Lecture 10
I/O

Prof. Yinqian Zhang

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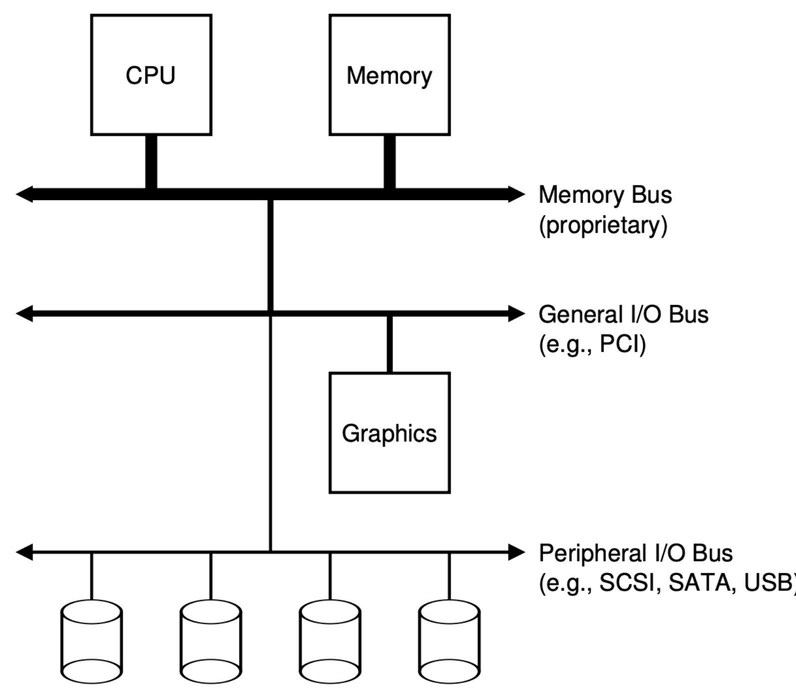
I/O Management

- So far, we have learned how to manage CPU and memory
- Challenges of I/O management
    - Diverse devices: each device is slightly different
        - How can we standardize the interfaces to these devices?
    - Unreliable device: media failures and transmission errors
        - How can we make them reliable?
    - Unpredictable and slow devices
        - How can we manage them if we do not know what they will do or how they will perform?

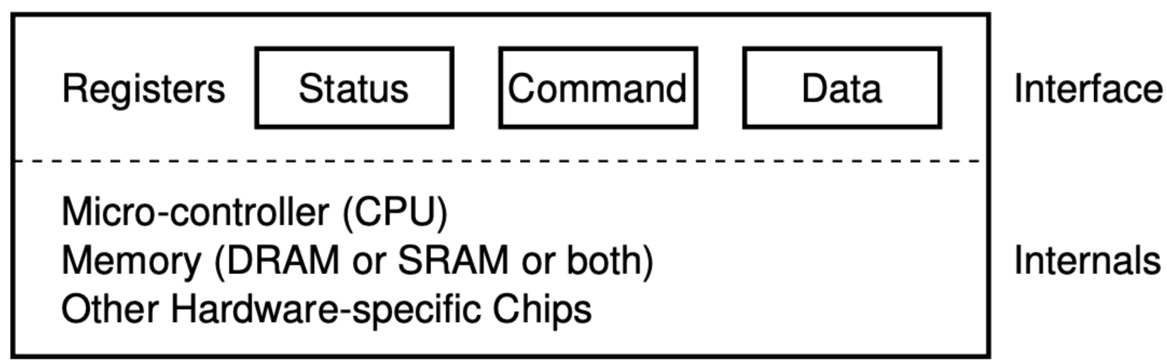
A Classic View of Computer System

- A **single CPU** attached to the **main memory** of the system via memory bus or interconnect.
- Some devices (**graphics** and some other **higher-performance I/O devices**) are connected to the system via a general I/O bus (e.g., PCI)
- Finally, a peripheral bus, such as SCSI, SATA, or USB, connects slow devices to the system, including **disks**, **mice**, and **keyboards**



A Canonical View of Devices

- Interface
  - The hardware interface a device present to the rest of the system
  - **Status** registers: check the current status of the device
  - **Command** register: tell the device to perform a certain task
  - **Data** register: pass data to the device or get data from the device.
- Internal structures
  - Implementation of the abstract of the device



