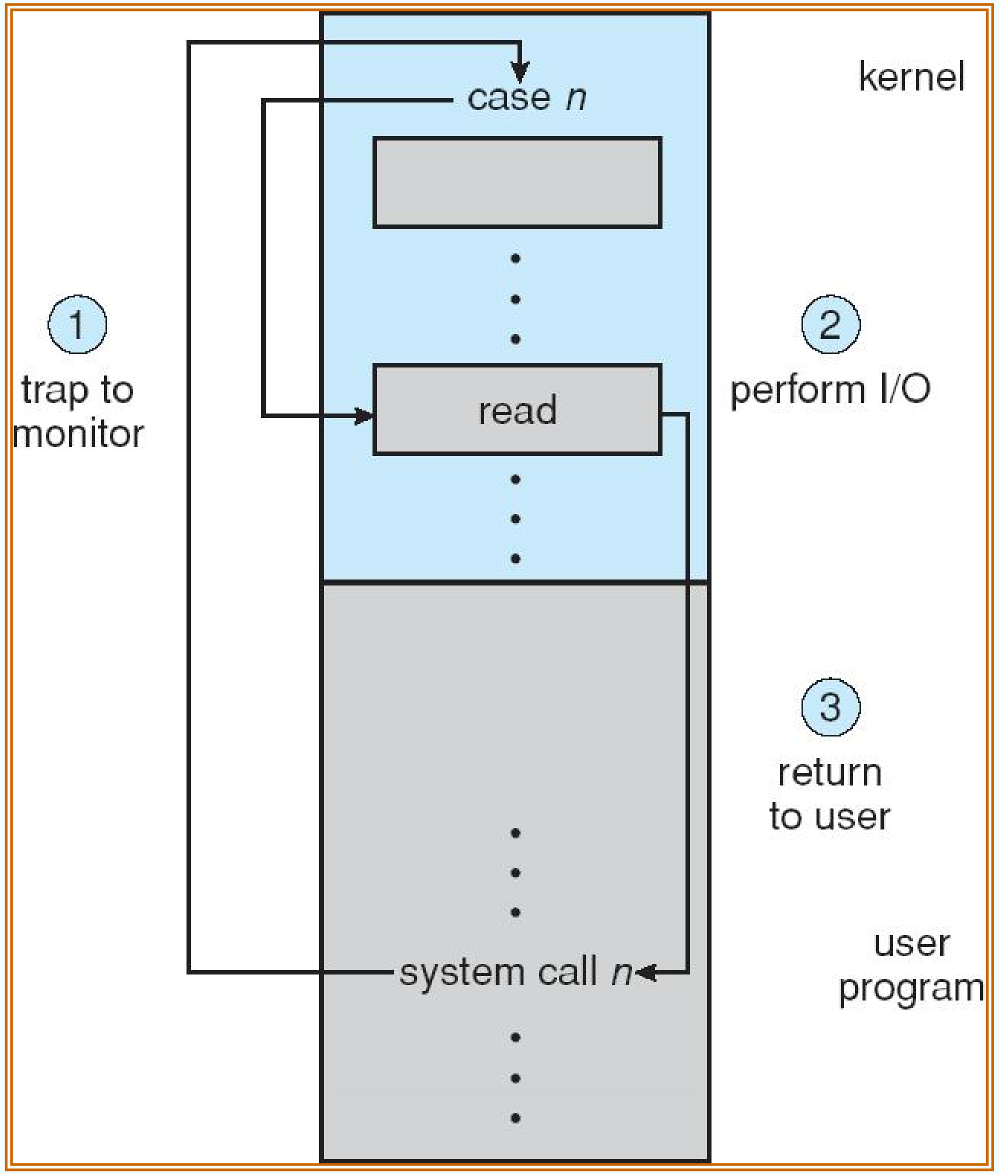
Error Handling

- OS can recover from disk read, device unavailable, transient write failures
- Most return an error number or code when I/O request fails
- System error logs hold problem reports

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– cannot be issued directly
  - I/O must be performed via system calls
    - Memory-mapped and I/O port memory locations must be protected too

