13. I/O Systems

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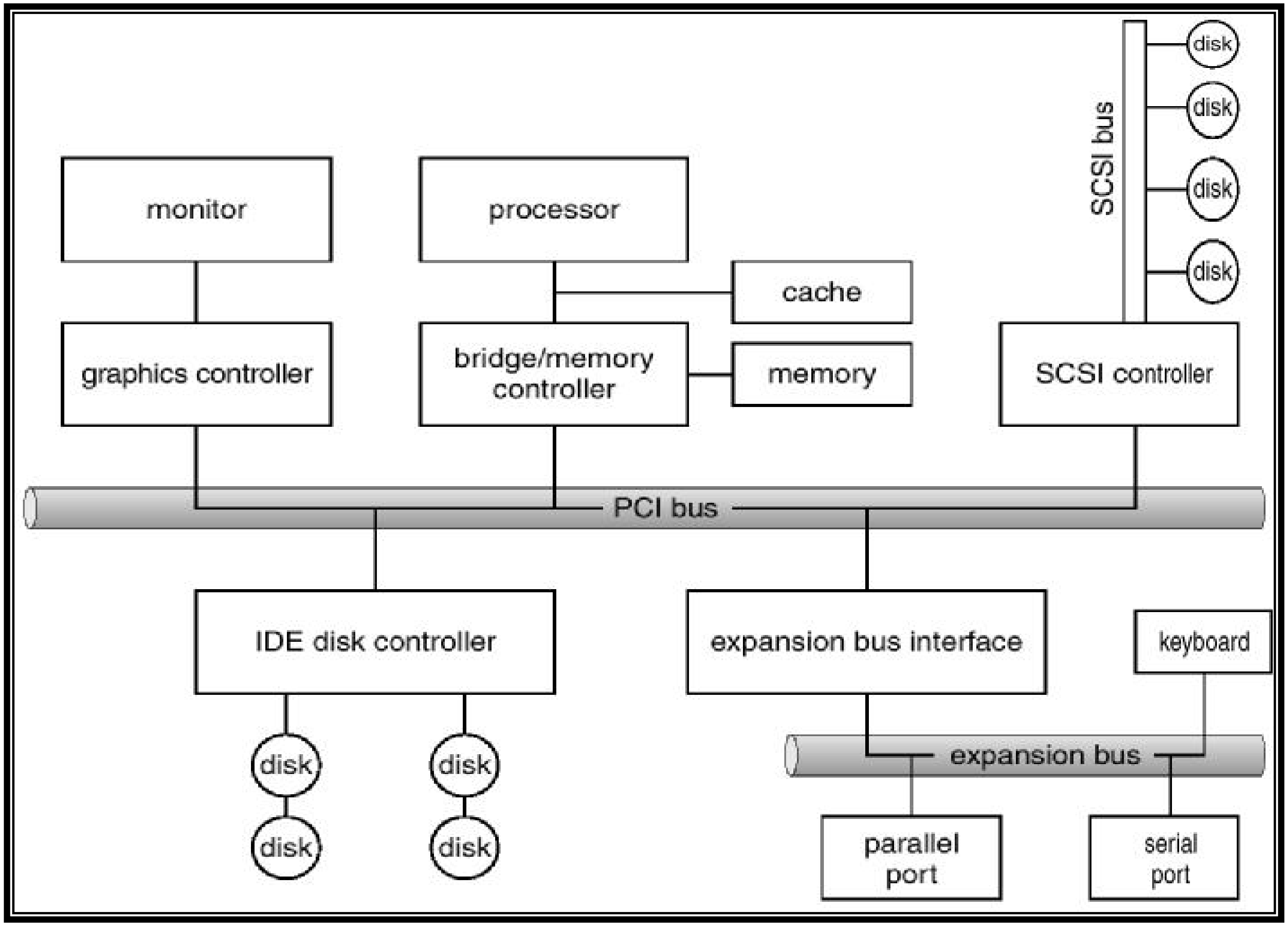
Contents

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

I/O Hardware

- Incredible variety of I/O devices
- Common concepts
  - Port
  - Bus (daisy chain or shared direct access)
  - Controller (host adapter)
- I/O instructions control devices
- Devices have addresses, used by
  - Direct I/O instructions
  - Memory-mapped I/O

A Typical PC Bus Structure



Device Controller

- Device controller (or host adapter)
  - I/O devices have components:
    - Mechanical component
    - Electronic component
  - The electronic component is the device controller
    - May be able to handle multiple devices
  - Controller's tasks
    - Convert serial bit stream to block of bytes
    - Perform error correction as necessary
    - Make available to main memory

Direct I/O

- Use special I/O instructions to an I/O port address

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

- The device control registers are mapped into the address space of the processor
  - The CPU executes I/O requests using the standard data transfer instructions
- I/O device drivers can be written entirely in C
- No special protection mechanism is needed to keep user processes from performing I/O
  - Can give a user control over specific devices but not others by simply including the desired pages in its page table
- Reading a device register and testing its value is done with a single instruction
- Memory-mapped regions should be uncacheable
- Memory-mapped device register is vulnerable to accidental modification through the use of incorrect pointers
  - Protected memory helps to reduce this risk

