CS 4410
Operating Systems

Hardware – OS & OS- Application interface

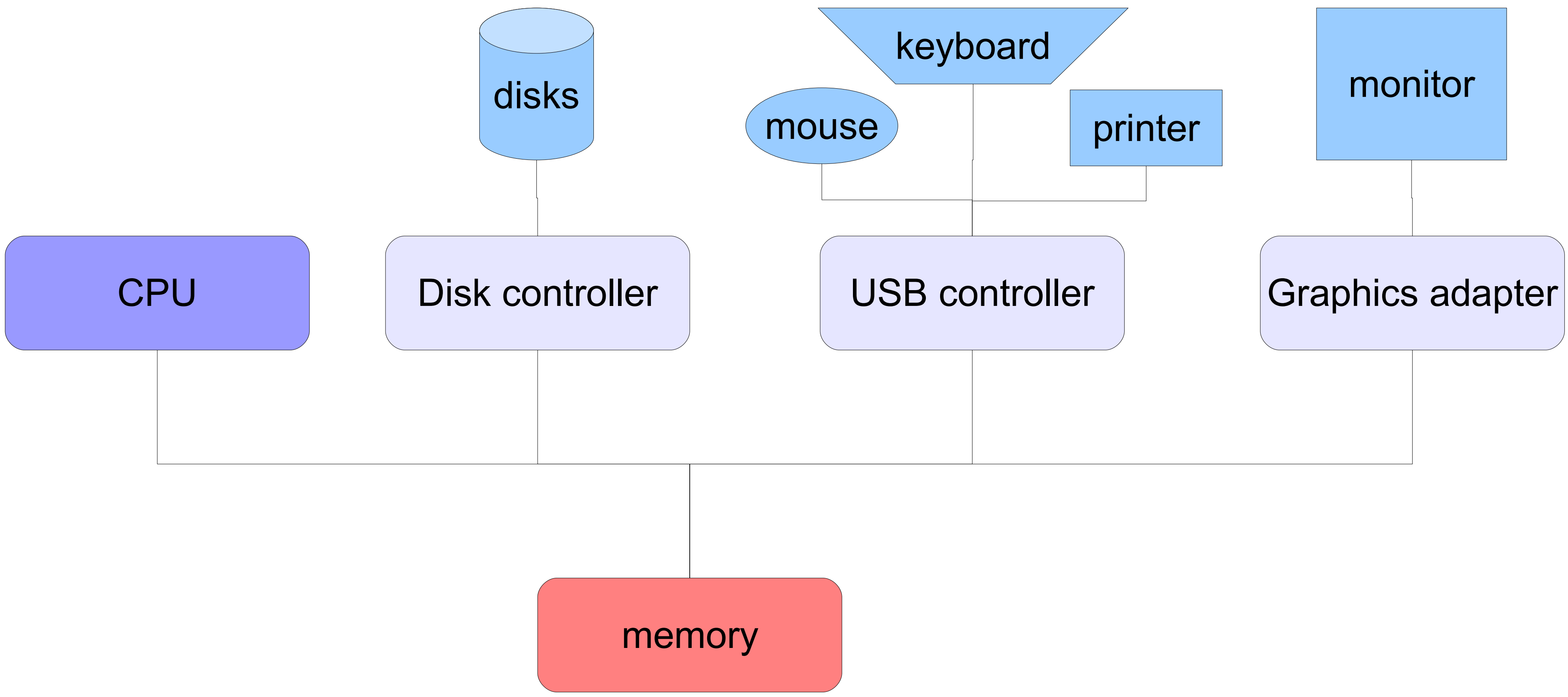
Summer 2011

Cornell University

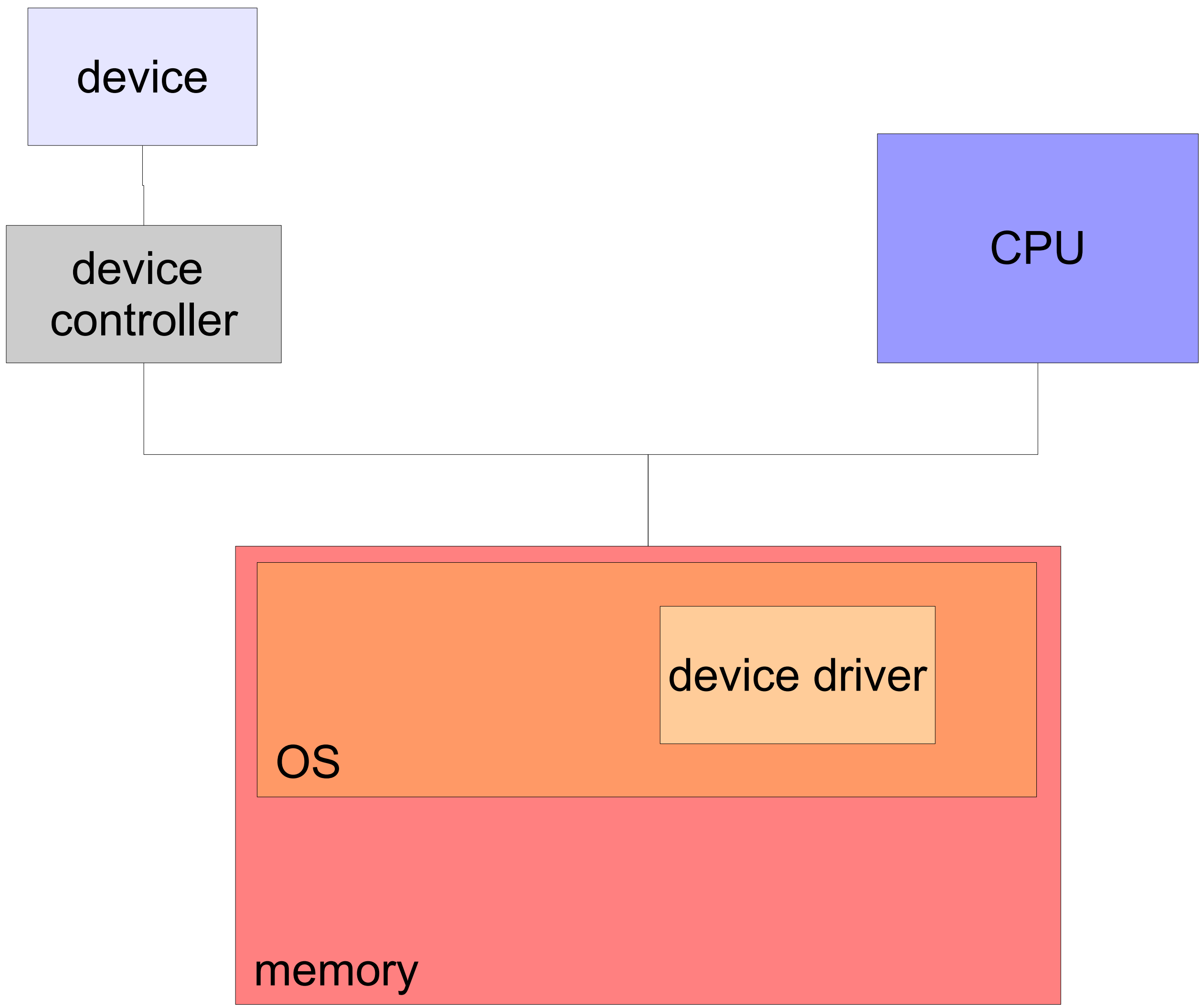
Today

- How my device becomes useful for the user?
- HW-OS interface
  - Device controller
  - Device driver
  - Interrupts
- OS-App interface
  - System Call
  - Privilege Levels
  - Exceptions