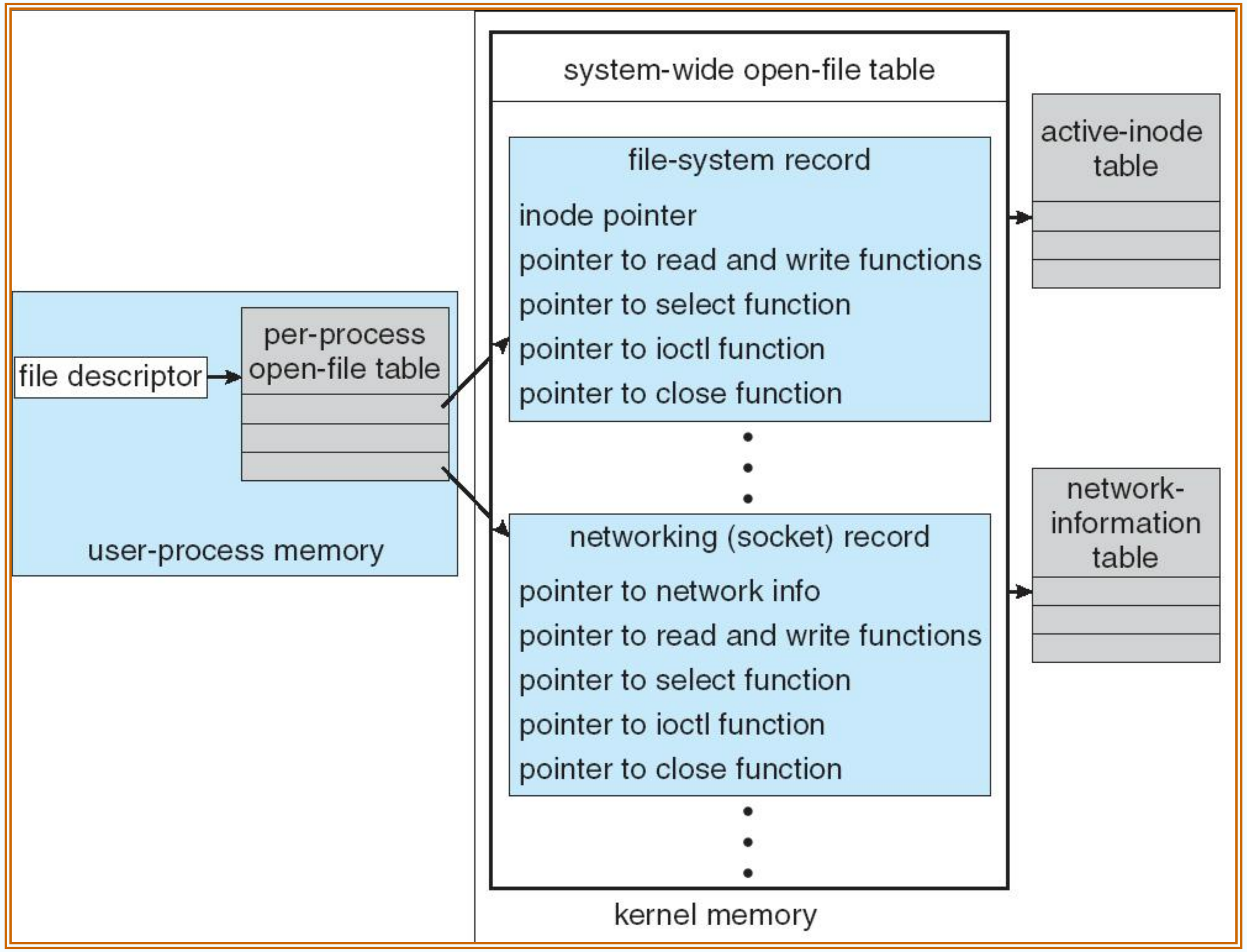
Use of a System Call to Perform I/O



Kernel Data Structures

- Kernel keeps state info for I/O components, including open file tables, network connections, character device state
- Many, many complex data structures to track buffers, memory allocation, “dirty” blocks
- Some use object-oriented methods and message passing to implement I/O. e.g. Unix provides file-system access to a variety of entities such as *user files, raw disk, network socket* etc.