Polling

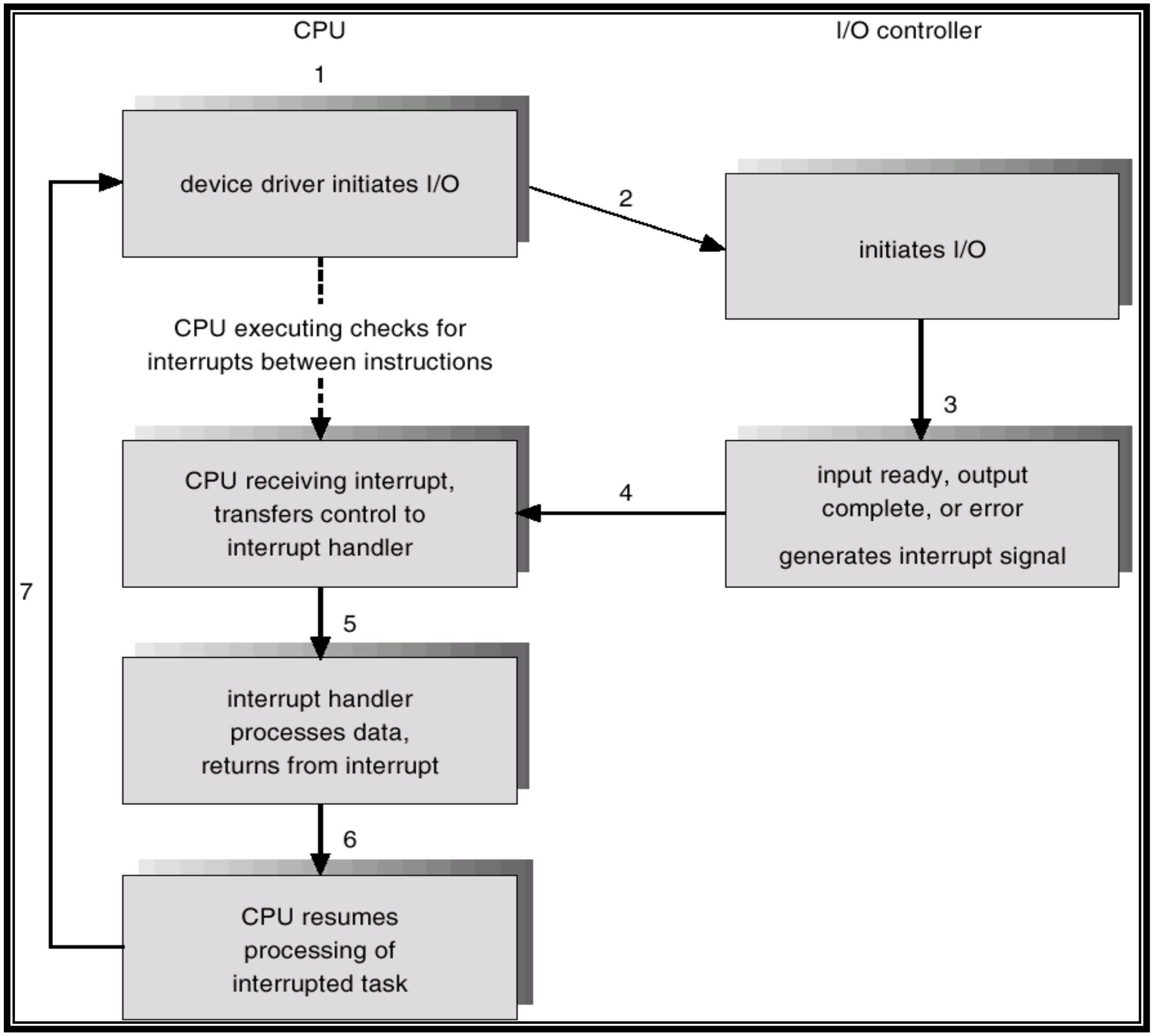
- Determines state of device
  - command-ready
  - busy
  - Error

- Busy-wait cycle to wait for I/O from device

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 unmaskable
- 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
19Ð31	(Intel reserved, do not use)
32Ð255	maskable interrupts

Polling vs. Interrupts

- Polled I/O
  - CPU asks (“polls”) devices if need attention
    - ready to receive a command
    - command status, etc.
  - Advantages
    - Simple
    - Software is in control
    - Efficient if CPU finds a device to be ready soon
  - Disadvantages
    - Inefficient in non-trivial system (high CPU utilization)
    - Low priority devices may never be serviced

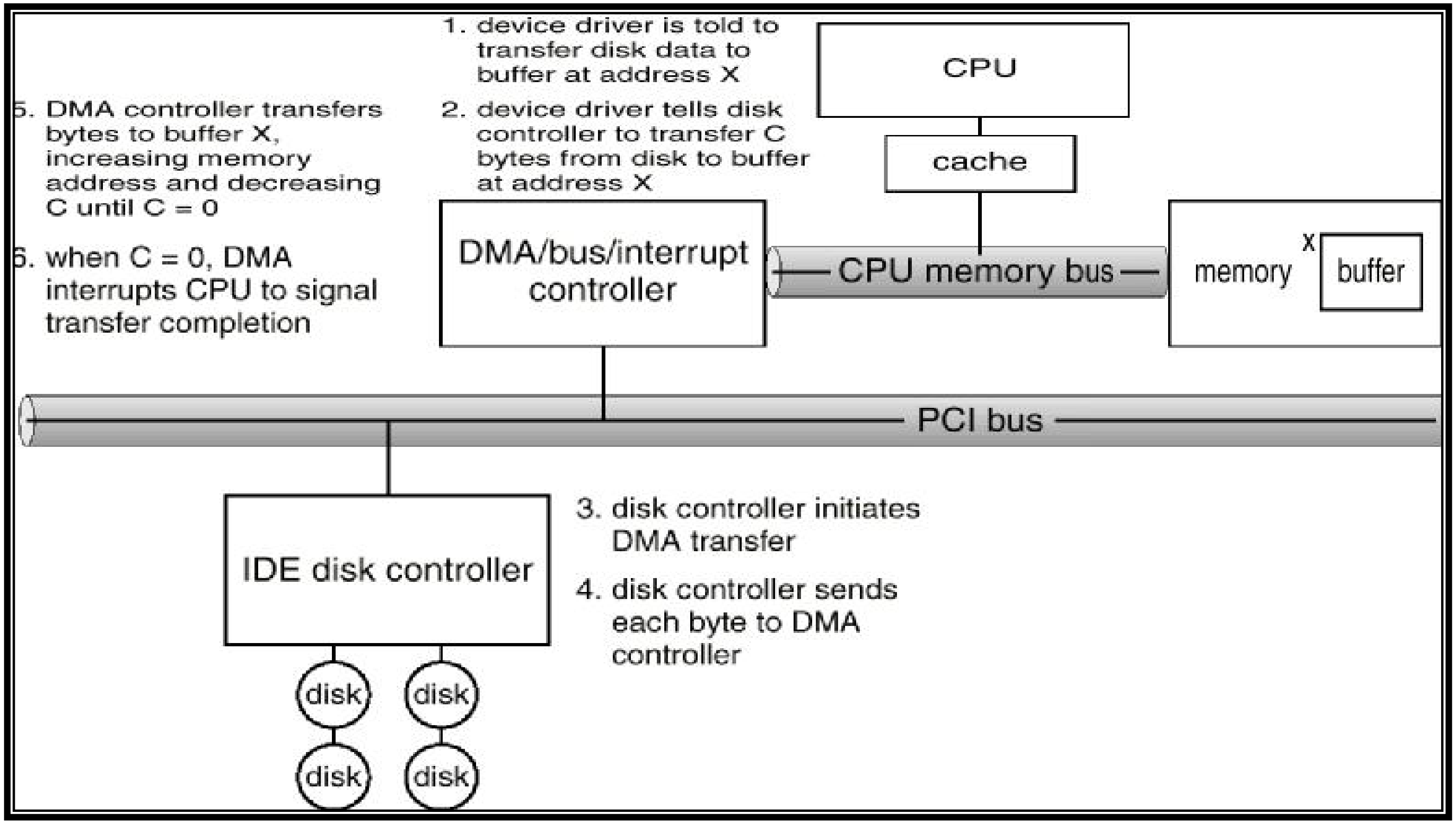
Polling vs. Interrupts (Cont'd)

