ECE 650
Systems Programming & Engineering

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I/O Handling

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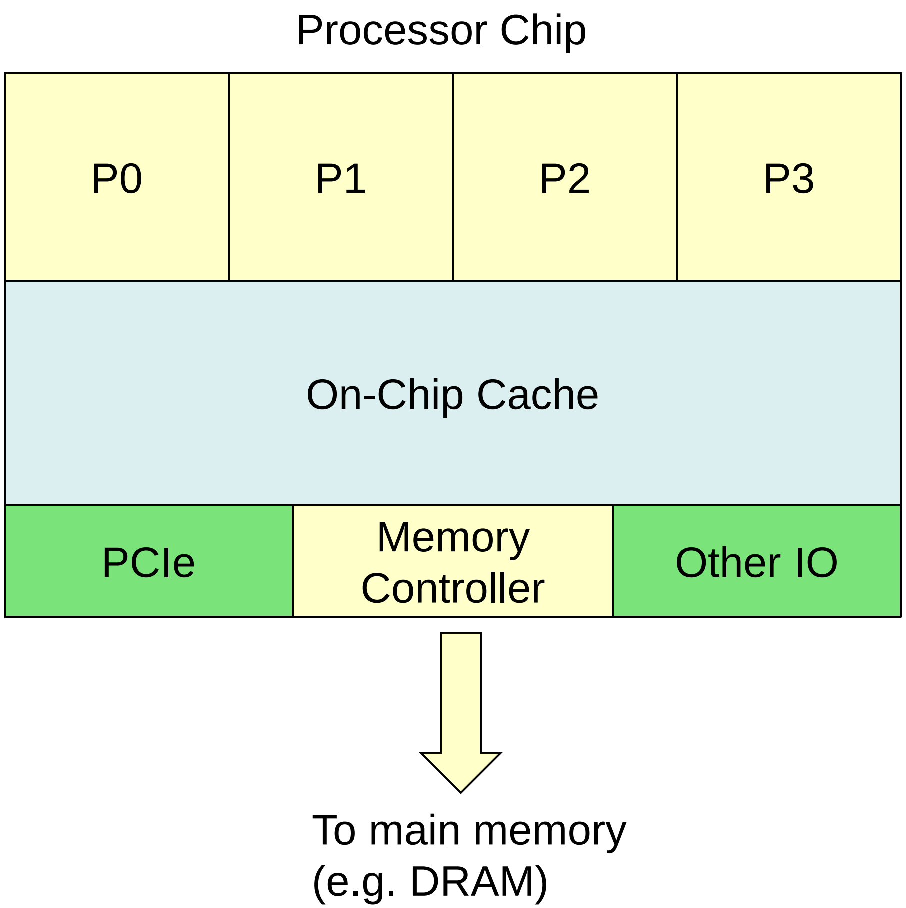
Slides are adapted from Brian Rogers (Duke)

Input/Output (I/O)

