CS 422/522 Design & Implementation of Operating Systems

Lecture 15: I/O Devices & Drivers

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The big picture

- Previous lectures
  - Management of CPU & concurrency
  - Management of main memory & virtual memory
- Future lectures --- "Management of I/O devices"

Concurrency: a summary

- Thread vs. process
- How to implement threads/processes ?
  - * thread/process state transition diagram
  - * thread/process scheduler
  - * context switch
  - * thread/process creation / finish
- How to write concurrent programs ?
  - * how to eliminate race condition ? how to synchronize?
  - * locks, condition variables, monitors, semaphore, message passing
- Multithreading model (kernel vs. user threads)
- How to deal with deadlocks
- Effective CPU scheduling (local + global)

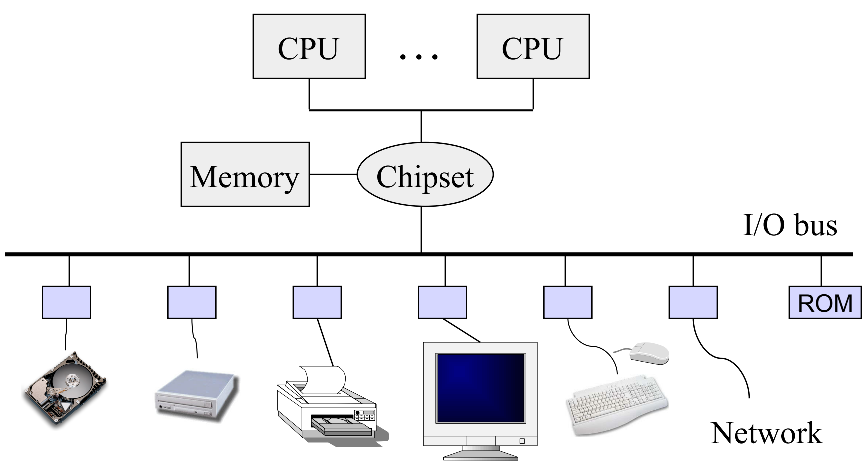
Virtual memory: a summary

- Goal: multiprogramming with protection + illusion of infinite memory
- Approaches
  - HW-based solution for protection
    - * **dual mode operation + address space**
  - address translation: virtual address -> physical address
    - * segmentation + paging + multilevel paging
  - making address translation faster? use TLB
  - demand paged virtual memory
  - techniques for dealing with thrashing
- Other topics
  - kernel memory allocator (similar to malloc-free packages)
  - virtual memory-based hack (exploiting page fault)

The big picture

- Previous lectures
  - Management of CPU & concurrency
  - Management of main memory & virtual memory
- Future lectures --- "Management of I/O devices"
  - This week: I/O devices & device drivers
  - This week: storage devices
  - Next week: file systems
    * File system structure
    * Naming and directories
    * Efficiency and performance
    * Reliability and protection

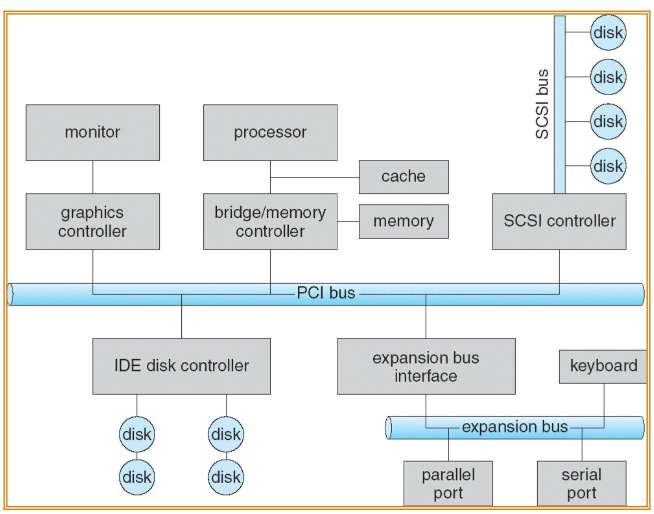
Raw hardware revisited



I/O hardware

- A computer = CPU(s) + Memory + I/O devices
- Common concepts
  - **Port** (a connection point between a machine and a device)
  - **Bus** (one or more devices share a common set of wires)
  - **Controller** (has private processor, microcode, memory)
- The processor gives commands and data to a controller to accomplish an I/O transfer
  - The controller has a few registers for data & control signals
    - typical registers: status, control, data-in, data-out
  - Special I/O instructions (w. port addr) or memory mapped I/O