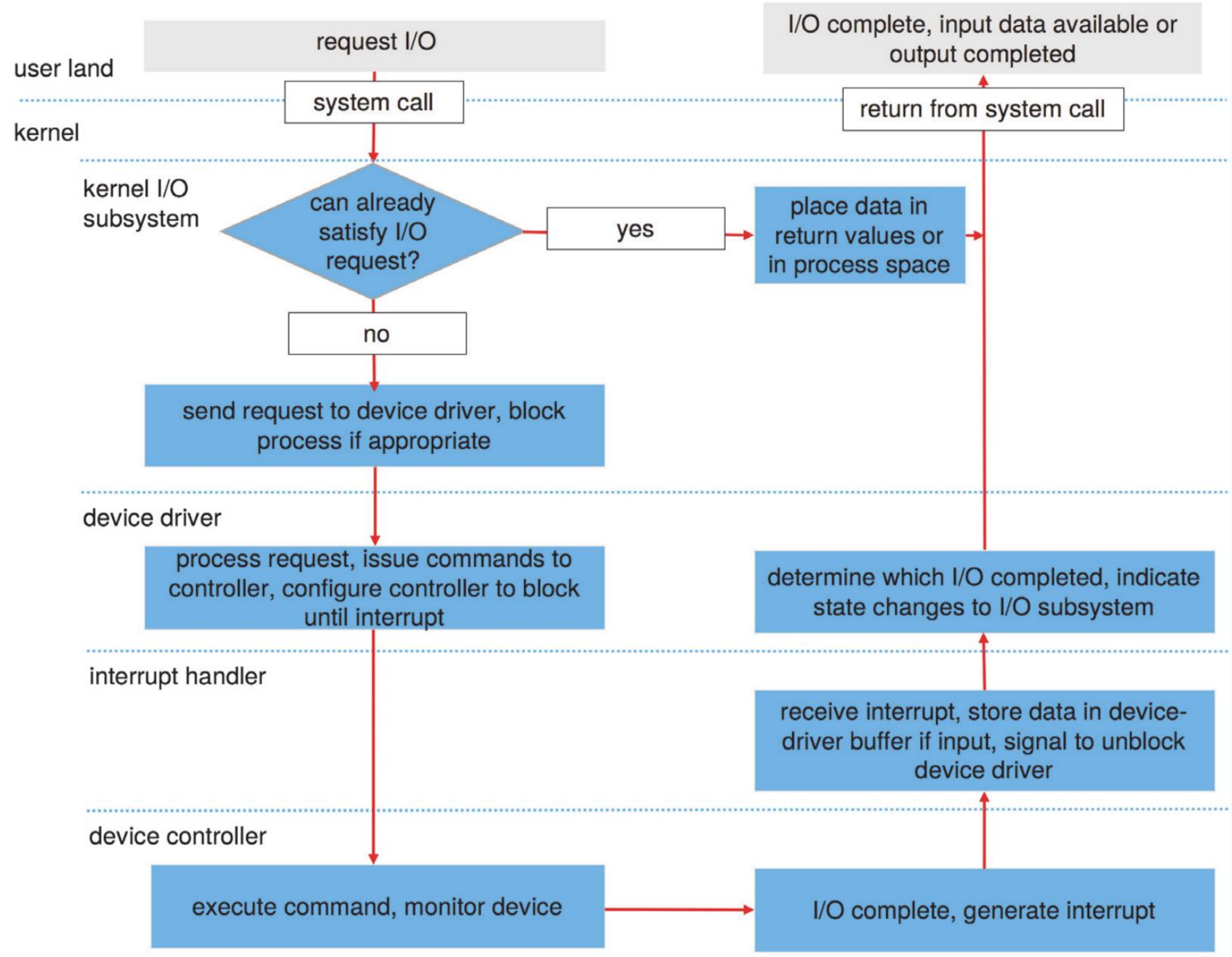
UNIX I/O Kernel Structure



Transforming I/O Requests to Hardware Operations

- Consider reading a file from disk for a process:
  - Determine device holding file
    - MS-DOS uses the ‘c:’ disk id; Unix uses the mount table
  - Translate name to device representation
  - Physically read data from disk into buffer
  - Make data available to requesting process
  - Return control to process

