I/O Systems

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Motivation

Overview

- I/O management is a major component of OS design and operation.
  - Important aspect of computer operation
  - I/O devices vary greatly
  - Various methods to control them
  - Performance management
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- Device drivers encapsulate device details.
  - Present uniform device-access interface to I/O subsystem.

I/O Hardware

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- Incredible variety of I/O devices
  - Storage, e.g., disks, tapes
  - Transmission, e.g., network connections, bluetooth
  - Human-interface, e.g., screen, keyboard, mouse, audio in and out

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- We only need to understand how the devices are attached and how the software can control the hardware.

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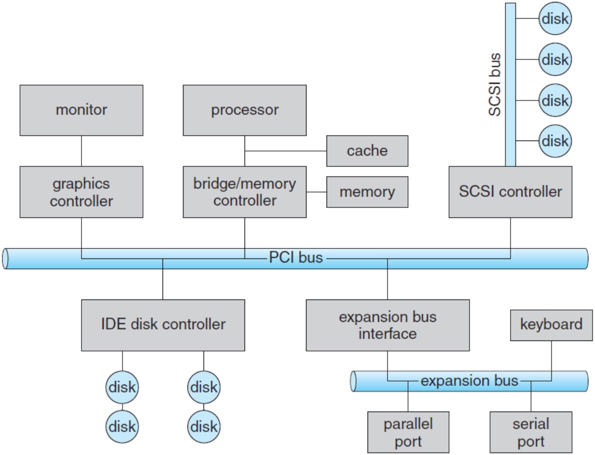
- Port: connection point for device
- Bus: set of wires and a protocol that specifies a set of messages that can be sent on the wires.
- Controller: a collection of electronics that can operate a port, a bus, or a device.
  - Sometimes integrated and sometimes separate circuit board (host adapter)
  - Contains processor, microcode, private memory, bus controller, etc

Bus

- PCI bus: connects the processor-memory subsystem to fast devices.
- Expansion bus: connects relatively slow devices.



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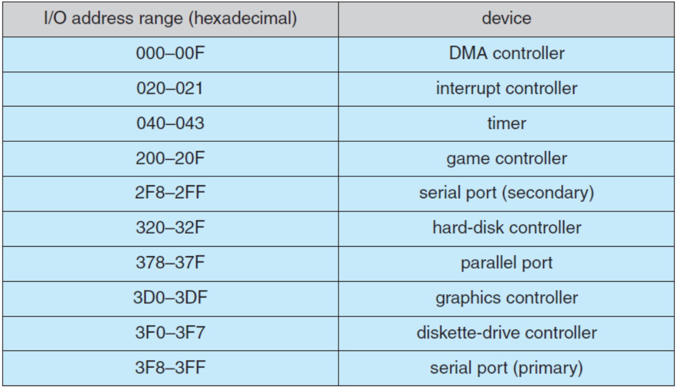
  - Memory-mapped I/O: device data and command registers mapped to processor address space.

Device I/O Port Locations on PCs



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)

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- The control register: written by the host to start a command or to change the mode of a device.

Host Device Interaction

- Polling
- Interrupt
- Direct memory access (DMA)

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  4. Controller sets the busy bit, executes transfer.
  5. Controller clears the busy bit, error bit, and command-ready bit when transfer done.

Polling (2/2)

- Step 1 is busy-wait cycle (polling) to wait for I/O from device.
  - Reasonable if device is fast.
  - But inefficient if device slow.
  - CPU switches to other tasks? but if miss a cycle data overwritten/lost.

