COS 318: Operating Systems

I/O Device Interactions and Drivers

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

Topics

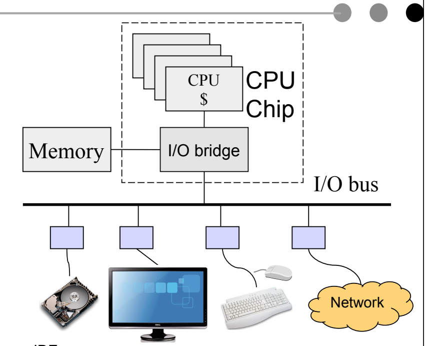
- So far:
  - Management of CPU and concurrency
  - Management of main memory and virtual memory
- Next: Management of the I/O system
  - Interacting with I/O devices
  - Device drivers
  - Storage Devices
- Then, File Systems
  - File System Structure
  - Naming and Directories
  - Efficiency/Performance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

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

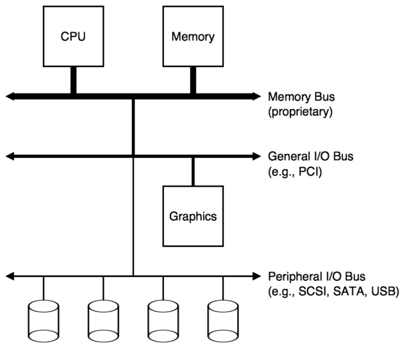
Revisit Hardware

- 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
    - Special I/O instructions (w. port addr.) or memory mapped I/O

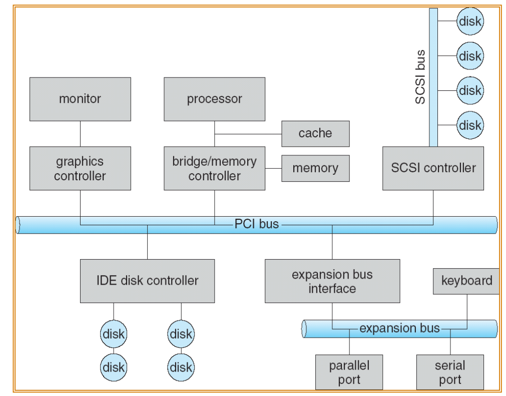


I/O Hierarchy

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

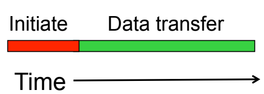


A typical PC bus structure



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

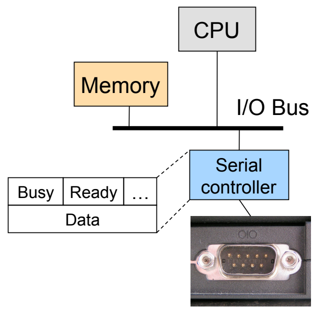
- A device has an interface, and an implementation
  - Interface exposed to external software, typically by device controller
  - Implementation may be hardware, firmware, software
- Mechanisms
  - Programmed I/O (PIO)
  - Interrupts
  - Direct Memory Access (DMA)

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

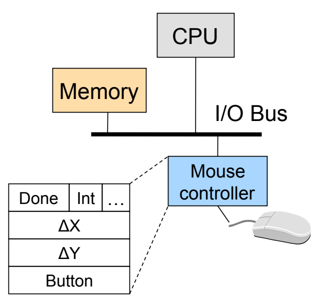
- Wait until device is not "busy"
  - A polling loop
  - May also poll to wait for device to complete its work
- Advantages
  - Simple
- Disadvantage
  - Slow
  - Waste CPU cycles
- Example
  - If a device runs 100 operations / second, CPU may need to wait for 10 msec or 10,000,000 CPU cycles (1Ghz CPU)

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



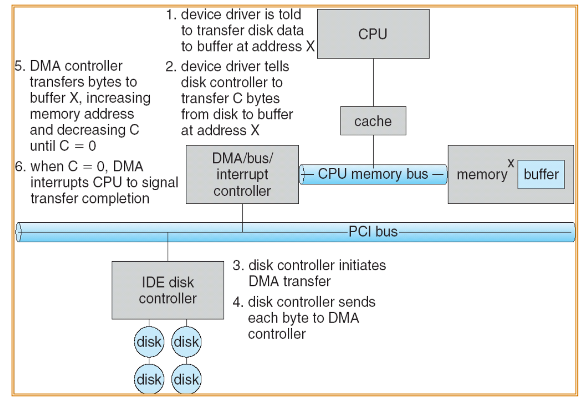
Interrupt Handling Revisited/Refined

- 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 context to PCB
- Run the interrupt service
- Unmask interrupts if needed
- Possibly change the priority of the process
- Run the 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)



Direct Memory Access (DMA)

