COS 318: Operating Systems

I/O Device Interactions and Drivers

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(http://www.cs.princeton.edu/courses/cos318/)

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Topics

- So far:
  - Management of CPU and concurrency
  - Management of main memory and virtual memory
- Next: Management of the I/O system
  - Interacting with I/O devices
  - Device drivers
  - Storage Devices
- Then, File Systems
  - File System Structure
  - Naming and Directories
  - Efficiency/Performance
  - Reliability and Protection

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Input and Output

- A computer
  - Computation (CPU, memory hierarchy)
  - **Move data into and out of a system** (locketween I/O devices and memory hierarchy)
- Challenges with I/O devices
  - Different categories with different characteristics: storage, networking, displays, keyboard, mouse ...
  - Large number of device drivers to support
  - Device drivers run in kernel mode and can crash systems
- Goals of the OS
  - Provide a generic, consistent, convenient and reliable way to access I/O devices
  - Achieve potential I/O performance in a system

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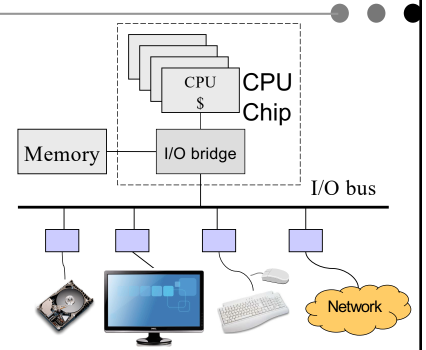
Revisit Hardware

- Compute hardware
  - CPU cores and caches
  - Memory
  - I/O
  - Controllers and logic
- I/O Hardware
  - I/O bus or interconnect
  - I/O device
  - I/O controller or adapter
    - Often on parent board
    - Cable connects it to device
    - Often using standard interfaces: IDE, SATA, SCSI, USB, FireWire…
    - Has registers for control, data signals
    - Processor gives commands and/or data to controller to do I/O



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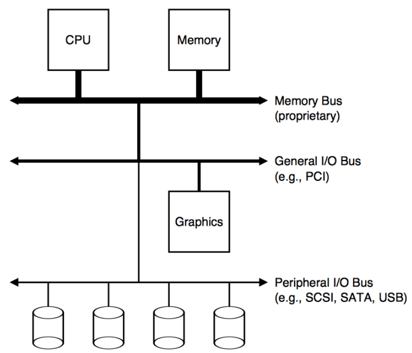
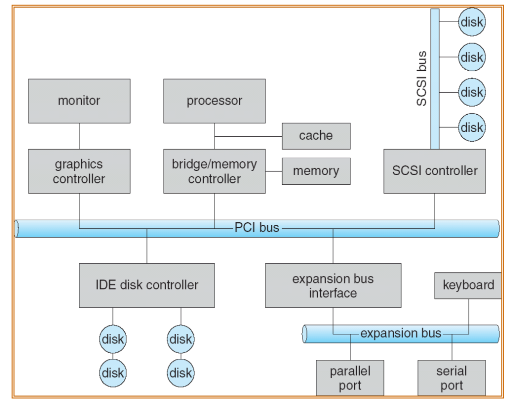
I/O Hierarchy

- As with memory, fast I/O with less “capacity” near CPU, slower I/O with greater “capacity” further away

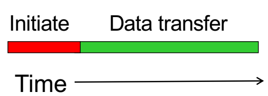


A typical PC bus structure



Performance Characteristics

- Overhead
  - CPU time to initiate an operation
- Latency
  - Time to transfer one bit
  - Overhead + time for 1 bit to reach destination
- Bandwidth
  - Rate at which subsequent bits are transferred or reach destination
  - Bits/sec or Bytes/sec
- In general
  - Different transfer rates
  - Abstraction of byte transfers
  - Amortize overhead over block of bytes as transfer unit



Device	Transfer rate
Keyboard	10Bytes/sec
Mouse	100Bytes/sec
…	…
10GE NIC	1.2GBytes/sec