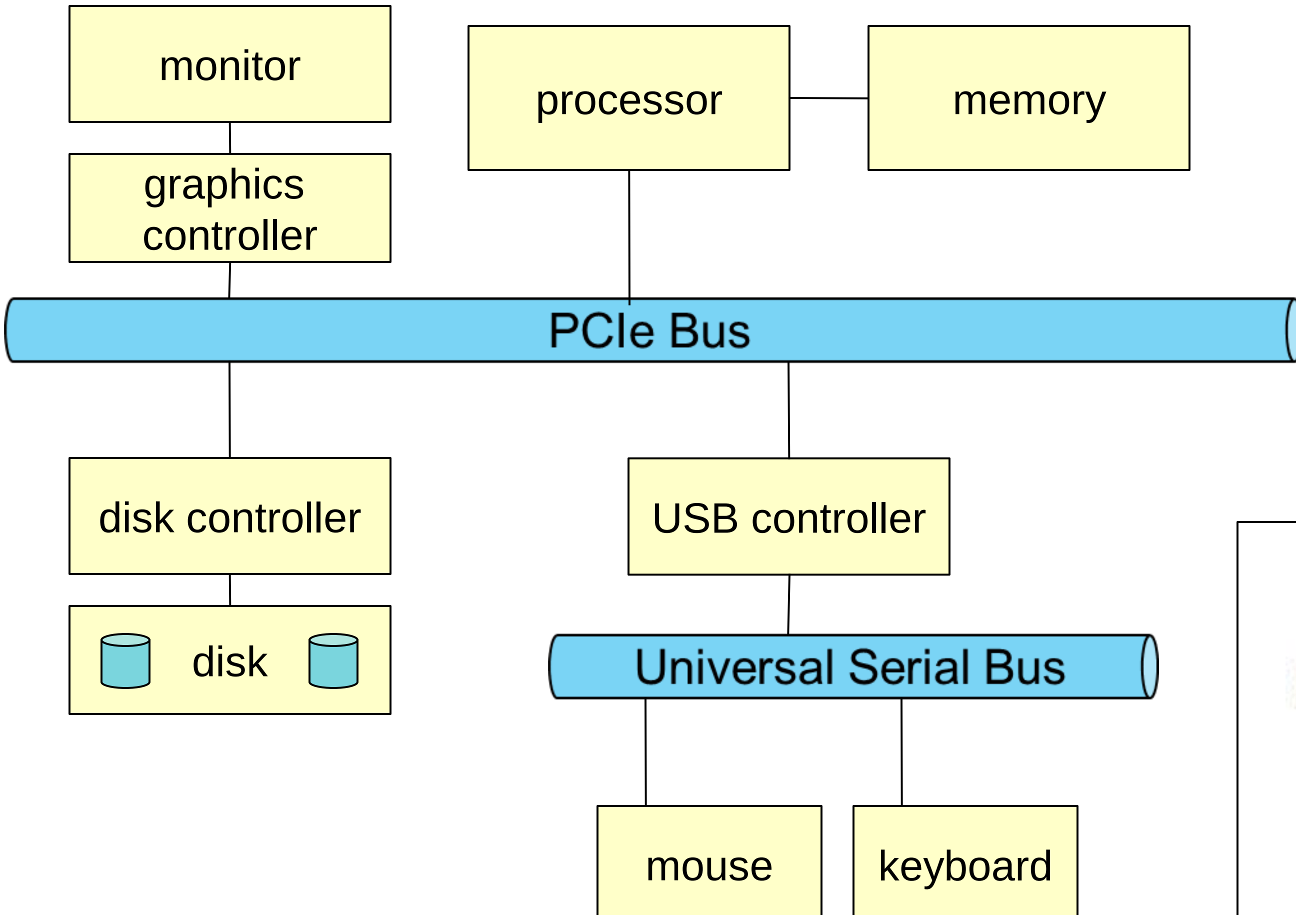
- Typical application flow consists of alternating phases
  - Compute
  - I/O operation
  - Often I/O is the primary component with very short compute bursts
- Recall that OS manages resources
  - Also includes I/O resources
  - Initiates and controls I/O operations
  - Controls I/O devices and device drivers
- I/O systems allow process to interact w/ physical devices
  - Both within the computer: Disks, printer, keyboard, mouse
  - And outside the computer: Network operations

Processor Interface to IO Devices



- Processor Chip has IO Pins
  - E.g. for connection to buses
    - Memory bus
    - PCIe bus
  - Other dedicated IO to chip
    - E.g. for power

IO System Connections



USB PCIe Card

IO System

- Devices connect via a port or a bus
  - A bus is a set of wires with a well defined protocol
- Controller operates a port, bus or device
  - Wide ranging complexities
    - Disk controllers can be very complex
  - Sometimes even a dedicated embedded processor is used
    - Runs the controller software
- Two sides of the communication
  - Processor:
    - On-chip hardware (e.g. PCIe controller) interfaces to the bus protocol
    - Or bridge / IO controller on separate chip in older systems
  - IO devices:
    - Via the controller mentioned above

Device Controller

- Processor interacts with controller for a target device
  - Processor can send commands / data (or receive)
- Controller contains registers for commands / data
  - Two ways for processor to communicate with these registers
    - Dedicated I/O instructions that transfer bits to I/O port address
    - Memory mapped I/O: controller regs are mapped to mem address
      - Standard load/store instructions can write to registers
      - E.g. graphics controller has large mem mapped space for pixel data
  - Control register bit patterns indicate different commands to device
- Usually at least 4 register
  - Data-in (to the processor) and Data-out (from the processor)
  - Status: state of the device (device busy, data ready, error, etc.)
  - Control Register: written by device to initiate command or change device settings