A modern computer system



HW-OS interface



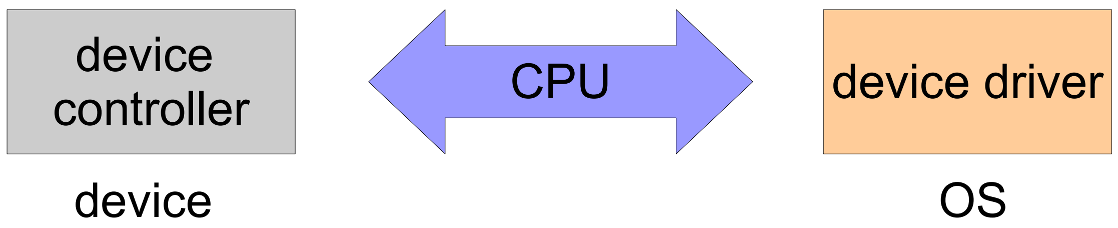
HW-OS interface

- Device Controller:
  - A **set of chips** on a plug-in board.
  - It has local **buffer** storage and/or a set of special purpose **registers**.
  - Responsible for moving **data** between **device** and **registers/buffer**.
  - Responsible for making **data** available to the device **driver.**

HW-OS interface

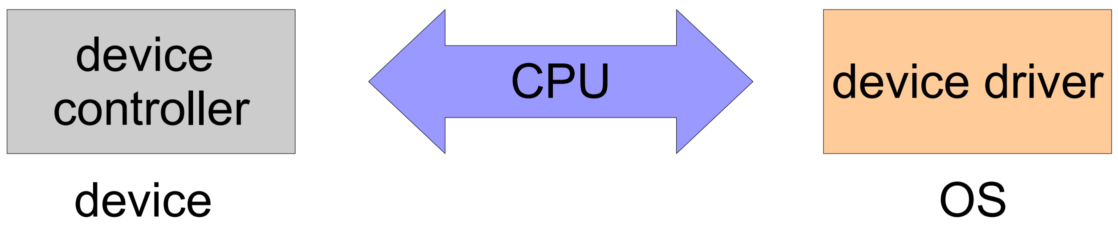
- Device Driver:
  - Belongs to the **OS**.
  - Communicates with the **device controller**.
  - Presents a **uniform interface** to the rest of the OS.

HW-OS interface



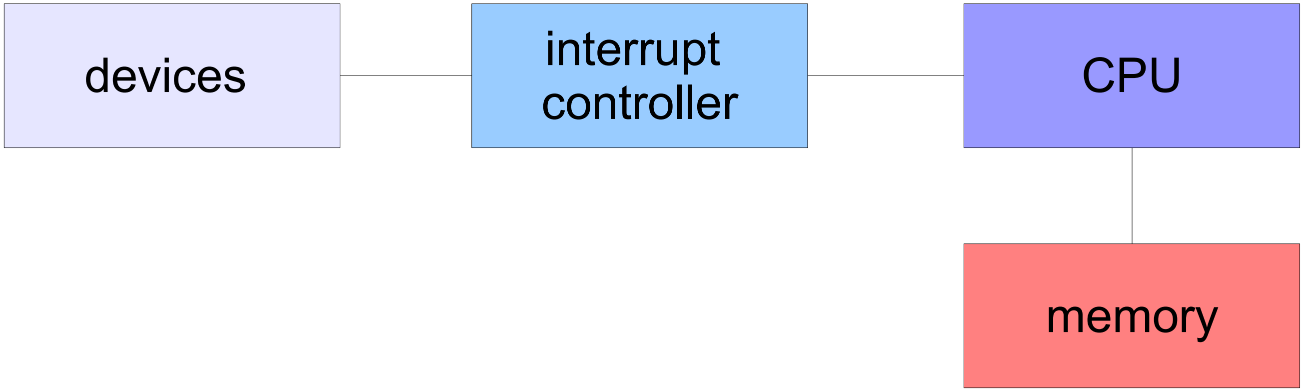
- Driver to Controller:
  - Memory-mapped I/O
    - Device communication goes over the memory bus
    - Reads/Writes to special addresses are converted into I/O operations by dedicated device hardware
    - Each device appears as if it is part of the memory address space
  - Programmed I/O
    - CPU has dedicated, special instructions
    - CPU has additional input/output wires (I/O bus)
    - Instruction specifies device and operation
  - Memory-mapped I/O is the predominant device interfacing technique in use