Interacting with Devices

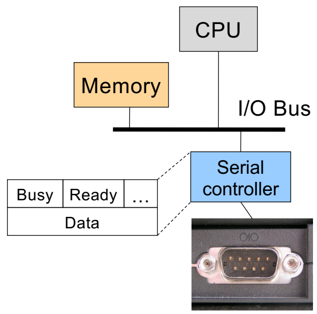
- A device has an interface, and an implementation
  - Interface exposed to external software, typically by device controller
  - Implementation may be hardware, firmware, software
- Mechanisms
  - Programmed I/O (PIO)
  - Interrupts
  - Direct Memory Access (DMA)

Programmed I/O

- Example
  - RS-232 serial port
- Simple serial controller
  - Status registers (ready, busy, …)
  - Data register
- Output

  CPU:
  - Wait until device is not "busy"
  - Write data to "data" register
  - Tell device "ready"

  Device
  - Wait until "ready"
  - Clear "ready" and set "busy"
  - Take data from "data" register
  - Clear "busy"



Polling in Programmed I/O

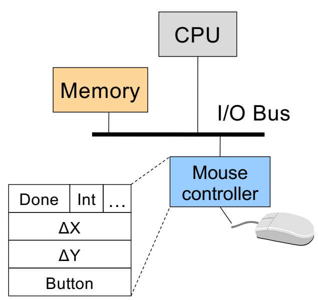
- Wait until device is not "busy"
  - A polling loop
- Advantages
  - Simple
- Disadvantage
  - Slow
  - Waste CPU cycles
- Example
  - If a device runs 100 operations / second, CPU may need to wait for 10 msec or 10,000,000 CPU cycles (1Ghz CPU)

Interrupt-Driven Device

- Allows CPU to avoid polling
- Example: Mouse
- Simple mouse controller
  - Status registers (done, int, …)
  - Data registers (ΔX, ΔY, button)
- Input

  Mouse:
  - Wait until "done"
  - Store ΔX, ΔY, and button into data registers
  - Raise interrupt

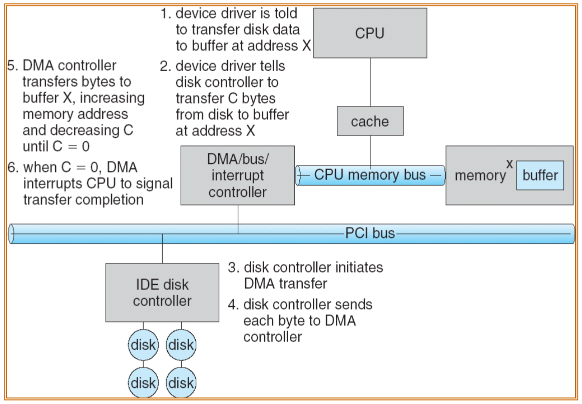
  CPU (interrupt handler)
  - Clear "done"
  - Move ΔX, ΔY, and button into kernel buffer
  - Set "done"
  - Call scheduler



Another Problem

- CPU has to copy data from memory to device
- Takes many CPU cycles, esp for larger I/Os
- Can we get the CPU out of the copying loop, so it can do other things in parallel while data are being copied?

Direct Memory Access (DMA)



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Direct Memory Access (DMA)

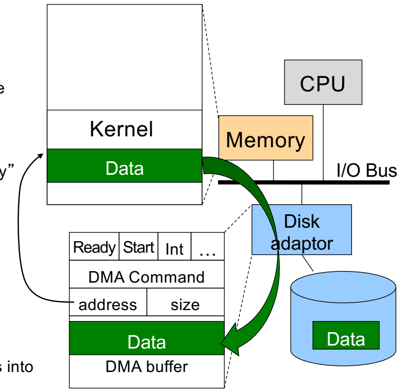
- Example of disk
- A simple disk adaptor
  - Status register (ready, …)
  - DMA command
  - DMA memory address and size
  - DMA data buffer
- DMA Write

  CPU:
  - Wait until DMA device is "ready"
  - Clear "ready"
  - Set DMAWrite, address, size
  - Set "start"
  - Block current thread/process

  Disk adaptor:
  - DMA data to device (size--; address++)
  - Interrupt when "size == 0"

  CPU (interrupt handler):
  - Put the blocked thread/process into ready queue

  Disk: Move data to disk



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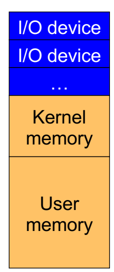
Where Are these I/O "Registers?"