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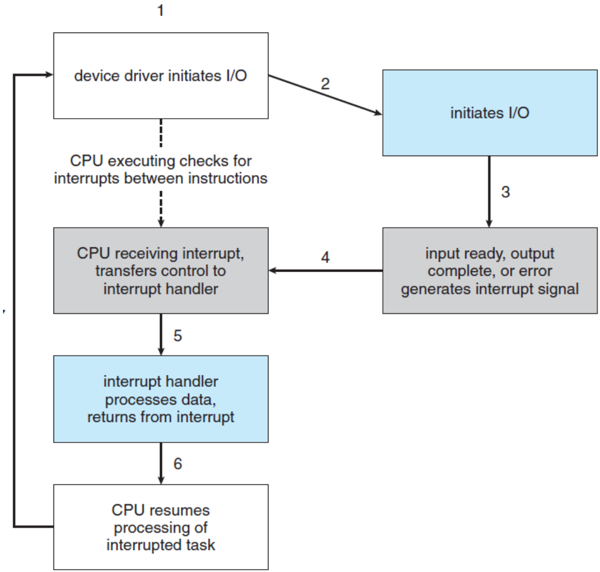
- Two interrupt request lines:
  - Nonmaskable: reserved for events such as unrecoverable memory errors.
  - Maskable: it can be turned off by the CPU.

Interrupt-Driven I/O Cycle



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

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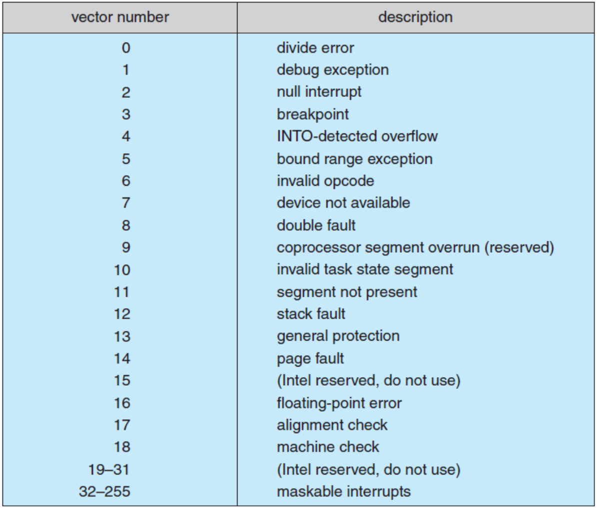
- Computers have more devices than they have address elements in the interrupt vector.
    - Use interrupt chaining: each element in the interrupt vector points to the head of a list of interrupt handlers.

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

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- System call executes via trap to trigger kernel to execute request.
- Multi-CPU systems can process interrupts concurrently.
- Used for time-sensitive processing, frequent, must be fast.

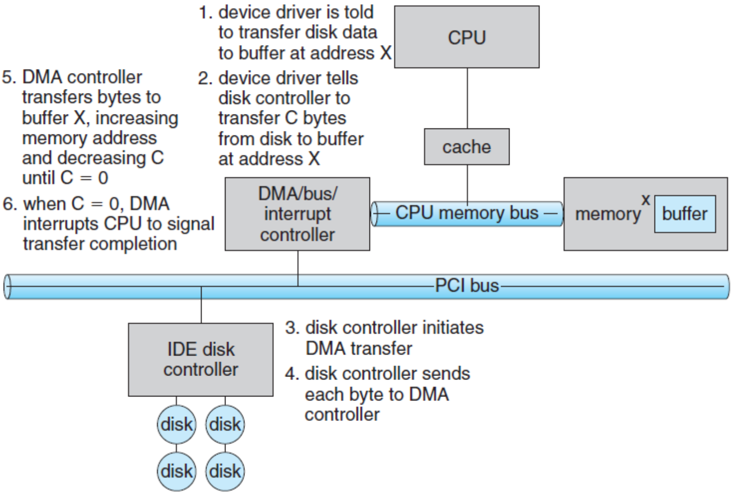
Direct Memory Access (1/2)

- Used to avoid programmed I/O (one byte at a time) for large data movement.
- Requires Direct Memory Access (DMA) controller
- Bypasses CPU to transfer data directly between I/O device and memory.
- Version that is aware of virtual addresses can be even more efficient.