HW-OS interface



- controller to driver:
  - Polling
    - CPU constantly checks controller for new data
    - Inefficient
  - Interrupts
    - Controller alert CPU for an event
    - Interrupt driven I/O
  - Interrupt driven I/O enables the CPU and devices to perform tasks concurrently, increasing throughput

Interrupt Driven I/O



- An interrupt controller mediates between competing devices
- Raises an interrupt flag to get the CPU's attention
- Identifies the interrupting device
- Can disable (aka mask) interrupts if the CPU so desires

Interrupt Management

- Interrupt controllers manage interrupts
  - Maskable interrupts: can be turned off by the CPU for critical processing
  - Nonmaskable interrupts: signifies serious errors (e.g. unrecoverable memory error, power out warning, etc)
- Interrupts contain a descriptor of the interrupting device
  - A priority selector circuit examines all interrupting devices, reports highest level to the CPU
- Interrupt controller implements interrupt priorities
  - Can optionally remap priority levels

Interrupt-driven I/O summary

- Normal interrupt-driven operation with memory-mapped I/O proceeds as follows
  - The device driver (OS) executes an I/O *command (e.g. to read from disk).*
  - CPU initiates a device operation (e.g. read from disk) by writing an operation descriptor to a device controller register.
  - CPU continues its regular computation.
  - The device asynchronously performs the operation.
  - When the operation is complete, the device controller interrupts the CPU.
  - The CPU stops the current computation.
  - The CPU transfers the execution to the service routine (in the device driver).
  - The interrupt service routine executes.
  - On completion, the CPU resumes the interrupted computation.
- BUT, this would incur high-overhead for moving bulk-data
  - One interrupt per byte!