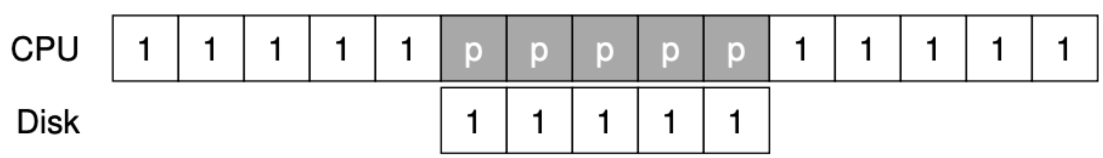
Basic I/O: Polling

- To write a byte of data to device
  - Step 1: OS waits until the device is ready to receive a command by repeatedly reading the status register;
  - Step 2: OS sends some data down to the data register;
  - Step 3: OS writes a command to the command register
  - Step 4: OS waits for the device to finish by again polling it in a loop, waiting to see if it is finished

```
While (STATUS == BUSY)
    ; // wait until device is not busy
Write data to DATA register
Write command to COMMAND register
    (starts the device and executes the command)
While (STATUS == BUSY)
    ; // wait until device is done with your request
```

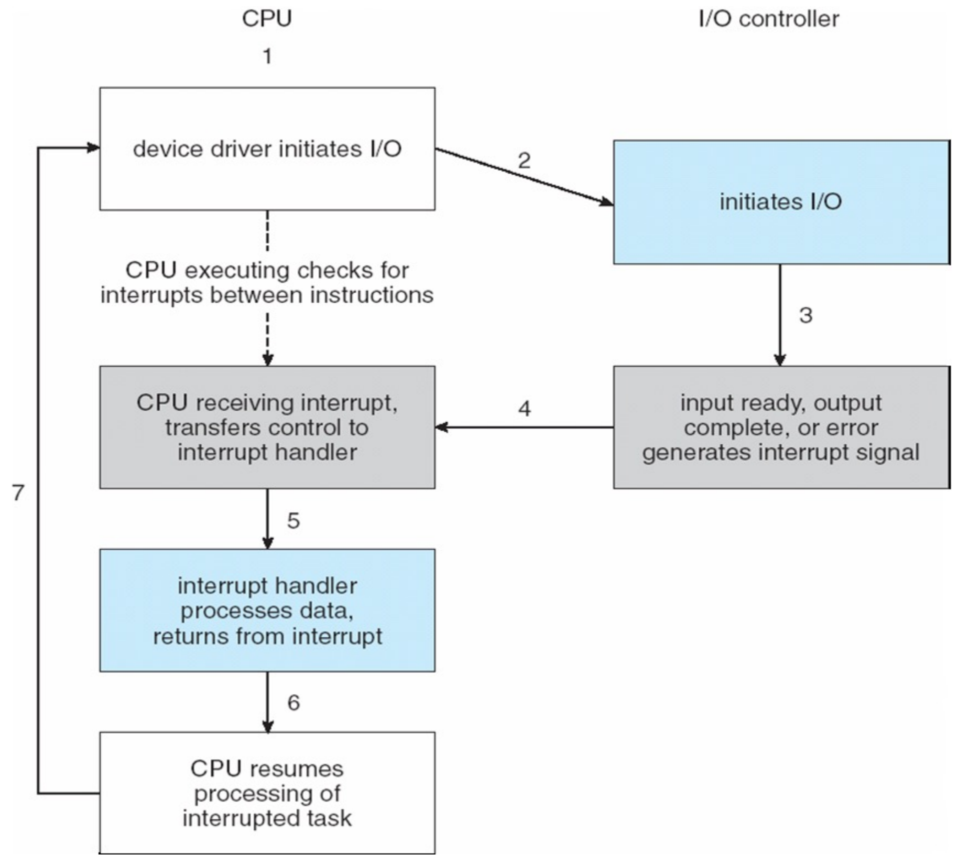
Issues of Polling

- Polling: frequent checking the status of I/O devices
- Polling is inefficient and inconvenient
  - Polling wastes CPU time waiting for slow devices to complete its activity
  - If CPU switches to other tasks, data may be overwritten
    - e.g., keyboard data overflow the buffer