- Interrupt-driven I/O
  - I/O devices request interrupt when need attention
  - Interrupt service routines specific to each device are invoked
  - Interrupts can be shared between multiple devices
  - Advantages
    - CPU only attends to device when necessary
    - More efficient than polling in general
  - Disadvantages
    - Excess interrupts slow (or prevent) program execution
    - Overheads (may need 1 interrupt per byte transferred)

Direct Memory Access

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

Six Step Process to Perform DMA Transfer



DMA

- DMA modes
  - (1) Cycle stealing
    - The DMA controller sneaks in and steals an occasional bus cycle from the CPU once in a while, delaying it slightly
  - (2) Burst mode
    - The DMA controller acquires the bus, issues a series of transfers, then releases the bus
    - More efficient than cycle stealing: acquiring the bus takes time and multiple words can be transferred for the price of one bus acquisition
    - It can block the CPU and other devices too long

DMA (Cont'd)

- Addressing in DMA
  - (1) Physical address
    - OS converts the virtual address of the intended memory buffer into a physical address and writes it into DMA controller's address register
  - (2) Virtual address
    - The DMA controller must use the MMU to have the virtual-to-physical translation done
    - Not common: only when the MMU is part of the memory rather than part of the CPU
  - In any case, the target memory region should be pinned (not paged out) during DMA

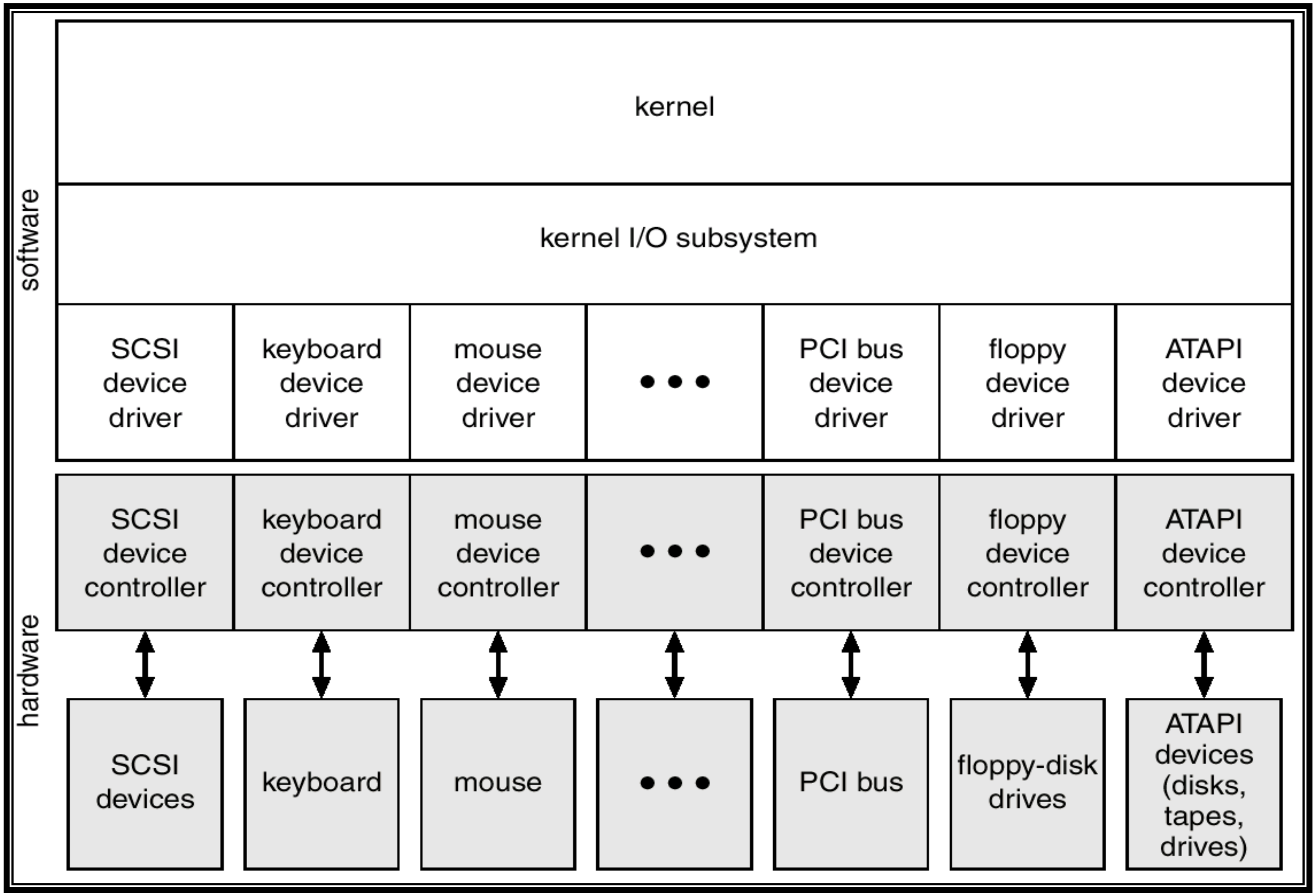
DMA (Cont’d)

- DMA types
  - (1) Sequential DMA
    - Data temporarily stored in DMA controller
    - Requires an extra bus cycle per word transferred
    - More flexible in that it can also perform device-to-device copies and even memory-to-memory copies
  - (2) Simultaneous DMA (or fly-by mode)
    - The DMA controller tells the device controller to transfer the data directly to main memory

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

A Kernel I/O Structure



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 readĐwrite	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*i*/2000 include socket interface
  - Separates network protocol from network operation
  - Includes `select` functionality