A typical PC bus structure



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)

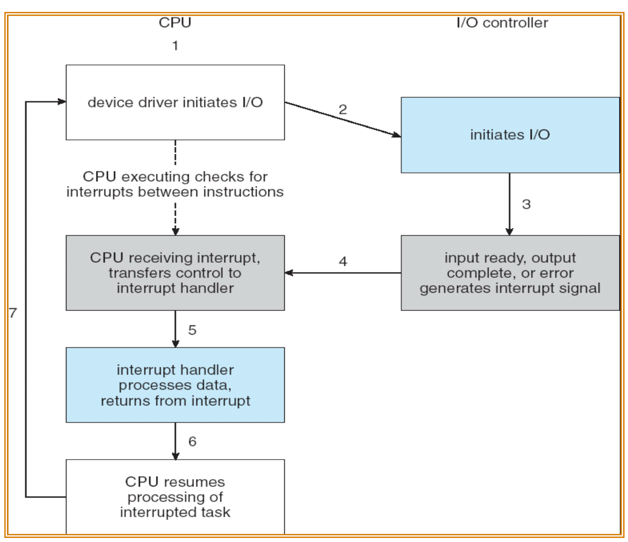
CPU – I/O interaction: polling

- the status register indicates the state of the device
  - a `command-ready` bit and a `busy` bit
- Procedure for writing out a byte:
  - the host reads the "busy" bit until it becomes clear
  - the host issues "write" command, puts the byte in "data-out"
  - The host sets the "command-ready" bit
  - The controller sees "command-ready", sets the "busy" bit
  - The controller executes the "write", does I/O
  - The controller clears the "command-ready" and "busy" bits
- Inefficient: busy-wait cycle to wait for device I/O

CPU – I/O interaction: 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



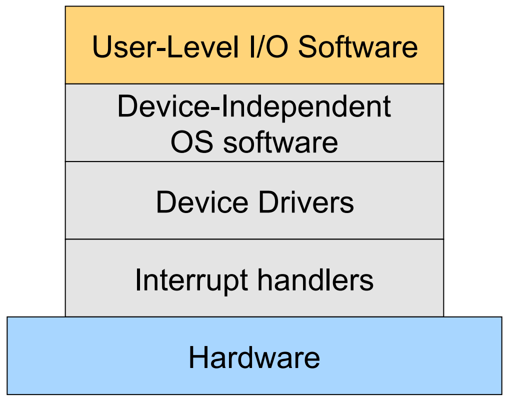
Intel processor event-vector table

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

Interrupt handling revisited/refined

- Save more context
- Mask interrupts if needed
- Set up a context for interrupt service
- Set up a stack for interrupt service
- Acknowledge the interrupt controller, enable it if needed
- Save entire context to PCB
- Run the interrupt service
- Unmask interrupts if needed
- Possibly change the priority of the process
- Run the scheduler