Direct Memory Access (2/2)

- OS writes DMA command block into memory.
  - Source and destination addresses
  - Read or write mode
  - Count of bytes
  - Writes location of command block to DMA controller
  - Bus mastering of DMA controller - grabs bus from CPU: cycle stealing from CPU but still much more efficient
  - When done, interrupts to signal completion

Six Step Process to Perform DMA Transfer



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

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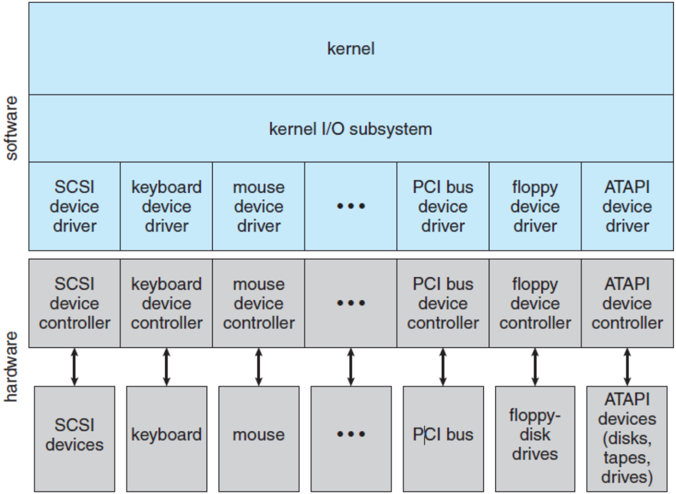
- Device-driver layer hides differences among I/O controllers from kernel.
- New devices talking already-implemented protocols need no extra work.
- Each OS has its own I/O subsystem structures and device driver frameworks.

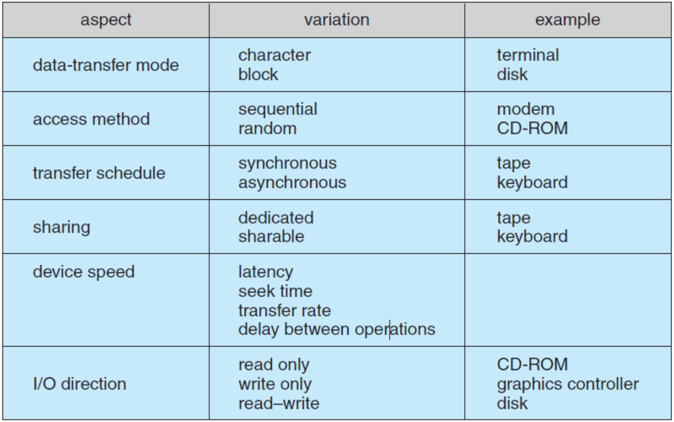
A Kernel I/O Structure



Characteristics of I/O Devices (1/2)

- Devices vary in many dimensions
    - Data-transfer mode: character or block
    - Access method: sequential or random-access
    - Transfer schedule: synchronous or asynchronous (or both)
    - Sharing: sharable or dedicated
    - Device speed: speed of operation
    - I/O direction: read-write, read only, or write only

Characteristics of I/O Devices (2/2)



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

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- Memory-mapped file access: file mapped to virtual memory and clusters brought via demand paging.

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- Linux, Unix, Windows and many others include socket interface.
    - Separates network protocol from network operation.
    - Includes `select()` functionality.

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- Normal resolution about 1/60 second.
- Some systems provide higher-resolution timers.

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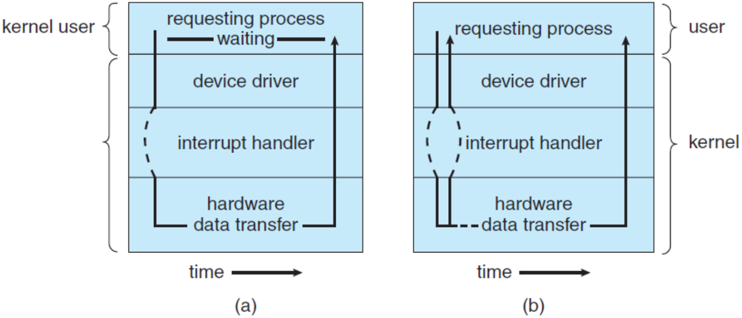
  - `select()` to find if data ready then `read()` or `write()` to transfers.
- Asynchronous: process runs while I/O executes
  - I/O subsystem signals process when I/O completed.