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

Clocks and Timers

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

Blocking and Nonblocking I/O

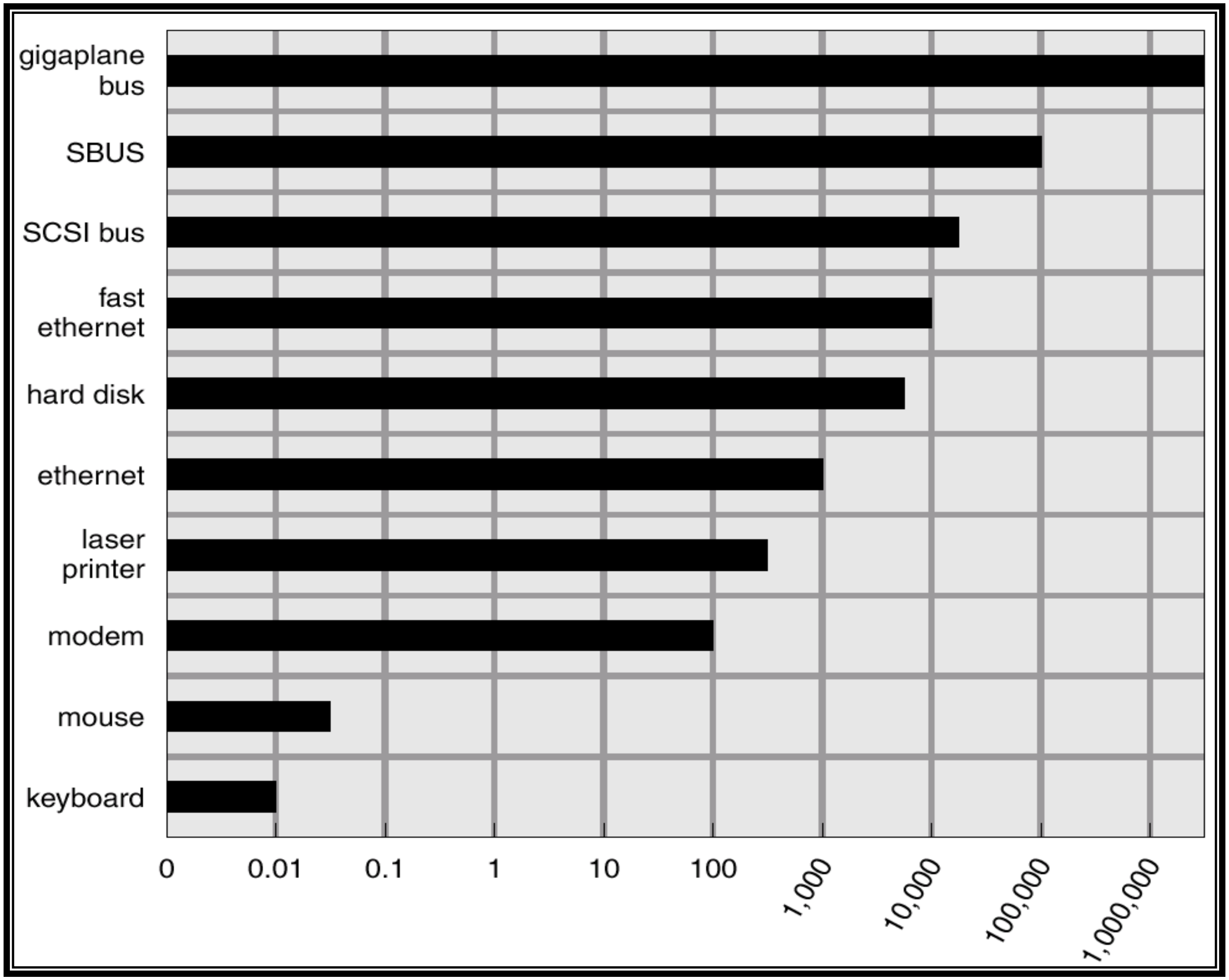
- Blocking - process suspended until I/O completed
  - Easy to use and understand
  - Insufficient for some needs
- Nonblocking - I/O call returns as much as available
  - User interface, data copy (buffered I/O)
  - Implemented via multi-threading
  - Returns quickly with count of bytes read or written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

Kernel I/O Subsystem

- Scheduling
  - Some I/O request ordering via per-device queue
  - Some OSs try fairness

- 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”