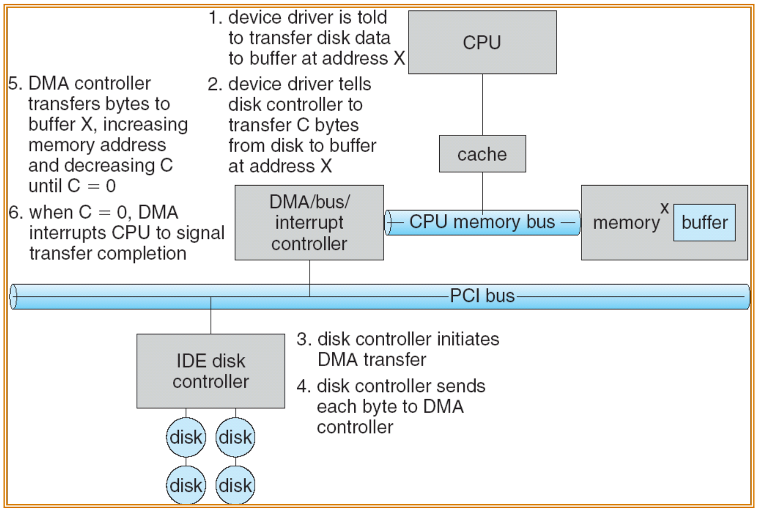
I/O software stack



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

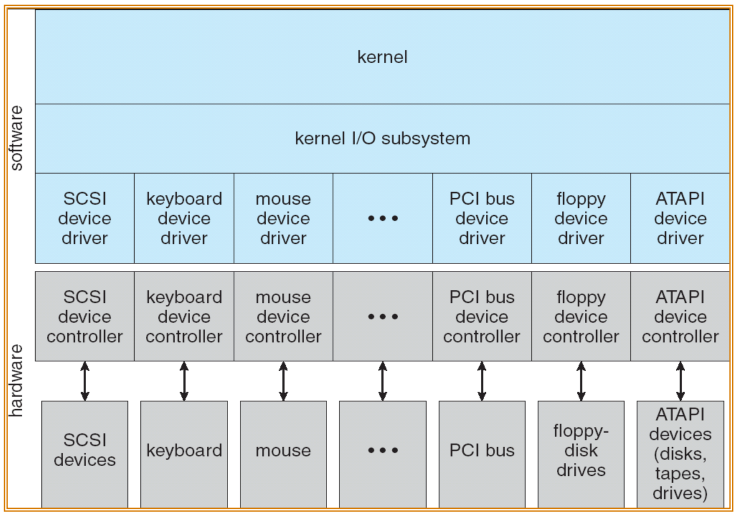
Performing DMA transfer



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**

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 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

- Different enough from the block & character devices to have own interface
- Unix and Windows/NT include socket interface
  - Separates network protocol from network operation
- Approaches vary widely (pipes, FIFOs, streams, queues, mailboxes)

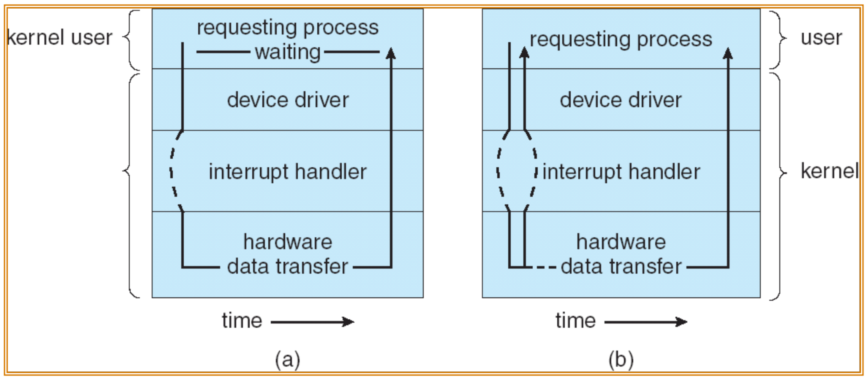
Clocks and timers

- 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

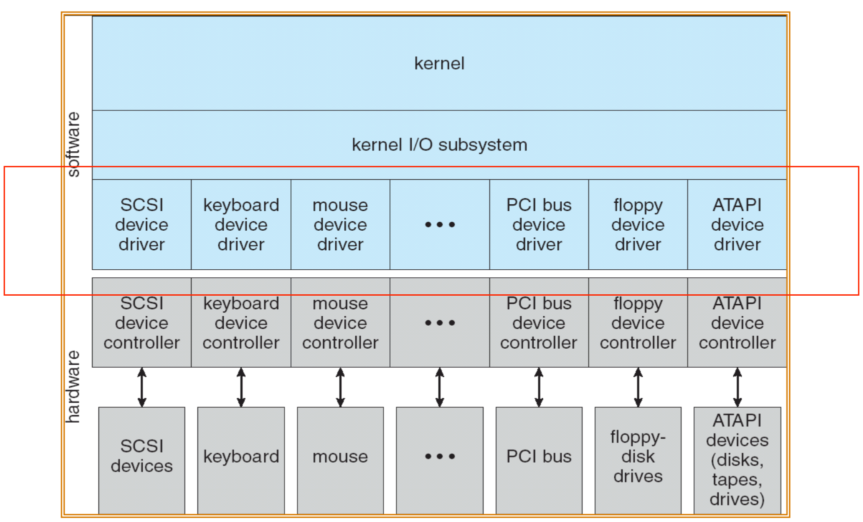
- **Blocking** - process suspended until I/O completed
  - Easy to use and understand
  - Insufficient for some needs
- **Nonblocking** - I/O call returns as much as available
  - User interface, data copy (buffered I/O)
  - Implemented via multi-threading
  - Returns quickly with count of bytes read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