- Explicit I/O "ports" for devices
  - Accessed by privileged instructions (in, out)
- Memory mapped I/O
  - A portion of physical memory for each device
  - Advantages
    - Simple and uniform
    - CPU instructions can access these "registers" as memory
  - Issues
    - These memory locations should not be cached. Why?
    - Mark them not cacheable
- Both approaches are used



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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)

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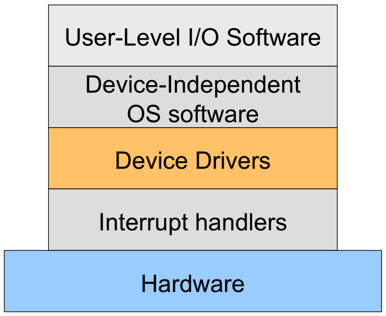
I/O Software Stack



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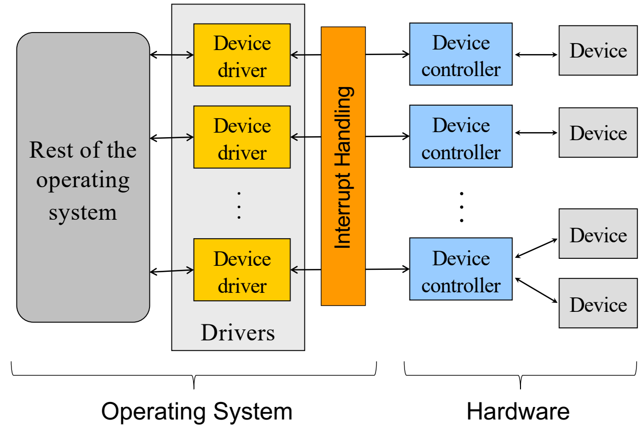
I/O Interface and Device Drivers



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I/O Interface and Device Drivers

- 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

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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

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What Does A Device Driver Do?

- Provide "the rest of the OS" with APIs
  - Init, Open, Close, Read, Write, …
- Interface with controllers
  - Commands and data transfers with hardware controllers
- Driver operations
  - Initialize devices
  - Interpret outstanding requests
  - Manage data transfers
  - Accept and process interrupts
  - Maintain the integrity of driver and kernel data structures

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Device Driver Operations

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

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Character and Block Interfaces

- Character device interface (keyboard, mouse, ports)
  - read(deviceNumber, bufferAddr, size)
    - Reads "size" bytes from a byte stream device to "bufferAddr"
  - write(deviceNumber, bufferAddr, size)
    - Write "size" bytes from "bufferAddr" to a byte stream device
- Block device interface (disk drives)
  - 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

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Network Devices

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

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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

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Unix Device Driver Entry Points

- `init()`
  - Initialize hardware
- `start()`
  - Boot time initialization
- `open(dev, flag, id)` and `close(dev, flag, id)`
  - Initialization resources for read or write and release resources
- `halt()`
  - Call before the system is shutdown
- `intr(vector)`
  - Called by the kernel on a hardware interrupt
- `read(…)` and `write()` calls
  - Data transfer
- `poll(pri)`
  - Called by the kernel 25 to 100 times a second
- `ioctl(dev, cmd, arg, mode)`
  - special request processing

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Synchronous and Asynchronous I/O

- Synchronous I/O
  - Read() or write() will block a user process until its completion
  - Easy to use and understand
  - OS overlaps synchronous I/O with another process
  - Blocking versus non-blocking variants
- Asynchronous I/O
  - Process runs while I/O executes
  - Let user process do other things before I/O completion
  - I/O completion will notify the user process