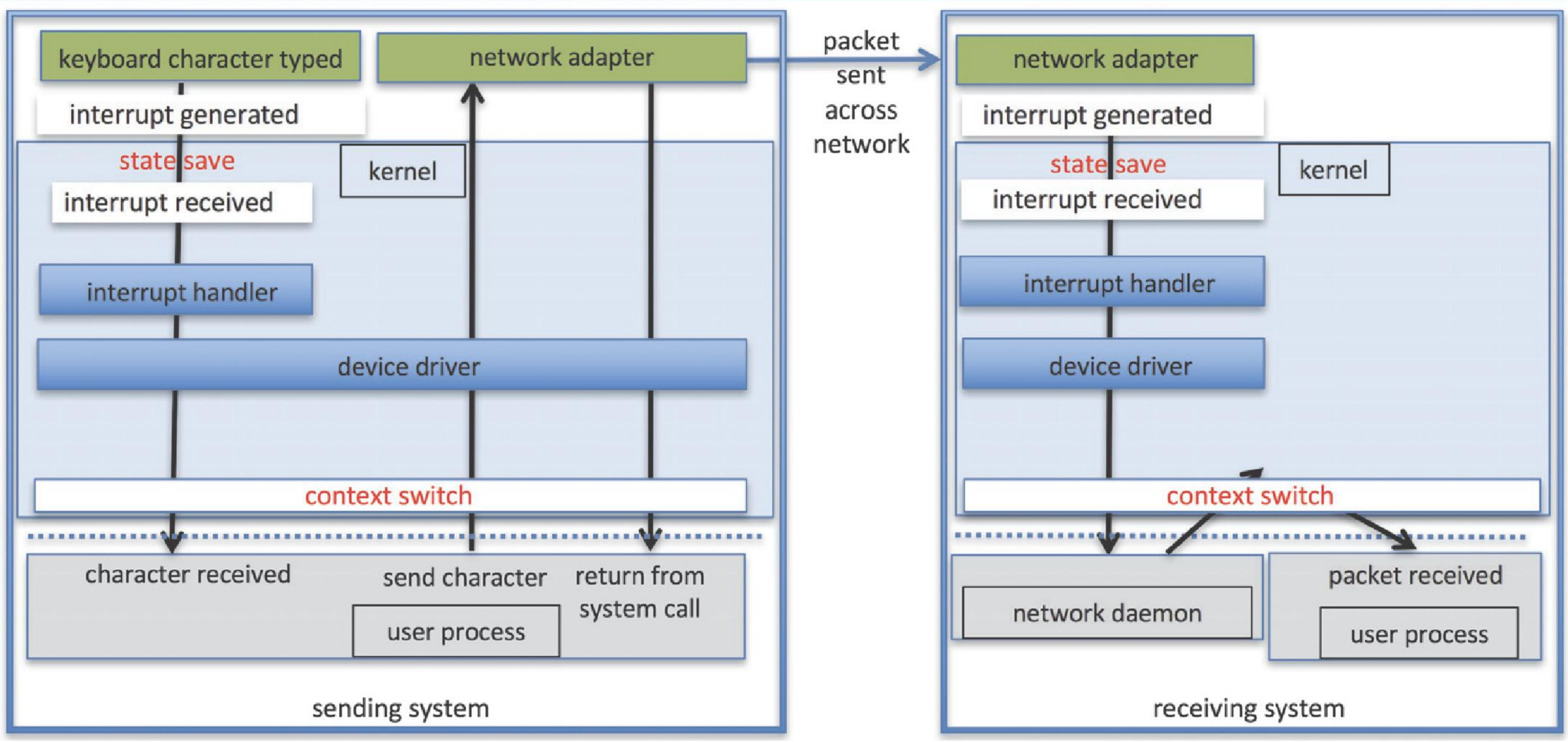
Life Cycle of An I/O Request



Performance

- I/O is a major factor in system performance:
  - Demands CPU to execute device driver, kernel I/O code
  - Context switches due to interrupts are heavy burden on CPU
  - Data copying
  - Network traffic especially stressful