Two I/O methods



Synchronous Asynchronous

Next: device drivers



Device driver design issues

- Operating system and driver communication
  - Commands and data between OS and device drivers
- Driver and hardware communication
  - Commands and data between driver and hardware
- Driver operations
  - Initialize devices
  - Interpreting commands from OS
  - Schedule multiple outstanding requests
  - Manage data transfers
  - Accept and process interrupts
  - Maintain the integrity of driver and kernel data structures

Device driver interface

- Open(deviceNumber)
  - Initialization and allocate resources (buffers)
- Close(deviceNumber)
  - Cleanup, deallocate, and possibly turnoff
- Device driver types
  - Block: fixed sized block data transfer
  - Character: variable sized data transfer
  - Terminal: character driver with terminal control
  - Network: streams for networking

Block device interface

- read(deviceNumber, deviceAddr, bufferAddr)
  - transfer a block of data from “deviceAddr” to “bufferAddr”
- write(deviceNumber, deviceAddr, bufferAddr)
  - transfer a block of data from “bufferAddr” to “deviceAddr”
- seek(deviceNumber, deviceAddress)
  - move the head to the correct position
  - usually not necessary

Character device interface

- read(deviceNumber, bufferAddr, size)
  - reads “size” bytes from a byte stream device to “bufferAddr”
- write(deviceNumber, bufferAddr, size)
  - write “size” bytes from “bufferSize” to a byte stream device

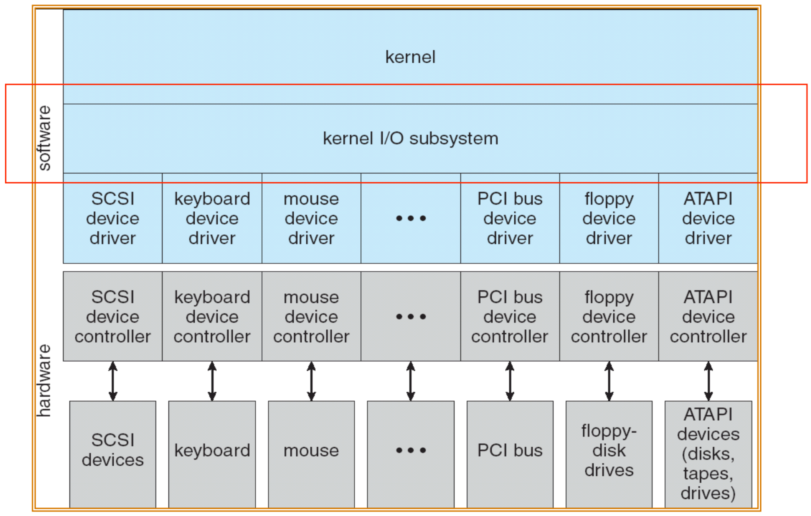
Unix device driver interface entry points

- init(): initialize hardware
- start(): boot time initialization (require system services)
- open(dev, flag, id): initialization for read or write
- close(dev, flag, id): release resources after read and write
- halt(): call before the system is shutdown
- intr(vector): called by the kernel on a hardware interrupt
- read/write calls: data transfer
- poll(pri): called by the kernel 25 to 100 times a second
- ioctl(dev, cmd, arg, mode): special request processing