Processor – Device Interaction

- Handshake protocol
  1. Host reads a busy bit in the status register until device free
  2. Host sets write bit in command register & writes data into data-out
  3. Host sets the command ready bit in the command register
  4. Controller detects command ready bit set & sets busy bit
  5. Controller reads command register; sees command; does I/O w/ device
  6. Controller clears command ready bit; clear error & busy bits in status reg
- How to handle step 1
  - Polling (busy-waiting) executing a small code loop
    - Load – branch if bit not set
    - Performance-inefficient if device is frequently busy
  - Interrupt mechanism to notify the CPU
    - Recall our previous lecture

More on Interrupts & I/O

- Steps for reading from disk
  - Initiate I/O read operations for disk drive
    - Bring data into kernel buffer in memory
  - Copy data from kernel space buffer into user space buffer
- Initiating I/O read ops from disk is high priority
  - Want to efficiently utilize disk
- Use pair of interrupt handlers
  - High priority handler handshakes w/ disk controller
    - Keeps I/O requests moving to disk
    - Raises low-priority interrupt when disk operations are complete
  - Low priority handler services interrupt
    - Moves data from kernel buffer to user space
    - Calls scheduler to move process to ready queue
- Threaded kernel architecture is a good fit

Direct Memory Access (DMA)

- We've talked about a tight control loop (handshake) so far
  - Processor monitors status bits (or interrupts)
  - Move data in bytes or words at a time via data-in / data-out regs
    - **Programmed I/O (PIO)**
- Some devices want to perform large data transfers
  - E.g. disk, network
- **Direct Memory Access (DMA)**:
  Typically done w/ dedicated HW engine or logic
  - Processor writes DMA commands to a memory buffer
    - Pointer to src and dest addresses, # of bytes to transfer
  - Processor writes address of DMA command block to DMA engine
  - DMA engine operates on memory & handshakes with device

DMA Operation

- DMA-request & DMA-acknowledge to device controller
  - Device asserts DMA-request when data is available to transfer
  - DMA controller obtains bus control
    - Puts appropriate request address on the bus
    - Asserts DMA-acknowledge wire
  - Device controller puts data on the bus
- DMA controller generates CPU interrupt when transfer is complete

Application Interface to I/O System

- Many different devices
  - All with different functionality, register control definitions, etc.
  - How can OS talk to new devices without modification?
  - How can OS provide consistent API to applications for I/O?
- Solution to all computer science problems
  - Either add a level of indirection (abstraction)…or cache it!
- Abstract away IO device details
  - Identify sets of similar devices; provide standard interface to each
  - Add a new layer of software to implement each interface
    - Device Drivers
    - Type of kernel module (OS extensions that can be loaded / unloaded)

Device Drivers

- Purpose: hide device-specific controller details from I/O subsystem as much as possible
  - OS is easier to develop & maintain
  - Device manufacturers can conform to common interfaces
    - Can attach new I/O devices to existing machines
- Device driver software is typically OS-specific
  - Different interface standards across OSes
- Several different device categories (each w/ interface)
  - Based on different device characteristics
    - Block I/O, Character-stream I/O, Memory-mapped file, Network sockets
  - OS also has low-level system calls (ioctl on Linux)
    - Look at man page

Block-Device Interface

- API for accessing block-oriented devices
  - read, write, seek (if random access device)
- Applications normally access via file system interface
- Low-level device operation & policies are hidden by API

- Examples: Hard drive, optical disc drive

Character-Stream Interface

- Keyboard, mice, for example
- API:
  - get(), put() a character at a time
- Often libraries are implemented on top of this interface
  - E.g. buffer and read a line at a time
  - Useful for devices that produce input data unpredictably

- Examples: Serial port, modem

Memory-mapped File Interface

- Layer on top of block-device interface
- Provides access to storage as bytes in memory
  - System call sets up this memory mapping
  - We've seen an example of this for memory-mapped disk files
- Processor can read & write bytes in memory
- Data transfers only performed as needed between memory & device