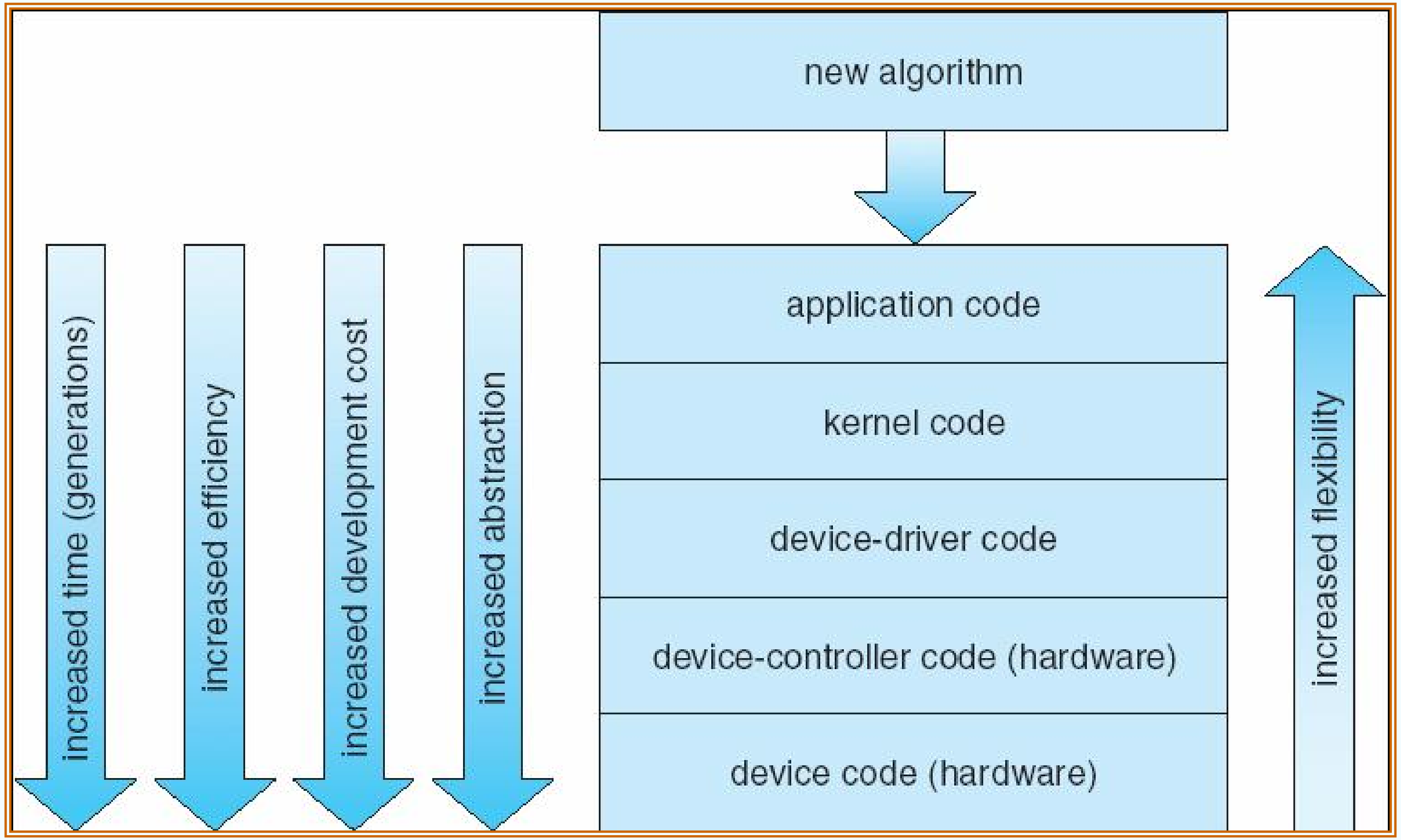
Intercomputer Communications



Improving Performance

- Reduce number of context switches
- Reduce data copying
- Reduce interrupts by using large transfers, smart controllers, polling
- Use DMA
- Balance CPU, memory, bus, and I/O performance for highest throughput

Device-Functionality Progression



End of Chapter 13

STREAMS

- **STREAM** – a full-duplex communication channel between a user-level process and a device in Unix System V and beyond

- A STREAM consists of:

  - STREAM head interfaces with the user process
  - driver end interfaces with the device
  - zero or more STREAM modules between them.

- Each module contains a **read queue** and a **write queue**

- Message passing is used to communicate between queues
- **STREAM** provides a framework for a modular and incremental approach to writing device drivers and network protocols.

The STREAMS Structure