Device driver: other design issues

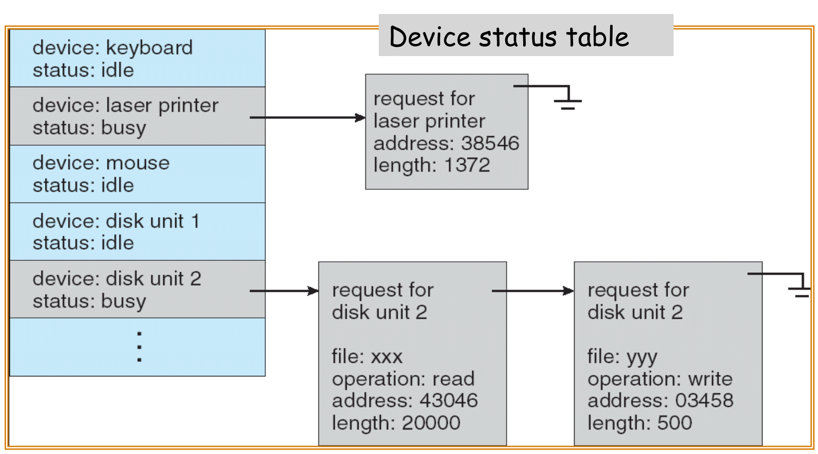
- Build device drivers
  - Statically
  - Dynamically
- How to down load device driver dynamically?
  - Load drivers into kernel memory
  - Install entry points and maintain related data structures
  - Initialize the device drivers

Next: kernel I/O subsystem



Kernel I/O subsystem: "Scheduling"

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



Kernel I/O subsystem (cont'd)

- Buffering - store data in memory while transferring between devices
  - To cope with device speed mismatch
  - To cope with device transfer size mismatch (e.g., packets in networking)
  - To maintain "copy semantics"
    - Copy data from user buffer to kernel buffer
- How to deal with address translation?
  - I/O devices see physical memory, but programs use virtual memory
- Caching - fast memory holding copy of data
  - Always just a copy
  - Key to performance
- Spooling - hold output for a device
  - If a device can serve only one request at a time, i.e., printing

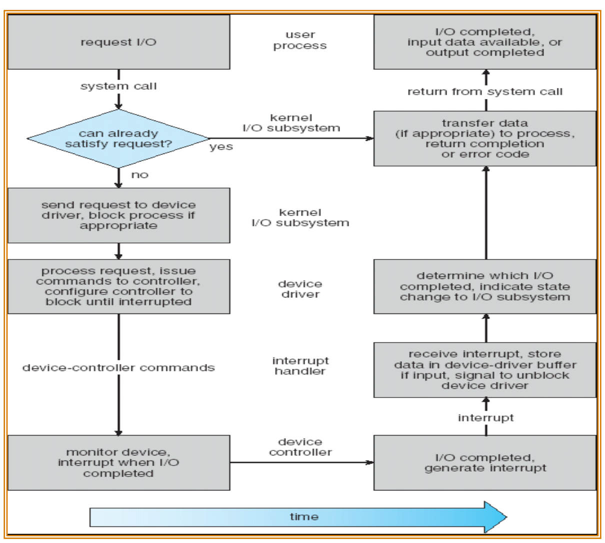
Error handling

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

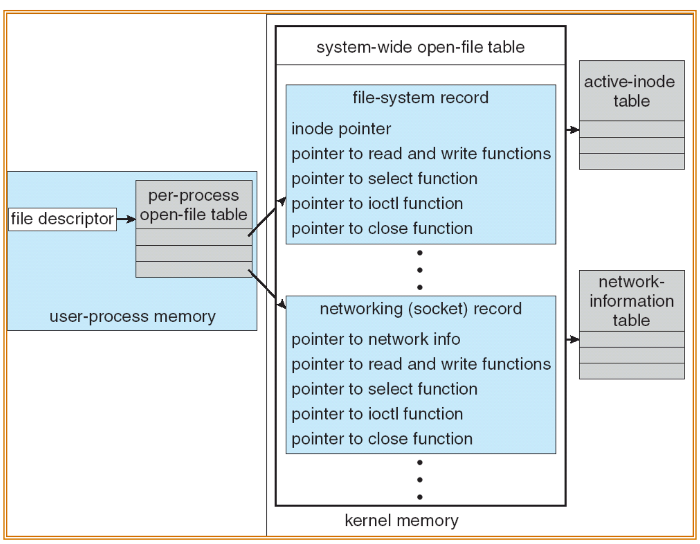
Life cycle of an I/O request



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

Another example: blocked read w. DMA

- A process issues a read call which executes a system call
- System call code checks for correctness and cache
- If it needs to perform I/O, it will issues a device driver call
- Device driver allocates a buffer for read and schedules I/O
- Controller performs DMA data transfer, blocks the process
- Device generates an interrupt on completion
- Interrupt handler stores any data and notifies completion
- Move data from kernel buffer to user buffer and wakeup blocked process
- User process continues