- Example: Video card (frame buffer)

Network Device Interface

- UNIX network sockets for example
- Applications can
  - Create socket
  - Connect a local socket to a remote address
    - Address = host IP address and port number
    - This will plug the socket into an application on the remote machine
  - Use select() to monitor activity on any of a number of sockets

- Example: Ethernet or WiFi NIC

Blocking vs. Nonblocking (vs. Async)

- Blocking
  - Process is suspended on issuing a blocking IO system call
  - Moved from ready queue to wait queue
  - Moved back to ready queue after IO completes
- Nonblocking
  - Process does not wait for IO call completion
    - Any data that is ready is returned
  - E.g. user Interface receives keyboard & mouse input
- Asynchronous
  - IO call returns immediately & IO operation is initiated
  - Process is notified of IO completion via later interrupt
  - E.g. select() w/ wait time of 0
    - Followed by read() if any source has data ready

OS Kernel I/O Subsystem

- Provides many services for I/O
  - Scheduling
  - Buffering
  - Caching
  - Spooling
  - Device Reservation
  - Error Handling
  - Protection of I/O

I/O Scheduling

- Scheduling = Ordering application requests to IO devices
  - OS does not necessarily have to send them in order received
- Can impact many aspects of the system
  - Performance
    - Average wait time by applications for I/O requests
    - IO device utilization (how often are they busy performing useful work)
  - Fairness
    - Do applications get uniform access to I/O devices?
    - Should some users / applications be prioritized?
- Implementation
  - OS implements a wait queue for requests to each device
  - Reorders queue to schedule requests to optimize metrics

Example: Disk Scheduling

- Traditional hard disk has two access time components
  - Seek time: disk arm moves heads to cylinder containing sector
  - Rotational latency: disk rotates to desired sector
  - Bandwidth is also important (# bytes per unit time)
- Somewhat analogous to CPU scheduling we discussed
  - FCFS: first-come, first-served
    - Fair, but generally not fast or high bandwidth
  - SSTF: shortest seek time first
    - Equivalent to SJF (see pros & cons from CPU scheduling)
  - SCAN: move disk arm from one end to the other, back & forth
    - Service requests as disk arm reaches their cylinder
    - "Elevator" algorithm
  - C-SCAN: move disk arm in a cyclical round trip (servicing forward, skipping back)
    - Improves wait time relative to SCAN

I/O Buffering

- Memory region to store in-flight data
  - E.g. between two devices or a device and application
- Reasons for buffering
  - Speed mismatch between source and destination device
    - E.g. data received over slow network going to fast disk
      - Want to write big blocks of data to disk at a time, not small pieces
    - Double buffering
      - Alternate which buffer is being filled from source and which is written to destination
      - Removes need for timing requirements between producer / consumer
  - Efficiently handle device data with different transfer sizes

I/O Caching

- Similar concept to other types of caching you've learned
  - CPU caching (L1, L2, L3 caches for main memory)
  - Disk caching using main memory
- Use memory to cache data regions for IO transfers
  - Similar to buffering, but for a different purpose
- E.g. for disk IO, cache buffers in main memory
  - Improves efficiency for shared files that are read/written often
  - Improve latency for reads; Reduce disk bandwidth for writes
    - Reads serviced by memory instead of slow disk
    - Writes can be "gathered" and a single bulk disk write done later

I/O Spooling

- Spool: type of buffer to hold data for device that cannot accept interleaved data streams
  - Printers!
- Kernel stores each applications print I/O data
  - Spooled to a separate disk file
- Later, the kernel queues a spool file to the printer
  - Often managed by a running daemon process
  - Allows applications to view pending jobs, cancel jobs, etc.
- Device Reservation:
  - For similar purposes as spooling
  - Kernel facility for allocating an idle device & deallocating later

I/O Error Handling & Protection

- I/O system calls return information about status
  - `errno` variable in UNIX
  - Indicate general nature of failure
  - Failures can happen due to transient problems
    - OS can compensate by re-trying failed operations
- Protection mechanisms for I/O by kernel
  - All I/O instructions are privileged
    - cannot be executed directly by user process
  - User process must execute system call
  - System call can check for valid request & data