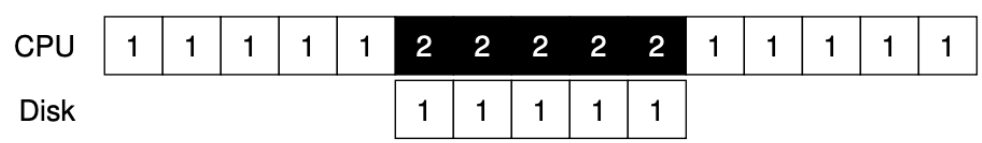
Efficient I/O: Interrupts

- Instead of polling the device repeatedly, the OS can issue a request, put the calling process to sleep, and context switch to another task.
- When the device is finally finished with the operation, it will raise a hardware interrupt, causing the CPU to jump into the OS at a predetermined **interrupt handler**



Polling or Interrupt?

- Polling works better for fast devices
  - Data fetched with first poll
- Interrupt works better for slow devices
  - Context switch is expensive
- Hybird approach if speed of the device is not known or unstable
  - Polls for a while
  - Then use interrupts



Hardware Support for Interrupts

- **Interrupt-request line,** a CPU wire, triggered by I/O device
  - Checked by processor after each instruction
  - Save CPU state and jumps to the interrupt handler
- **Interrupt-controller hardware**
  - Defer interrupt handling during critical processing
  - Dispatch to proper interrupt handler
  - Support multi-level interrupts, high- and low-priority interrupts

Software Support for Interrupts

- **Interrupt handler** receives interrupts
    - **Maskable** to ignore or delay some interrupts
    - Some are **nonmaskable**, e.g., unrecoverable memory errors.
- A table of **interrupt vectors** to specify interrupt-handling routine
    - Dispatch interrupt to correct handler
    - **Interrupt chaining** if more than one device at the same interrupt number
        - Interrupt handlers on the corresponding chain are called one by one
    - The size of the interrupt table (i.e., number of interrupt vectors) and length of interrupt chains are results of system design trade-off.
    - Priority of interrupts: high-priority interrupts can preempt low-priority interrupts

Aside: Interrupts and Exceptions

- Interrupt mechanism also used for **exceptions**
  - Page fault is an exception that raises interrupts
  - Dividing by 0
  - Attempting to execute a privileged instruction from user mode
- Software interrupts, or **traps**
  - System call is made by executing a special instruction called software interrupts to trigger kernel to execute request
  - Lower priority interrupt
- Multi-CPU systems can process interrupts concurrently
  - If operating system designed to handle it

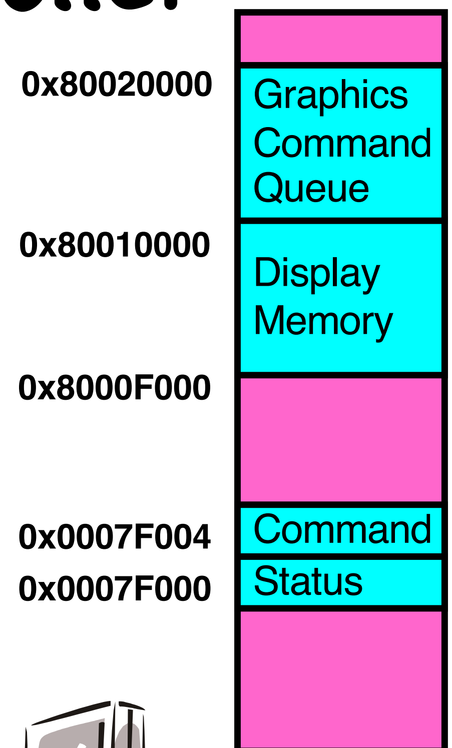
Programmed I/O

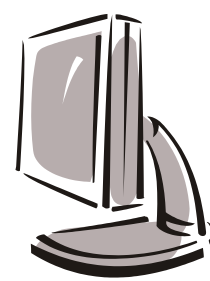
- Explicit I/O instructions
  - in/out instructions on x86: out 0x21,AL
  - I/O instructions are privileged instructions
- Memory-mapped I/O
  - Registers/memory appear in physical address space
  - I/O accomplished with load and store instructions
  - I/O protection with address translation