Sun Enterprise 6000 Device-Transfer Rates



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

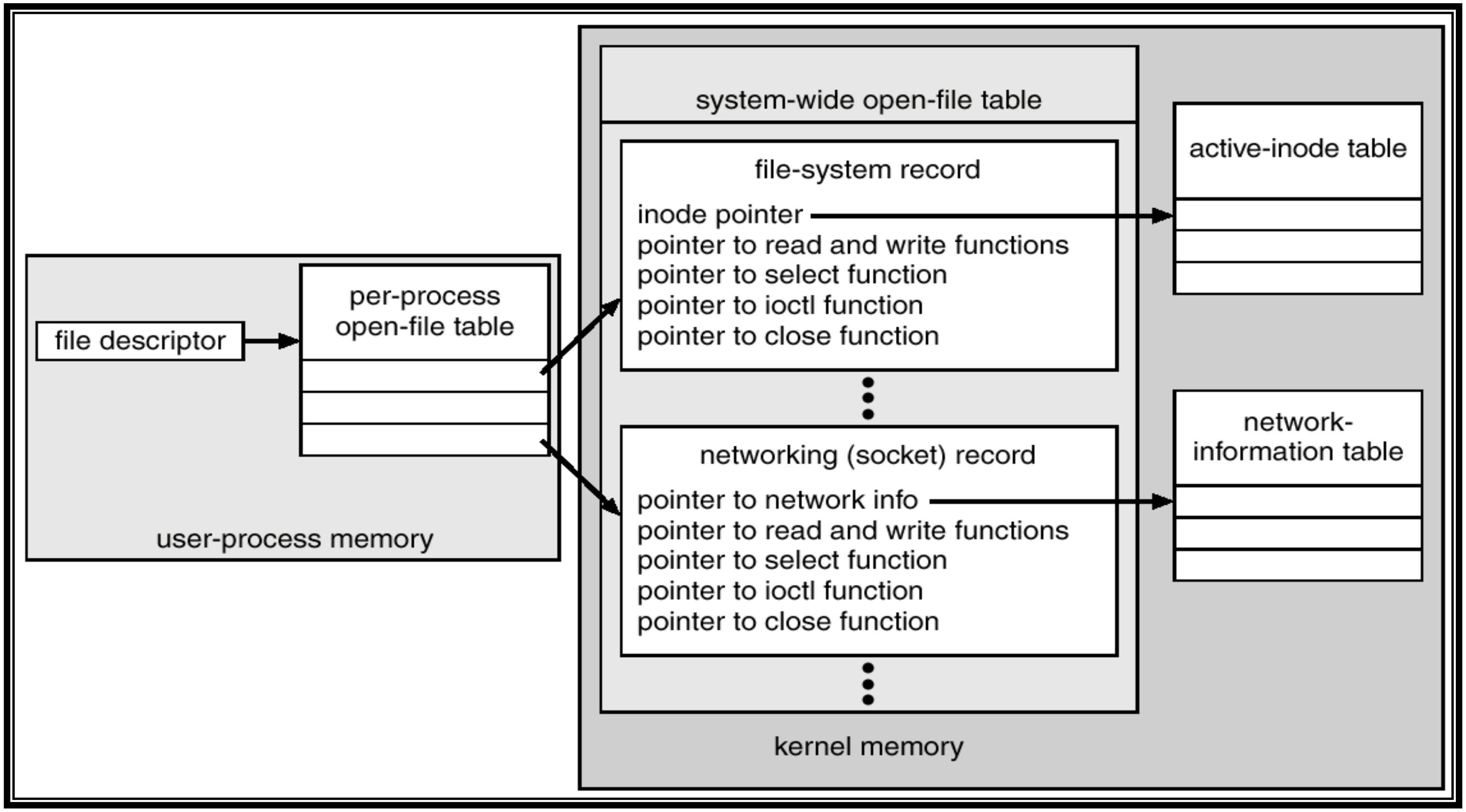
Error Handling

- 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

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

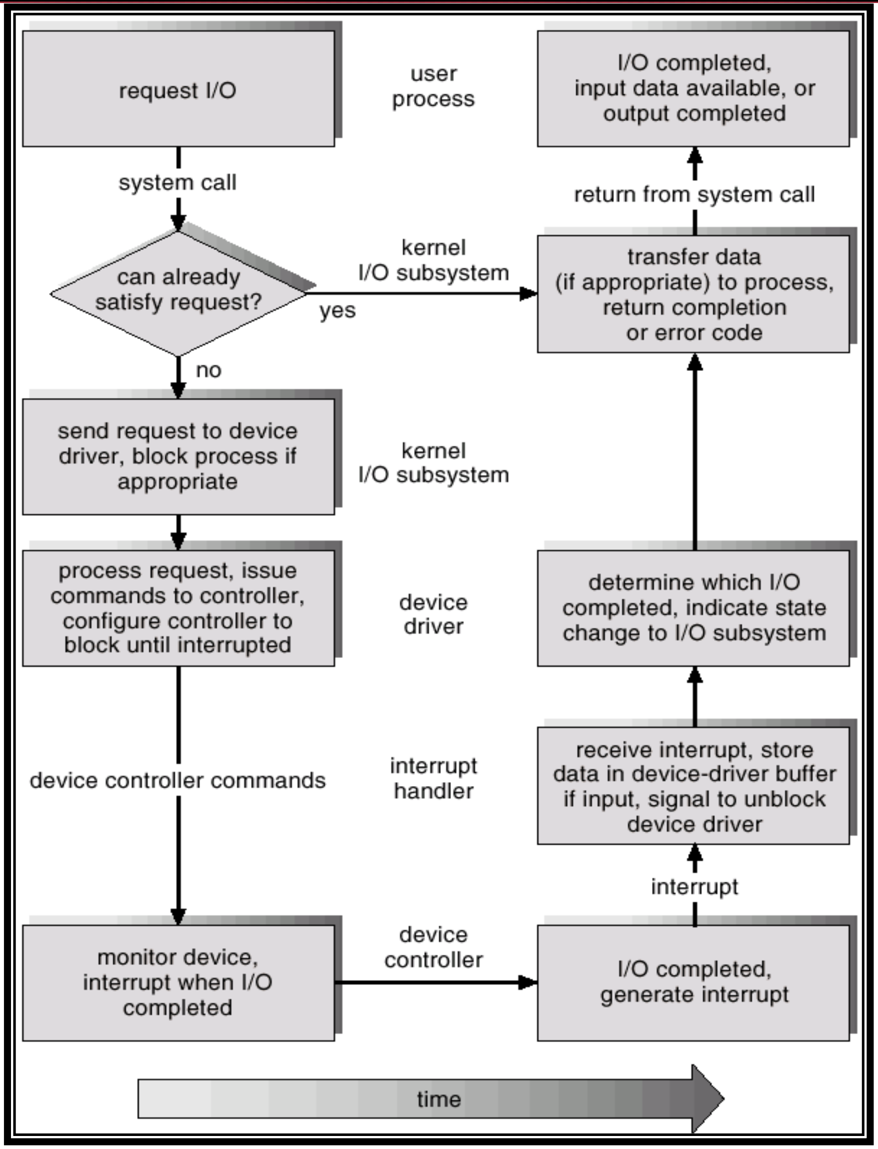
UNIX I/O Kernel Structure



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



STREAMS

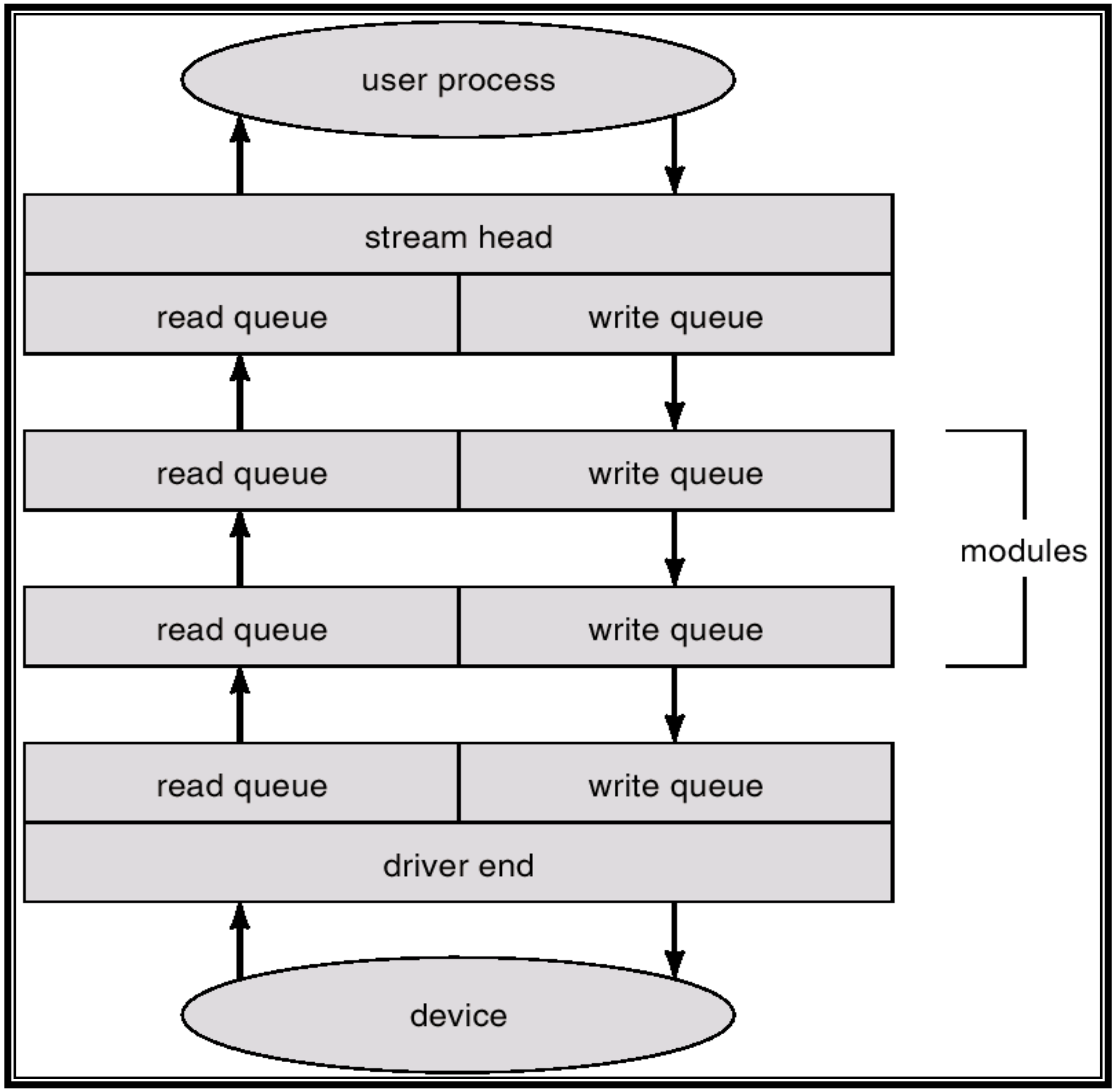
- **STREAM**
  - a full-duplex communication channel between a user-level process and a device