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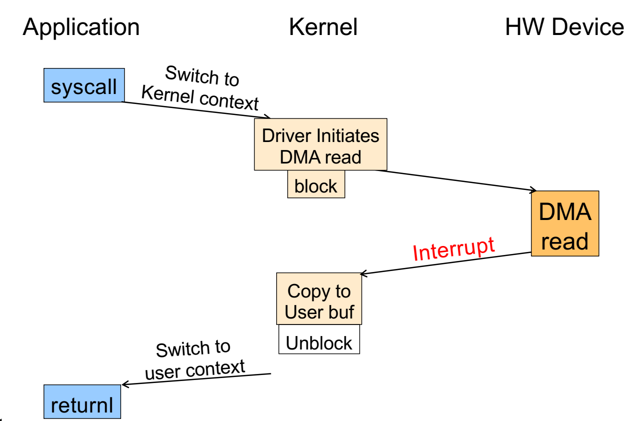
Synchronous Blocking Read



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Synchronous Blocking Read

- A process issues a read call which executes a system call
- System call code checks for correctness and buffer cache
- If it needs to perform I/O, it will issue a device driver call
- Device driver allocates a buffer for read and schedules I/O
- Initiate DMA read transfer
- Block the current process and schedule a ready process
- Device controller performs DMA read transfer
- Device sends an interrupt on completion
- Interrupt handler wakes up blocked process (make it ready)
- Move data from kernel buffer to user buffer
- System call returns to user code
- User process continues

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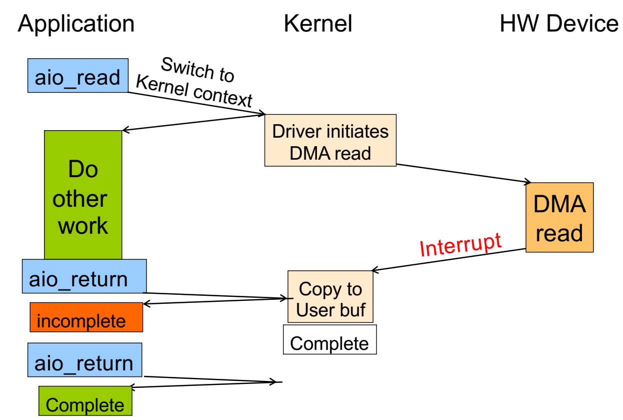
Asynchronous Read



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Asynchronous I/O

POSIX P1003.4 Asynchronous I/O interface functions:
(available in Solaris, AIX, Tru64 Unix, Linux 2.6,…)

- aio_read: begin asynchronous read
- aio_write: begin asynchronous write
- aio_cancel: cancel asynchronous read/write requests
- aio_error: retrieve Asynchronous I/O error status
- aio_fsync: asynchronously force I/O completion, and sets errno to ENOSYS
- aio_return: retrieve status of Asynchronous I/O operation
- aio_suspend: suspend until Asynchronous I/O completes
- lio_listio: issue list of I/O requests

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Other Device Driver Design Issues

- Statically install device drivers
  - Reboot OS to install a new device driver
- Dynamically download device drivers
  - No reboot, but use an indirection
  - Load drivers into kernel memory
  - Install entry points and maintain related data structures
  - Initialize the device drivers

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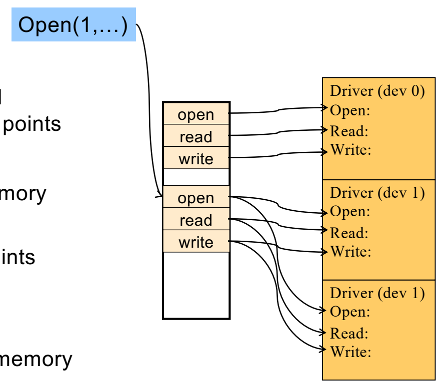
Dynamic Binding of Device Drivers