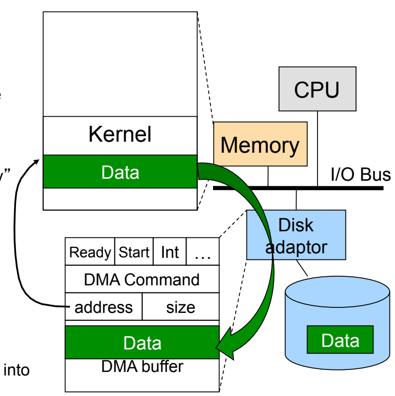
- Example of disk
- A simple disk adaptor
  - Status register (ready, …)
  - DMA command
  - DMA memory address and size
  - DMA data buffer
- DMA Write

  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"

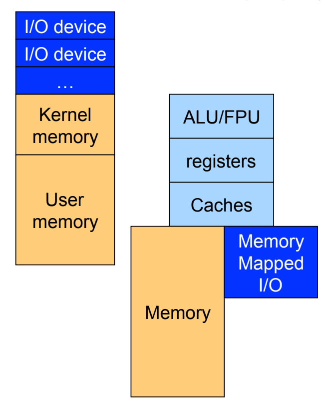
  CPU (interrupt handler):
  - Put the blocked thread/process into ready queue

  Disk: Move data to disk



Where Are these I/O "Registers?"

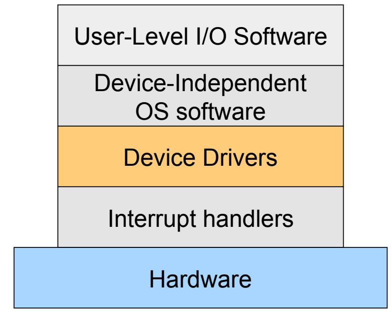
- Explicit I/O "ports" for devices
  - Accessed by privileged instructions (in, out)
- Memory mapped I/O
  - A portion of physical memory for each device
  - Advantages
    - Simple and uniform
    - CPU instructions can access these "registers" as memory
  - Issues
    - These memory locations should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



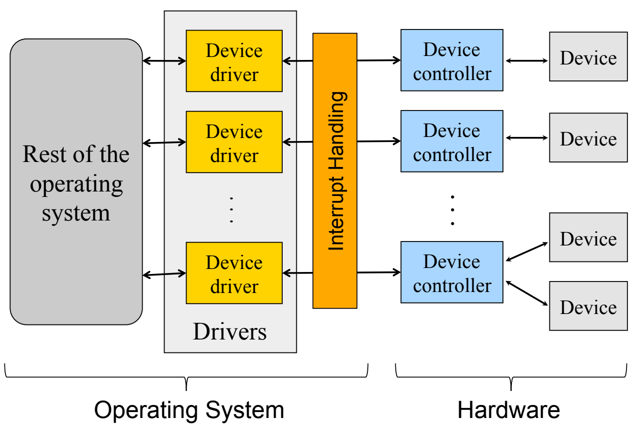
Device I/O port locations on PCs (partial)

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)

I/O Software Stack



I/O Interface and Device Drivers



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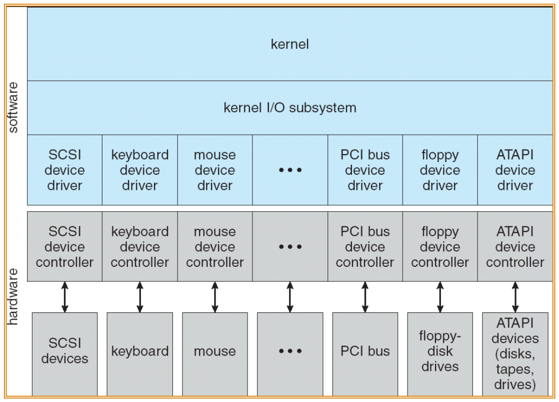
I/O Interface and Device Drivers

- 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

Example 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

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

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
  - Block: fixed sized block data transfer
  - Terminal: character driver with terminal control
  - Network: streams for networking

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

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

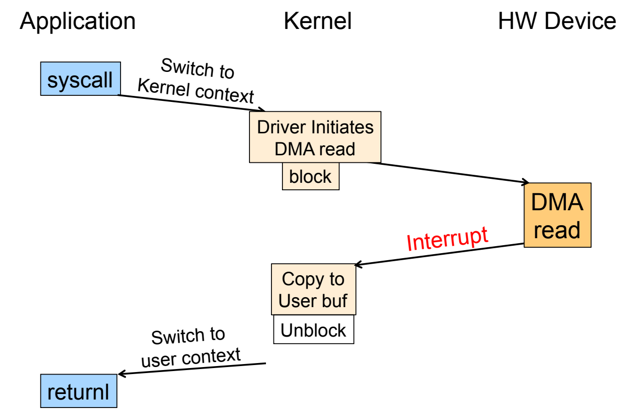
Unix Device Driver Entry Points

- `init()`
  - Initialize hardware
- `start()`
  - Boot time initialization (require system services)
- `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

Synchronous and Asynchronous I/O

- Synchronous I/O
  - Calling process waits for I/O call to return before doing anything
  - Blocking 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
  - Nonblocking I/O
    - Return as much data (and count of it) as avaialble right away
- 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