- 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

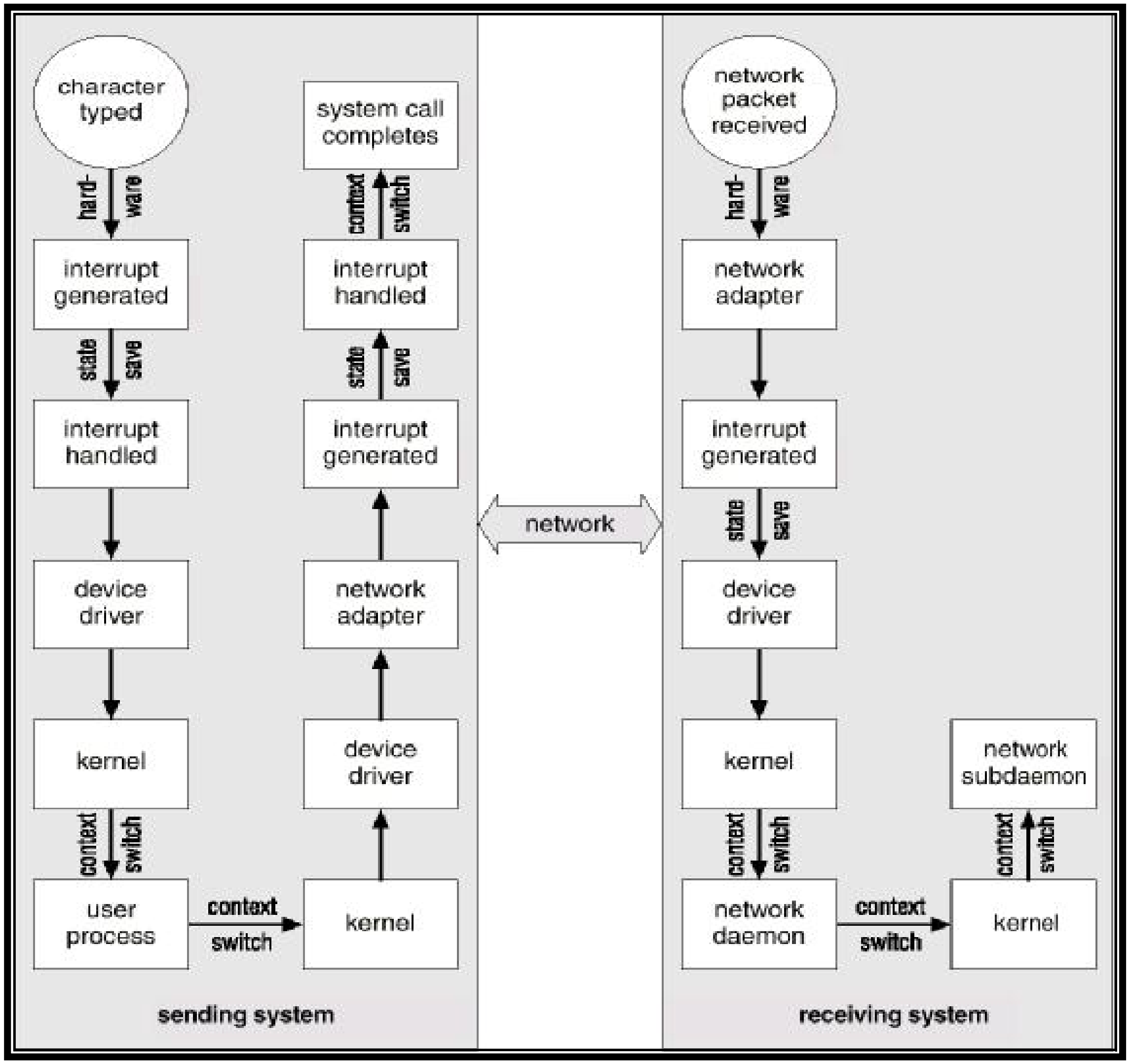
The STREAMS Structure



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

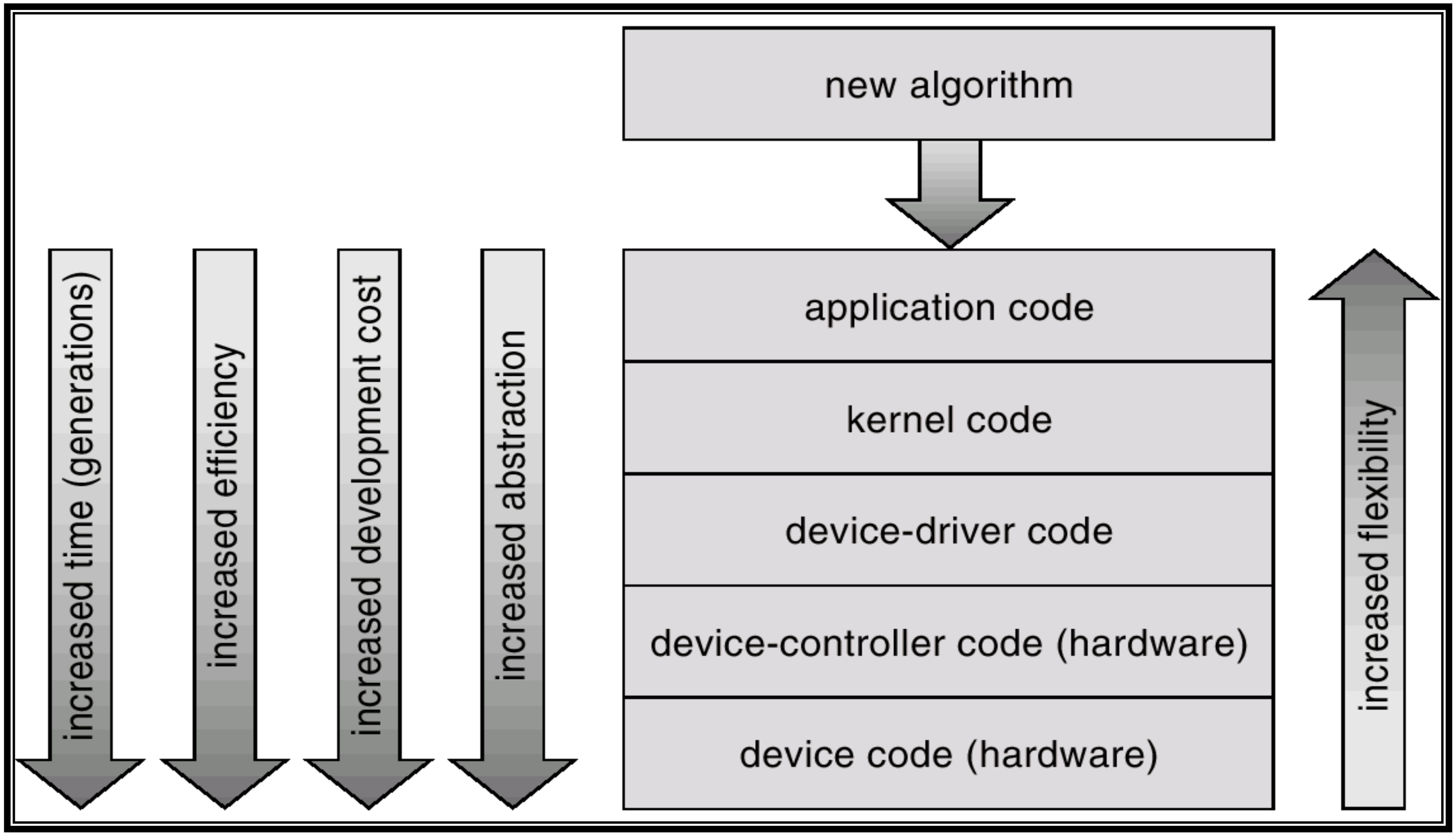
Intercomputer Communications



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

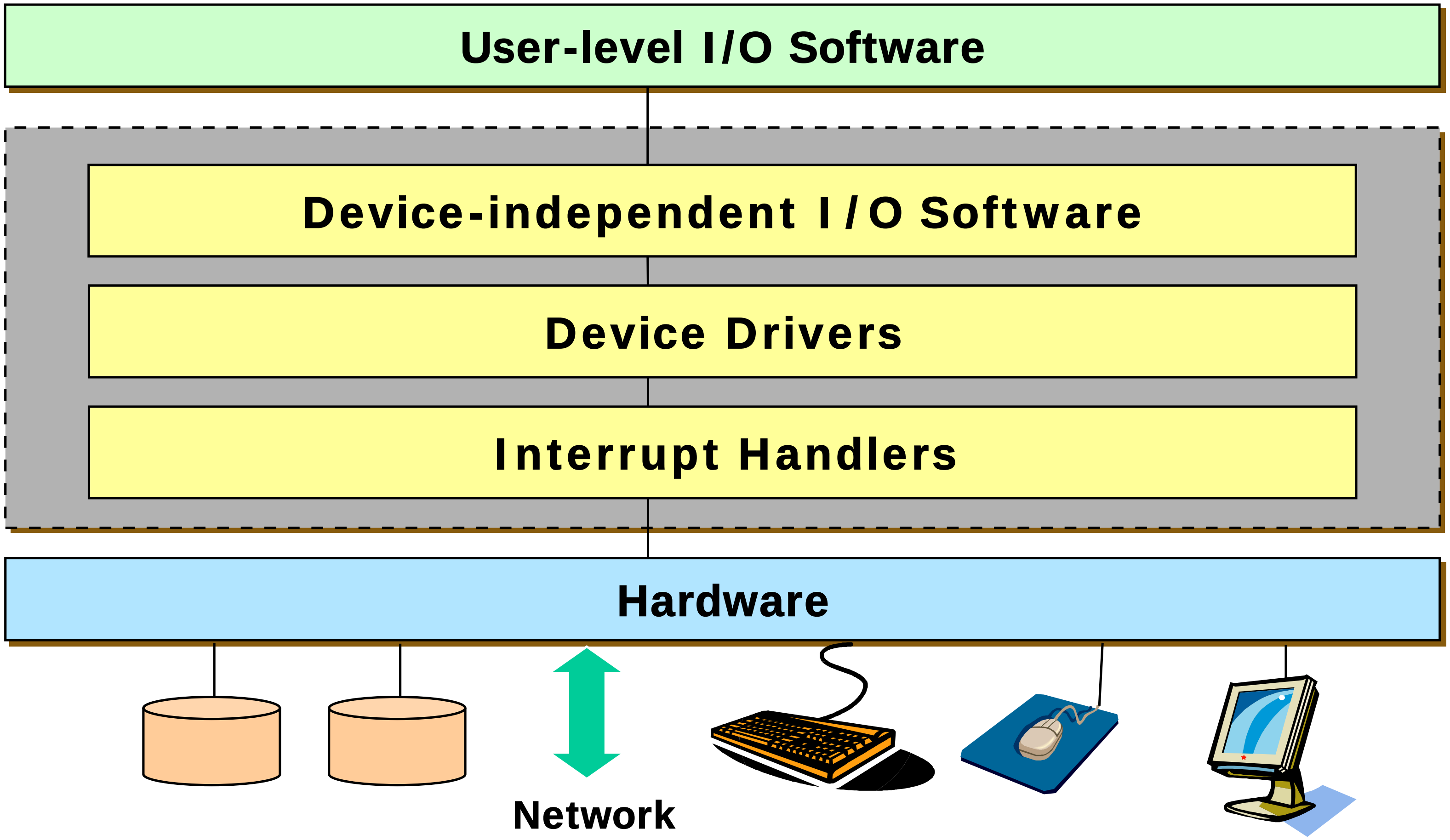
Device-Functionality Progression



Goals of I/O Software

- Goals
  - Device independence
    - Programs can access any I/O device without specifying device in advance
  - Uniform naming
    - Name of a file or device should simply be a string or an integer
  - Error handling
    - Handle as close to the hardware as possible
  - Synchronous vs. asynchronous
    - blocked transfers vs. interrupt-driven
  - Buffering
    - Data coming off a device cannot be stored in final destination
  - Sharable vs. dedicated devices
    - Disks vs. tape drives
    - Unsharable devices introduce problems such as deadlocks