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)

Memory-Mapped Display Controller

- Memory-Mapped I/O
  - Hardware maps control registers and display memory into physical address space
    - Addresses set by HW jumpers or at boot time
  - Simply writing to display memory (also called the "frame buffer") changes image on screen
    - Addr: 0x8000F000 – 0x8000FFFF
  - Writing graphics description to cmd queue
    - Say enter a set of triangles describing some scene
    - Addr: 0x80010000 – 0x8001FFFF
  - Writing to the command register may cause on-board graphics hardware to do something
    - Say render the above scene
    - Addr: 0x0007F004



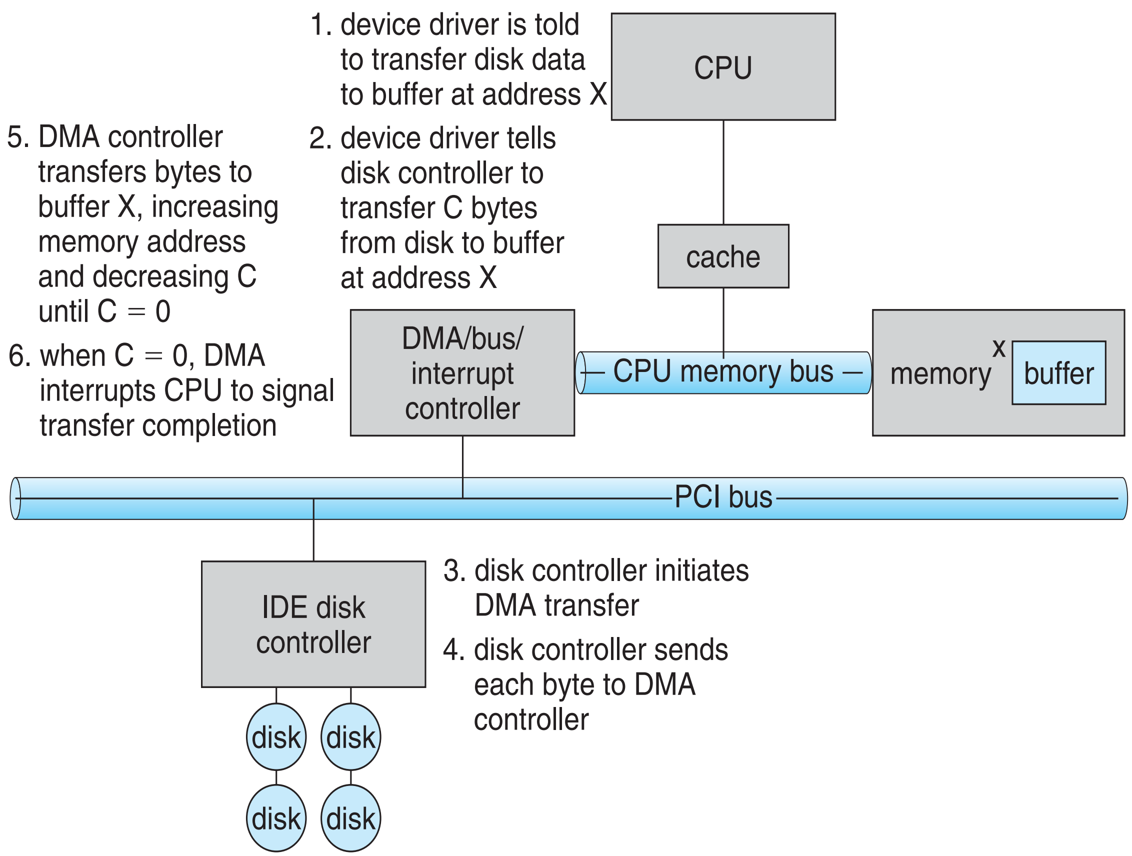


Physical Address Space

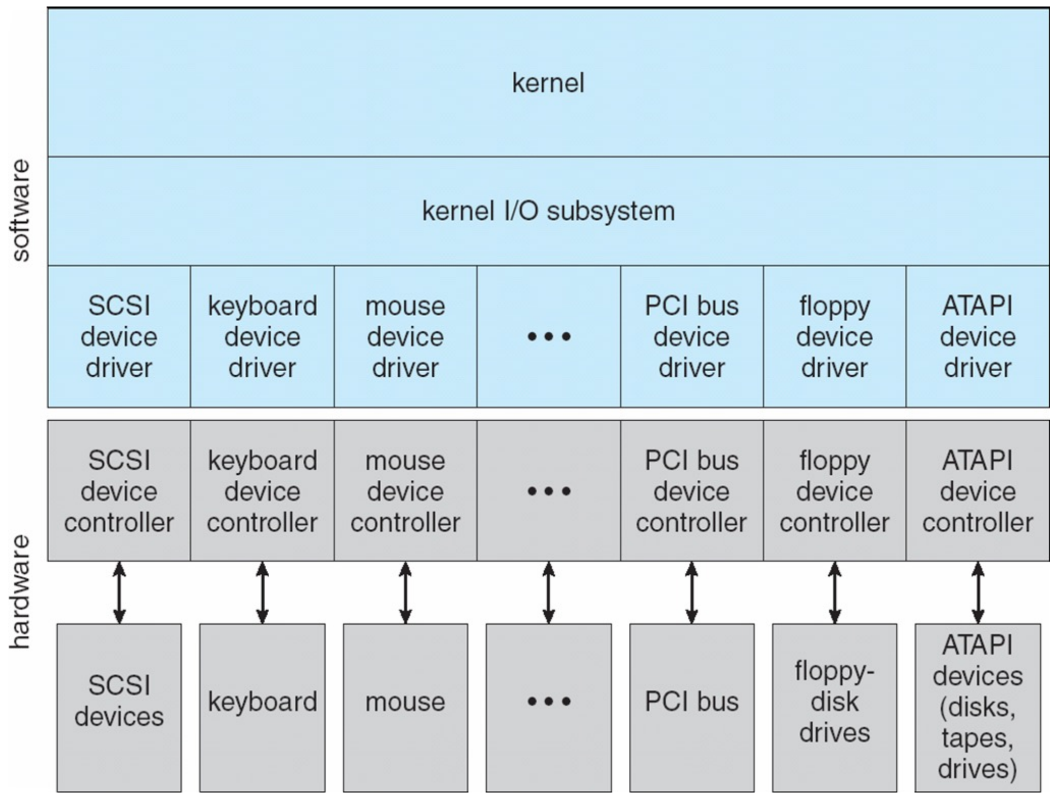
More Efficient Data Movement: DMA

- DMA is used to avoid **programmed I/O** for large data movement
  - Programmed I/O (PIO): when CPU is involved in data movement
  - PIO consumes CPU time
  - bypasses CPU to transfer data directly between I/O device and memory
- OS writes DMA command block into memory
  - Source and destination addresses
  - Read or write mode
  - Count of bytes
  - Writes location to DMA controller
  - Bus mastering of DMA controller – grabs bus from CPU
    - **Cycle stealing** from CPU but still much more efficient
  - When done, interrupts to signal completion

More Efficient Data Movement: DMA



Kernel I/O Structure



Device Drivers

- Device Driver: Device-specific code in the kernel that interacts directly with the device hardware
  - Supports a standard, internal interface
  - Same kernel I/O system can interact easily with different device drivers
  - Special device-specific configuration supported with the ioctl() system call
- Device Drivers typically divided into two pieces:
  - Top half: accessed in call path from system calls
    - implements a set of standard, cross-device calls like open(), close(), read(), write(), ioctl(), strategy()
    - This is the kernel's interface to the device driver
    - Top half will *start* I/O to device, may put thread to sleep until finished
  - Bottom half: run as interrupt routine
    - Gets input or transfers next block of output
    - May wake sleeping threads if I/O now complete

