# COS 318: Operating Systems

# I/O Device and Drivers

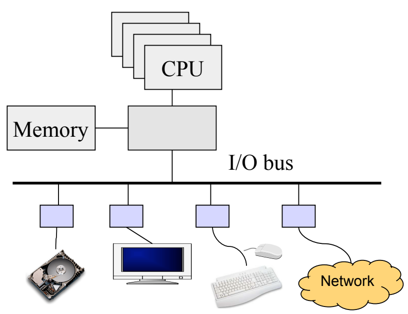
## Input and Output

- A computer's job is to process data
  - Computation (CPU, cache, and memory)
  - **Move data into and out of a system** (between I/O devices and memory)
- Challenges with I/O devices
  - Different categories: storage, networking, displays, etc.
  - 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
  - As device-independent as possible
  - Don't hurt the performance capability of the I/O system too much



## Revisit Hardware

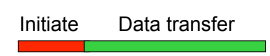
- Compute hardware
  - CPU and caches
  - Chipset
  - Memory
- I/O Hardware
  - I/O bus or interconnect
  - I/O controller or adaptor
  - I/O device
- Two types of I/O
  - Programmed I/O (PIO)
    - CPU does the work of moving data
  - Direct Memory Access (DMA)
    - CPU offloads the work of moving data to DMA controller





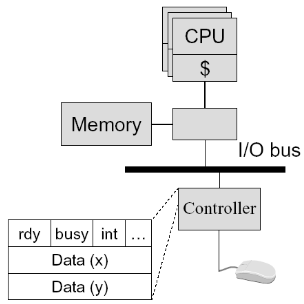

## Definitions and General Method

- Overhead
  - Time that the CPU is tied up initiating/ ending an operation
- Latency
  - Time to transfer one bit (typ. byte)
  - Overhead + 1 bit reaches destination
- Bandwidth
  - Rate of I/O transfer, once initiated
  - Mbytes/sec
- General method
  - Higher level abstractions of byte transfers
  - Batch transfers into block I/O for efficiency to amortize overhead and latency over a large unit



## Programmed Input Device

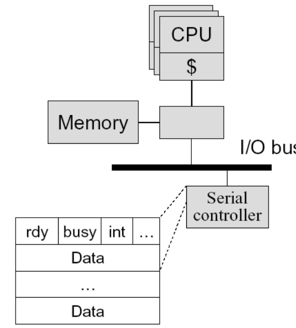
- Device controller
  - Status register
    ready: tells if the host is done
    busy: tells if the controller is done
    int: interrupt
    …
  - Data registers
- A simple mouse design
  - Put (X, Y) in data registers on a move
  - Interrupt
- Input on an interrupt
  - Read values in X, Y registers
  - Set ready bit
  - Wake up a process/thread or execute a piece of code






## Programmed Output Device

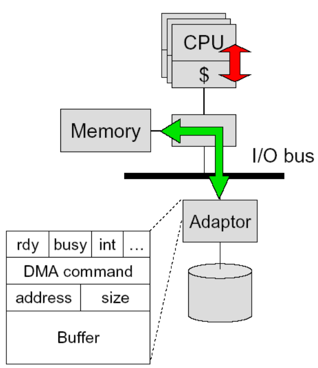
- Device
  - Status registers (ready, busy, … )
  - Data registers
- Example
  - A serial output device
- Perform an output
  - Wait until ready bit is clear
  - Poll the busy bit
  - Writes the data to register(s)
  - Set ready bit
  - Controller sets busy bit and transfers data
  - Controller clears the ready bit and busy bit