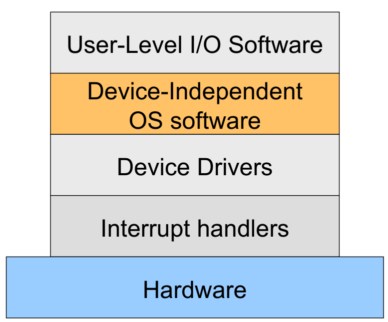
- Indirection
  - Indirect table for all device driver entry points
- Download a driver
  - Allocate kernel memory
  - Store driver code
  - Link up all entry points
- Delete a driver
  - Unlink entry points
  - Deallocate kernel memory



Issues with Device Drivers

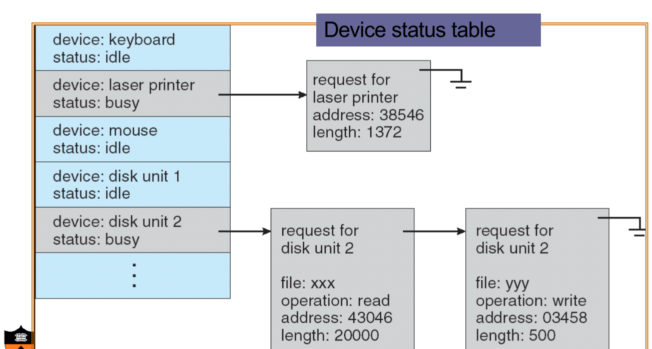
- Flexible for users, ISVs and IHVs
  - Users can download and install device drivers
  - Vendors can work with open hardware platforms
- Dangerous
  - Device drivers run in kernel mode
  - Bad device drivers can cause kernel crashes and introduce security holes
- Progress on making device drivers more secure
- How much of OS code is device drivers?

I/O Software Stack



Kernel I/O subsystem: "Scheduling"

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



Kernel I/O subsystem (contd.)

- 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)
- How to deal with address translation?
  - I/O devices see physical memory, but programs use virtual memory
  - E.g. DMA may require contiguous physical addresses
- Caching - fast memory holding copy of data
  - Reduce need to go to devices, key to performance
- Spooling - hold output for a device
  - If a device can serve only one request at a time, i.e., printing
  - Used to avoid deadlock problems

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Kernel I/O Subsystem (contd.)

- Error handling
  - OS can recover from disk read, device unavailable, transient write failures
  - Most return an error no. or code when I/O request fails
  - System error logs hold problem reports
- 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 locations must be protected too

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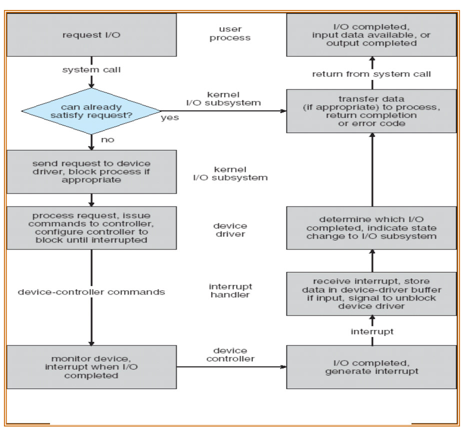
Life cycle of an I/O request



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Kernel data structures

- State info for I/O components, including open file tables, network connections, character device state
- Many complex data structures to track buffers, memory allocation, “dirty” blocks
- Some use object-oriented methods and message passing to implement I/O

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Summary

- IO Devices
  - Programmed I/O is simple but inefficient
  - Interrupt mechanism supports overlap of CPU with I/O
  - DMA is efficient, but requires sophisticated software
- Synchronous and Asynchronous I/O
  - Asynchronous I/O allows user code to perform overlapping
- Device drivers
  - Dominate the code size of OS
  - Dynamic binding is desirable for many devices
  - Device drivers can introduce security holes
  - Progress on secure code for device drivers but completely removing device driver security is still an open problem
- Role of device-independent kernel software

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