Synchronous vs. Asynchronous I/O Methods



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- For example, Unix `readve()` accepts a vector of multiple buffers to read into or write from.

Kernel I/O Subsystem

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- Kernels provide many services related to I/O:
  - Scheduling
  - Buffering
  - Caching
  - Spooling
  - Device reservation
  - Error handling

Scheduling (1/2)

- Determine a good order in which to execute I/O requests.
- Some I/O request ordering via per-device queue.
- Some OSs try fairness.

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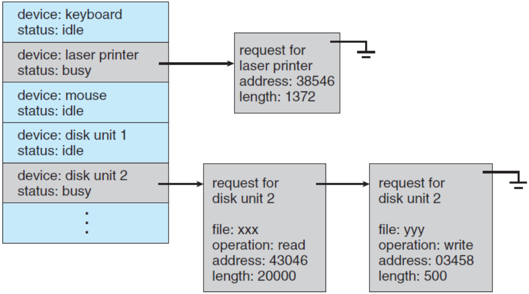

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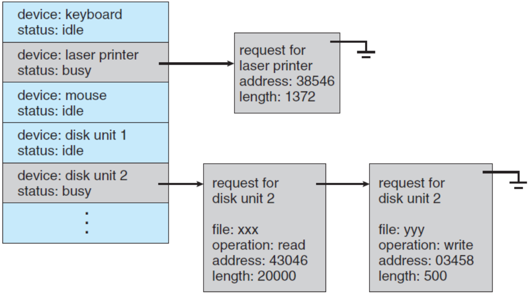

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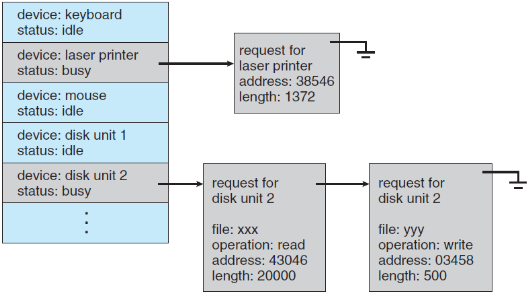
  - The OS attaches the wait queue to a device-status table.
  - The table contains an entry for each I/O device.
  - If the device is busy with a request, the type of request and other parameters will be stored in the table entry for that device.



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- Caching: faster device holding copy of data.
  - Always just a copy
  - Key to performance
  - Sometimes combined with buffering

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- Spooling: a buffer that holds output for a device.
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- Device reservation: provides exclusive access to a device.
  - System calls for allocation and de-allocation
  - Watch out for deadlock

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- System error logs hold problem reports.

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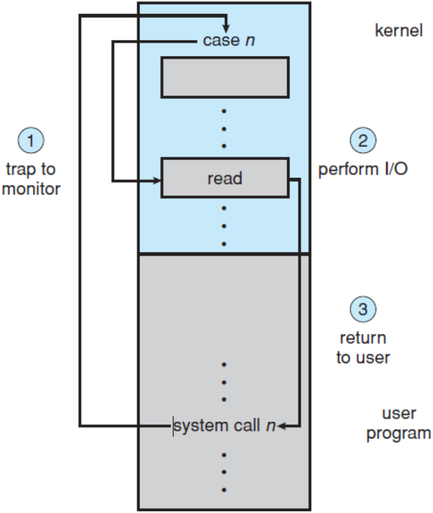
- I/O must be performed via system calls.
- Memory-mapped and I/O port memory locations must be protected too.