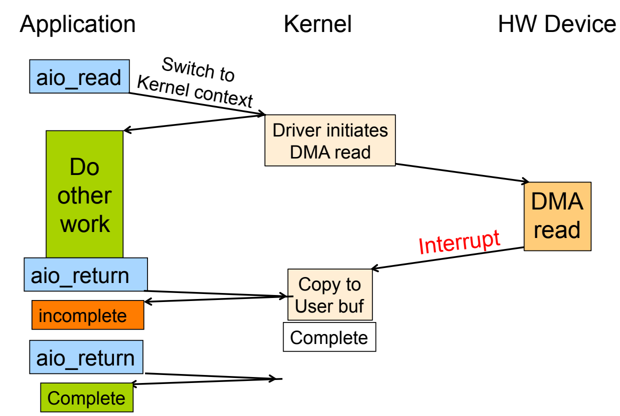
Synchronous Blocking Read



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

Asynchronous Read



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

Why Buffering in Kernel?

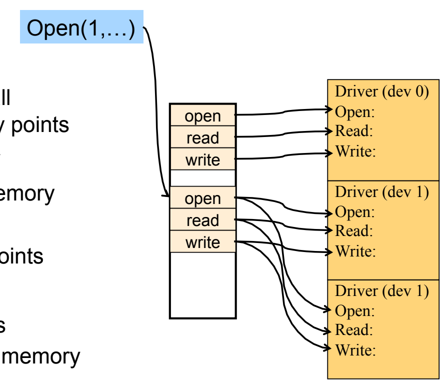
- Speed mismatch between the producer and consumer
  - Character device and block device, for example
  - Adapt different data transfer sizes (packets vs. streams)
- DMA requires contiguous physical memory
  - I/O devices see physical memory
  - User programs use virtual memory
- Spooling
  - Avoid deadlock problems
- Caching
  - Reduce I/O operations

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

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 driver more secure
- How much of OS code is device drivers?

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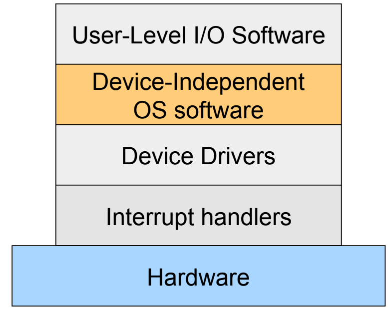
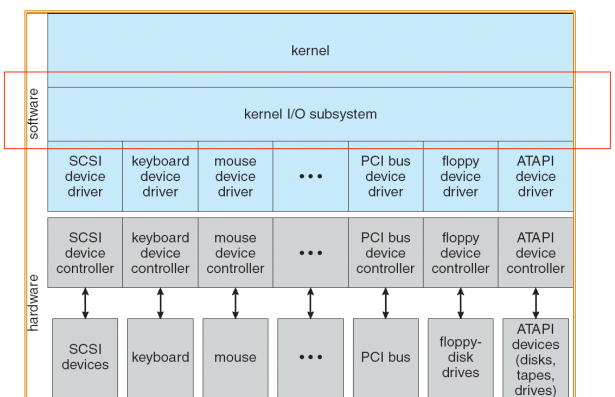
I/O Software Stack

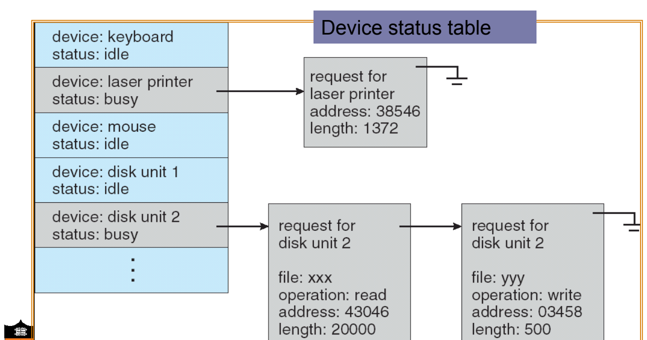


Next: Kernel I/O Subsystem



Kernel I/O subsystem: "Scheduling"

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



Kernel I/O subsystem (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)
  - 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
  - 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

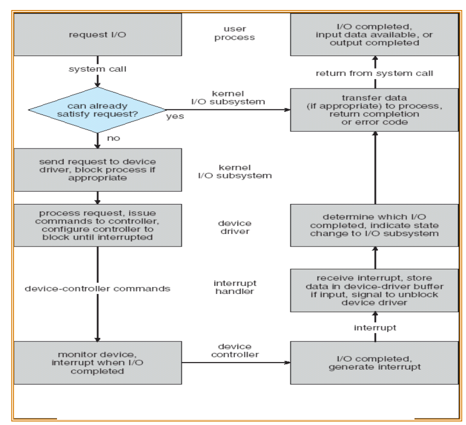
Error handling

- 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

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

- 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

From User Request 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

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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