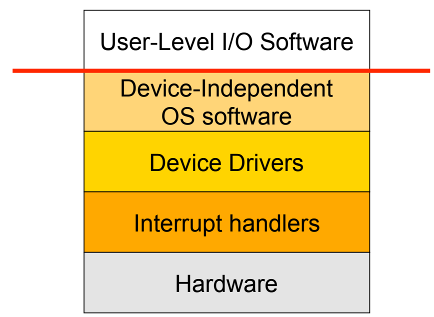

## Direct Memory Access (DMA)

- DMA controller or adaptor
  - Status register
    (ready, busy, interrupt, …)
  - DMA command register
  - DMA register (address, size)
  - DMA buffer
- Host CPU initiates DMA
  - Device driver call (kernel mode)
  - Wait until DMA device is free
  - Initiate a DMA transaction
    (command, memory address, size)
  - Block
- Controller performs DMA
  - DMA data to device
    (size--; address++)
  - Interrupt on completion (size == 0)
- Interrupt handler (on completion)
  - Wakeup the blocked process






## I/O Software Stack

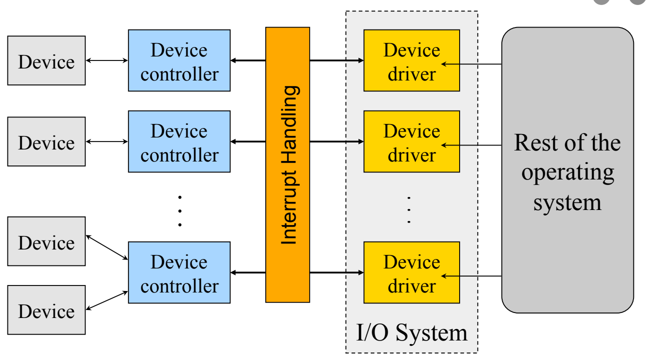


## Recall Interrupt Handling

- Save context (registers that hw hasn't saved, PSW etc)
- Mask interrupts if needed
- Set up a context for interrupt service
- Set up a stack for interrupt service
- Acknowledge interrupt controller, perhaps enable it
- Save entire context to PCB
- **Run the interrupt service**
- Unmask interrupts if needed
- Possibly change the priority of the process
- Run the scheduler
- Then OS will set up context for next process, load registers and PSW, start running process …



## Device Drivers




- Manage the complexity and differences among specific types of devices (disk vs. mouse, different types of disks …)
- Each handles one type of device or small class of them (eg SCSI)



## Typical Device Driver Design

- 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 responsibilities
  - 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



## Simplified Device Driver Behavior

- Check input parameters for validity, and translate them to device-specific language
- Check if device is free (wait or block if not)
- Issue commands to control device
  - Write them into device controller's registers
  - Check after each if device is ready for next (wait or block if not)
- Block or wait for controller to finish work
- Check for errors, and pass data to device-indept software
- Return status information
- Process next queued request, or block waitng for next
- Challenges:
  - Must be reentrant (can be called by an interrupt while running)
  - Handle hot-pluggable devices and device removal while running
  - Complex and many of them; bugs in them can crash system

## Types of I/O Devices

- Block devices
  - Organize data in fixed-size blocks
  - Transfers are in units of blocks
  - Blocks have addresses and data are therefore addressable
  - E.g. hard disks, USB disks, CD-ROMs
- Character devices
  - Delivers or accepts a stream of characters, no block structure
  - Not addressable, no seeks
  - Can read from stream or write to stream
  - Printers, network interfaces, terminals
- Like everything, not a perfect classification
  - E.g. tape drives have blocks but not randomly accessed
  - Clocks are I/O devices that just generate interrupts

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## Typical Device Speeds

| | | |
|---|---|---|
| Keyboard | 10 | B/s |
| Mouse | 100 | B/s |
| Compact Flash card | 40 | MB/s |
| USB 2.0 | 60 | MB/s |
| 52x CD-ROM | 7.8 MB/s | |
| Scanner | 400 | KB/s |
| 56K modem | 7 | KB/s |
| 802.11g wireless net | 6.75 | MB/s |
| Gigabit Ethernet | 320 | MB/s |
| FireWire-1 | 50 | MB/s |
| FireWire 800 | 100 | MB/s |
| SCSI Ultra-2 disk | 80 | MB/s |
| SATA disk | 300 | MB/s |
| PCI bus | 528 | MB/s |
| Ultrium tape | 320 | MB/s |