Use of a System Call to Perform I/O



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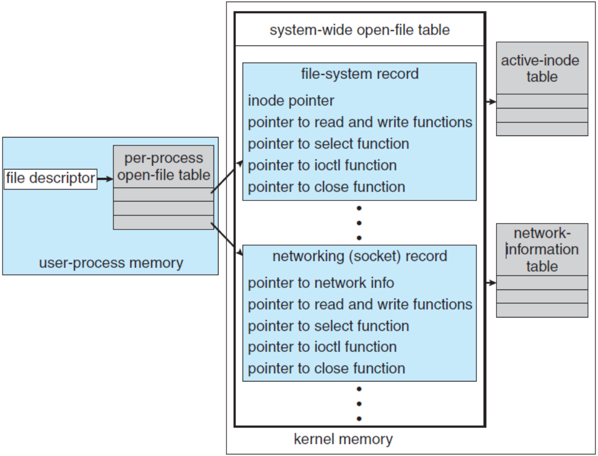
- Some use object-oriented methods and message passing to implement I/O
- E.g., Windows uses message passing.
  - Message with I/O information passed from user mode into kernel.
  - Message modified as it flows through to device driver and back to process.

UNIX I/O Kernel Structure

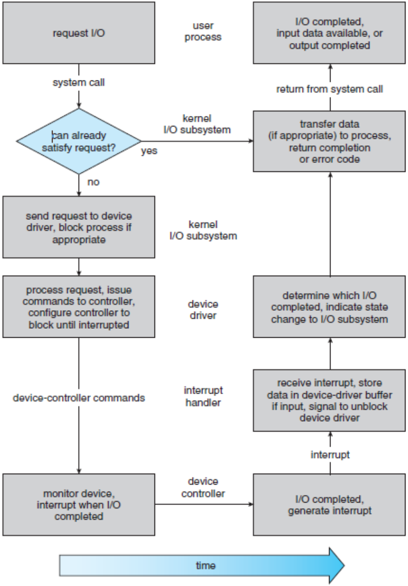


Transforming I/O Requests to Hardware Operations

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

STREAMS (1/2)

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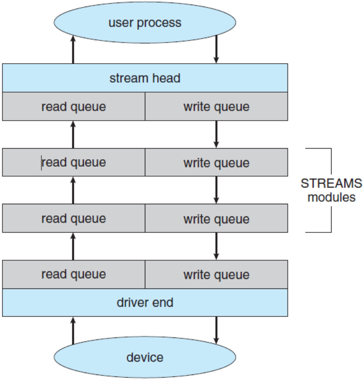
- A STREAM consists of:
  - STREAM head: interfaces with the user process.
  - Driver end: interfaces with the device.
  - Zero or more STREAM modules between them.

STREAMS (2/2)

- Each module contains a read queue and a write queue.
- Message passing is used to communicate between queues.
- Asynchronous internally, synchronous where user process communicates with stream head.

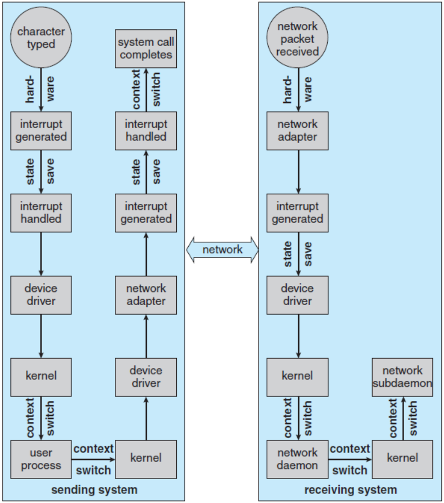


Performance

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
  - Data copying
  - Network traffic especially stressful

Inter-computer Communications



Improving Performance

- Reduce number of context switches

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- Balance CPU, memory, bus, and I/O performance for highest throughput
- Move user-mode processes to kernel

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Questions?

Acknowledgements

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