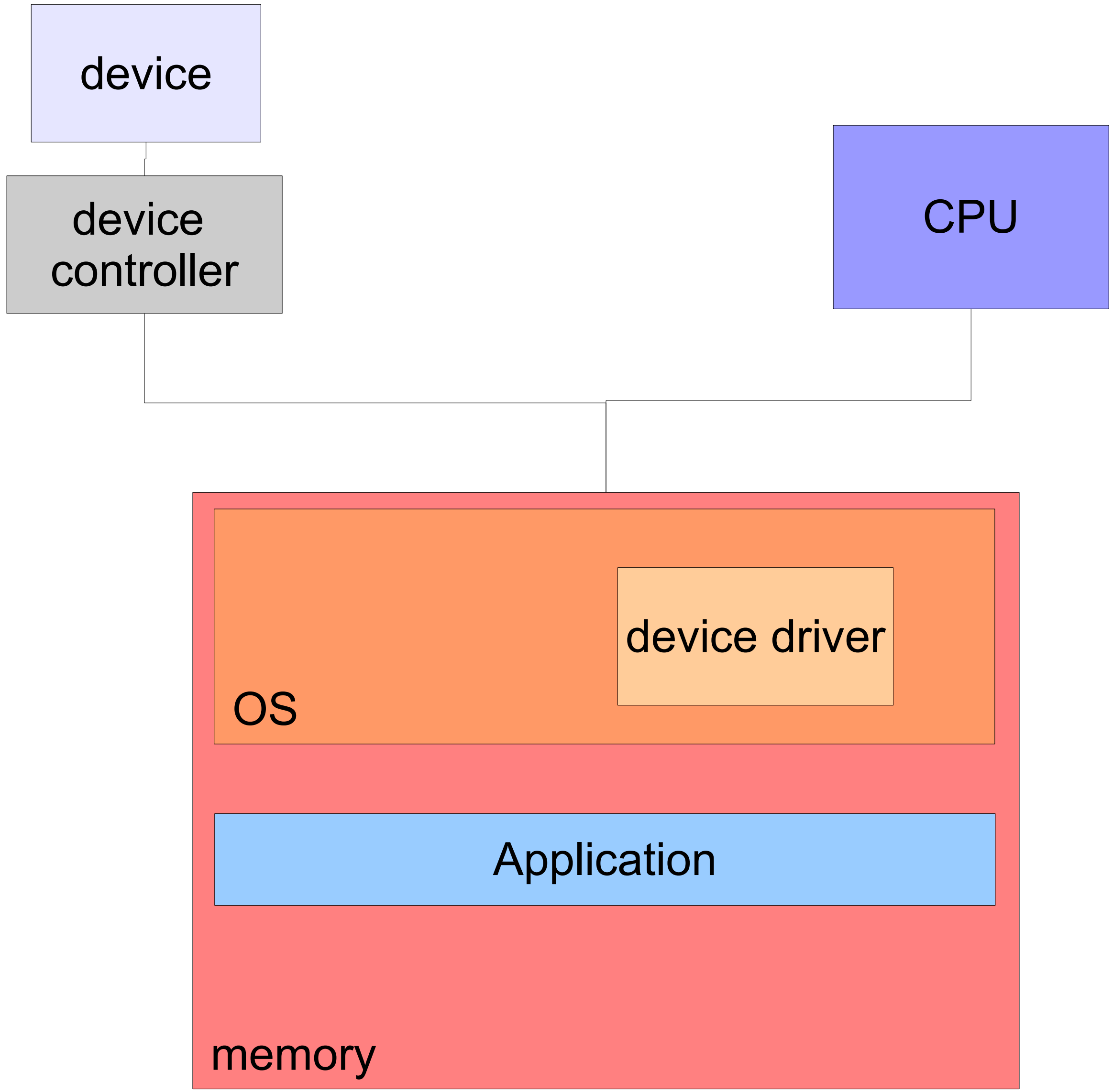
Direct Memory Access (DMA)

- Transfer data **directly** between **device** and **memory**
  - No CPU intervention required for moving bits

- Device raises interrupts solely when the block transfer is complete

- Critical for high-performance devices
  - Examples?

OS-App interface



OS-App interface

- Application to Driver:
  - System Calls
  - Like calling a routine of the OS.
- Driver to Application:
  - Pass data from OS memory space to application memory space.
- There are always alternatives!

System Calls

- Why do we need System Calls?
  - Some processor functionality cannot be made accessible to **untrusted** user applications
    - e.g. HALT, change MMU settings, set clock, reset devices, manipulate device settings, …
  - Need to have a designated **mediator** between untrusted/untrusting applications
    - The operating system (OS)
  - Systems Calls provide an **interface** to the **services** made available by an **OS**.

Privilege Levels

- How the CPU knows if an application has the right to execute a privileged command?
  - Use a “privilege mode” bit in the processor
  - **0** = Untrusted = **user**, **1** = Trusted = **OS**

Privilege Mode

- Privilege mode bit indicates if the current program can perform privileged operations
  - On system startup, privilege mode is set to 1, and the processor jumps to a well-known address
  - The operating system (OS) boot code resides at this address
  - The OS sets up the devices, initializes the MMU, loads applications, and resets the privilege bit before invoking the application

- Applications must transfer control back to OS for privileged operations
- Back to System Calls ...