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## 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
- Interfaces for block and character/stream oriented devices (at least) are different
  - Like to preserve same interface within each category

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## Character and Block Device Interfaces

- 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 “bufferAddr” to a byte stream device
- 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

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## Unix Device Driver Interface 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 afterwards
- `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 vs. Asynchronous I/O

- Synchronous I/O
  - read() or write() will block a user process until its completion
  - OS overlaps synchronous I/O with another process
- Asynchronous I/O
  - read() or write() will not block a user process
  - user process can do other things before I/O completion
  - I/O completion will notify the user process



## Detailed Steps of Blocked Read

- A process issues a read call which executes a system call
- System call code checks for correctness
- 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
- Block the current process and schedule a ready process
- Device generates an interrupt on completion
- Interrupt handler stores any data and notifies completion
- Move data from kernel buffer to user buffer
- Wakeup blocked process (make it ready)
- User process continues when it is scheduled to run



## Asynchronous I/O

- API
  - Non-blocking read() and write()
  - Status checking call
  - Notification call
  - Different form the synchronous I/O API
- Implementation
  - On a write
    - Copy to a **system buffer**, initiate the write and return
    - Interrupt on completion or check status
  - On a read
    - Copy data from a **system buffer** if the data are there
    - Otherwise, return with a special status

## Why Buffering?

- Speed mismatch between the producer and consumer
  - Character device and block device, for example
  - Adapt different data transfer sizes (packets vs. streams)
- Deal with address translation
  - I/O devices see physical memory
  - User programs use virtual memory
- Caching
  - Avoid I/O operations
- User-level and kernel-level buffering
- Spooling
  - Avoid user processes holding up resources in multi-user environment



## Think About Performance

- A terminal connects to computer via a serial line
  - Type character and get characters back to display
  - RS-232 is bit serial: start bit, character code, stop bit (9600 baud)
- Do we have any cycles left?
  - What should the overhead of an interrupt be
- Technique to minimize interrupt overhead
  - Interrupt coalescing

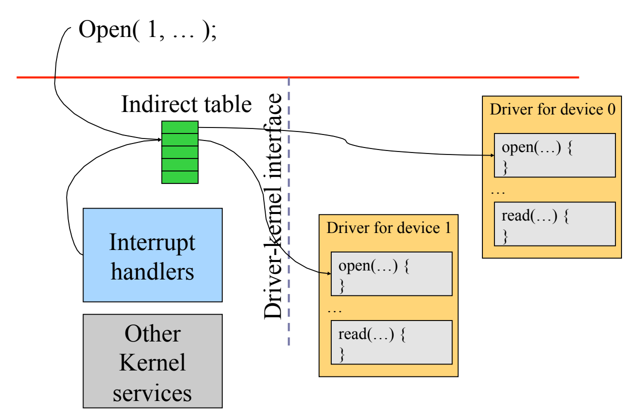


## Other Design Issues

- Build device drivers
  - Statically
    - A new device driver requires reboot OS
  - Dynamically
    - Download a device driver without rebooting OS
    - Almost every modern OS has this capability
- How to down load device driver dynamically?
  - Load drivers into kernel memory
  - Install entry points and maintain related data structures
  - Initialize the device drivers



## Dynamic Binding: Indirection



## 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 methods
  - Device drivers run in kernel mode
  - Bad device drivers can cause kernel crashes and introduce security holes
- Progress on making device driver more secure
  - Checking device driver codes
  - Build state machines for device drivers

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## Summary

- Device controllers
  - Programmed I/O is simple but inefficient
  - DMA is efficient (asynchronous) and complex
- Device drivers
  - Dominate the code size of OS
  - Dynamic binding is desirable for desktops or laptops
  - Device drivers can introduce security holes
  - Progress on secure code for device drivers but completely removing device driver security is still an open problem

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