I/O Software Layers



- Handling interrupts

Critical actions

: Acknowledge an interrupt to the PIC.
: Reprogram the PIC or the device controller.
: Update data structures accessed by both the device and the processor.

Reenable interrupts

Noncritical actions

: Update data structures that are accessed only by the processor.
(e.g., reading the scan code from the keyboard)

Return from interrupts

Noncritical deferred actions

: Actions may be delayed.
: Copy buffer contents into the address space of some process (e.g., sending the keyboard line buffer to the terminal handler process).
Bottom half (Linux)

Device Drivers

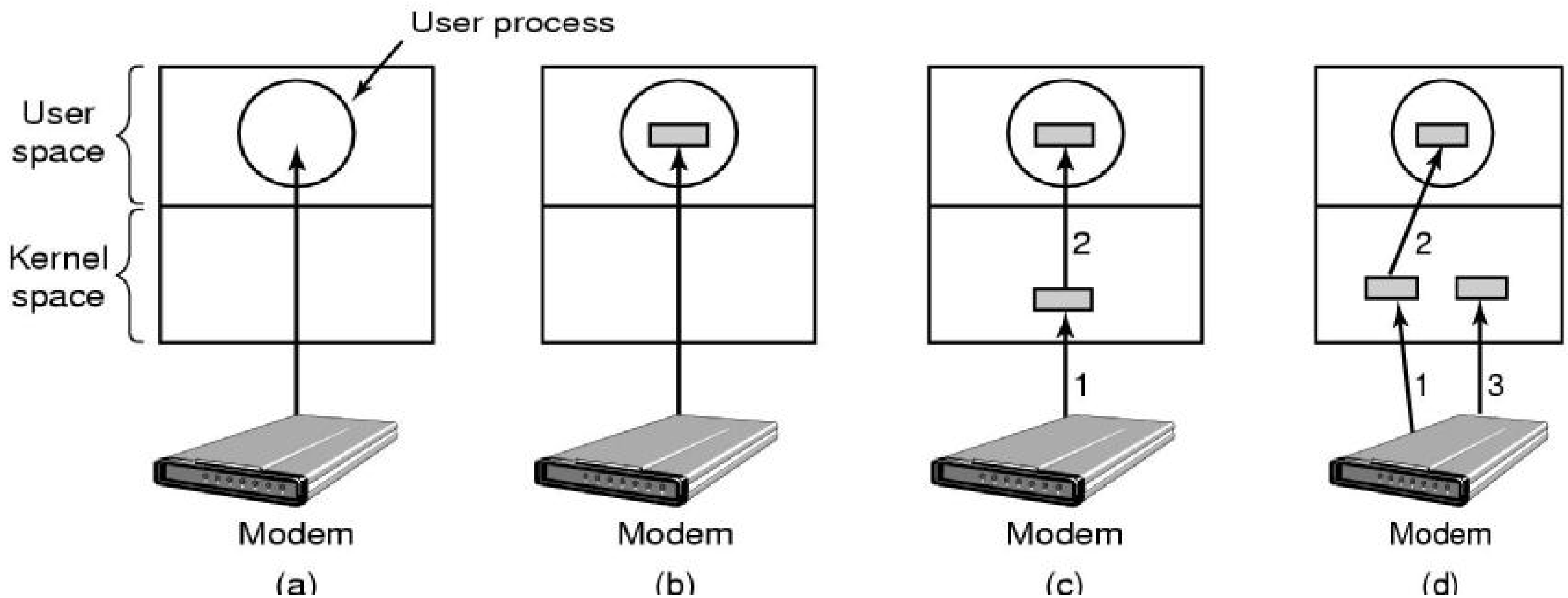
- Device drivers
  - Device-specific code to control each I/O device interacting with device-independent I/O software and interrupt handlers
  - Requires to define a well-defined model and a standard interface of how they interact with the rest of the OS
  - Implementing device drivers:
    - Statically linked with the kernel
    - Selectively loaded into the system during boot time
    - Dynamically loaded into the system during execution (especially for hot pluggable devices)

Device-Independent I/O Software

- Uniform interfacing for device drivers
  - In Unix, devices are modeled as special files
    - They are accessed through the use of system calls such as open(), read(), write(), close(), ioctl(), etc.
    - A file name is associated with each device
  - Major device number locates the appropriate driver
    - Minor device number (stored in i-node) is passed as a parameter to the driver in order to specify the unit to be read or written
  - The usual protection rules for files also apply to I/O devices

Device-Independent I/O Software (Cont'd)

- Buffering
  - (a) Unbuffered
  - (b) Buffered in user space
  - (c) Buffered in the kernel space
  - (d) Double buffering in the kernel



Device-Independent I/O Software (Cont’d)

- Error reporting
  - Many errors are device-specific and must be handled by the appropriate driver, but the framework for error handling is device independent
  - Programming errors vs. actual I/O errors
  - Handling errors
    - Returning the system call with an error code
    - Retrying a certain number of times
    - Ignoring the error
    - Killing the calling process
    - Terminating the system

Device-Independent I/O Software (Cont'd)

- Allocating and releasing dedicated devices
  - Some devices cannot be shared
  - (1) Require processes to perform open()'s on the special files for devices directly
    - The process retries if open() fails
  - (2) Have special mechanisms for requesting and releasing dedicated devices
    - An attempt to acquire a device that is not available blocks the caller

- Device-independent block size
  - Treat several sectors as a single logical block
  - The higher layers only deal with abstract devices that all use the same block size

User-Space I/O Software

- Provided as a library
  - Standard I/O library in C
    - fopen() vs. open()

- Spooling
  - A way of dealing with dedicated I/O devices in a multiprogramming system
  - Implemented by a daemon and a spooling directory
  - Printers, network file transfers, USENET news, mails, etc.

I/O Systems Layers