Life Cycle of An I/O Request

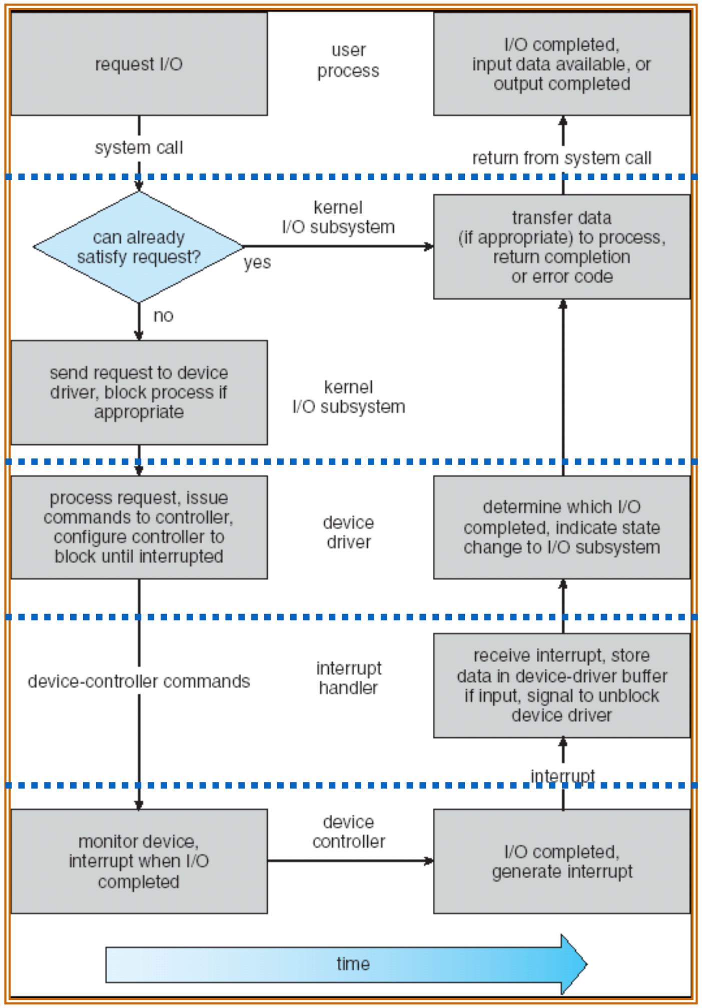
User Program

Kernel I/O Subsystem

Device Driver Top Half

Device Driver Bottom Half

Device Hardware



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
- New devices talking already-implemented protocols need no extra work
- Each OS has its own I/O subsystem structures and device driver frameworks
- Devices vary in many dimensions
  - **Character-stream** or **block**
  - **Sequential** or **random-access**
  - **Synchronous** or **asynchronous**
  - **Sharable** or **dedicated**
  - **Speed of operation**
  - **read-write, read only,** or **write only**

Characteristics of I/O Devices (Cont'd)

- Subtleties of devices handled by device drivers
- Broadly I/O devices can be grouped by the OS into
  - Block I/O
  - Character I/O (Stream)
  - Memory-mapped file access
  - Network sockets
- For direct manipulation of I/O device specific characteristics from user-space applications
  - Unix `ioctl()` call to send arbitrary bits to a device control register and data to device data register

Block and Character Devices

- Block devices include disk drives
  - Commands include read, write, seek
  - **Raw I/O**, allows direct file-system access
    - Applications (e.g., database) do not need buffering or locking by filesystems
  - Memory-mapped file access possible
    - File mapped to virtual memory via demand paging
  - DMA
- Character devices include keyboards, mice, serial ports
  - Commands include **`get()`**, **`put()`** of one character
  - Libraries layered on top allow line editing

Nonblocking and Asynchronous I/O

- **Blocking** - process suspended until I/O completed
  - Processes moved from run queue to wait queue
- **Nonblocking** - I/O call returns as much as available
  - Returns quickly with count of bytes read or written
- **Asynchronous** - process runs while I/O executes
  - An alternative to nonblocking I/O
  - I/O request will be completed at some future time
  - I/O subsystem signals process when I/O completed
    - Software interrupt
    - Signal
    - Callback routine

Summary

- Two techniques to make I/O more efficient
  - Interrupts
  - DMA
- Two approaches to control devices
  - Explicity I/O instructions
  - Memory-mapped I/O
- The notion of device drivers
  - OS encapsulates low-level details and makes it easier to build the rest of the OS in a device-neutral fashion.