Sample System Calls

- **Print** character to screen
  - Needs to multiplex the shared screen resource between multiple applications
- **Send** a packet on the network
  - Needs to manipulate the internals of a device whose hardware interface is unsafe
- **Allocate** a page
  - Needs to update page tables & MMU

System Calls

- A system call is a **controlled transfer** of execution from **unprivileged** code to the **OS**
  - A potential alternative is to make OS code read-only, and allow applications to just jump to the desired system call routine. Why is this a bad idea?

- A **SYSCALL** instruction transfers control to a system call handler at a fixed address (software interrupt).

SYSCALL instruction

- SYSCALL instruction does an atomic jump to a controlled location
  - Switches the SP to the kernel stack
  - Saves the syscall number
  - Saves arguments
  - Saves the old (user) SP, PC (next command), privilege mode
  - Sets the new privilege mode to 1
  - Sets the new PC to the kernel syscall handler

- Kernel system call handler carries out the desired system call
  - Saves callee-save registers
  - Examines the syscall number
  - Checks arguments for sanity
  - Performs operation
  - Stores result in v0
  - Restores callee-save registers
  - Performs a “return from syscall” instruction, which restores the privilege mode, SP and PC

Libraries and Wrappers

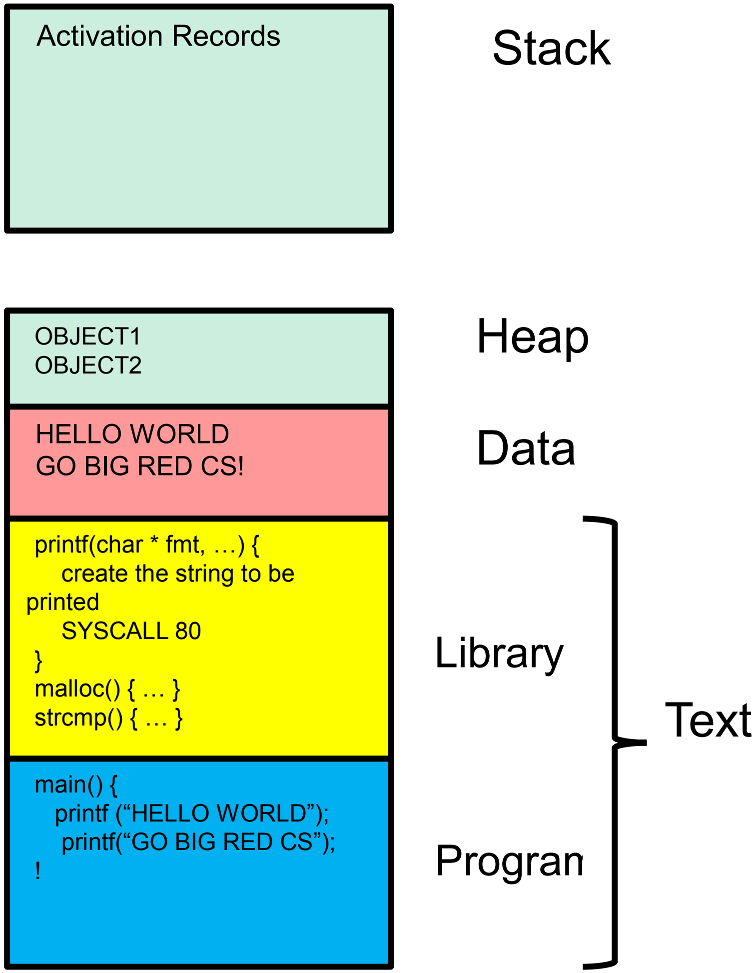
- Compilers do not emit SYSCALL instructions
  - They do not know the interface exposed by the OS

- Instead, applications are compiled with standard libraries, which provide “syscall wrappers”
  - printf() -> write(); malloc() -> sbrk(); recv(); open(); close(); …

- Wrappers are:
  - written in **assembler**,
  - internally issue a **SYSCALL** instruction,
  - pass **arguments** to **kernel**,
  - pass **result** back to **calling application**

Typical Process Layout

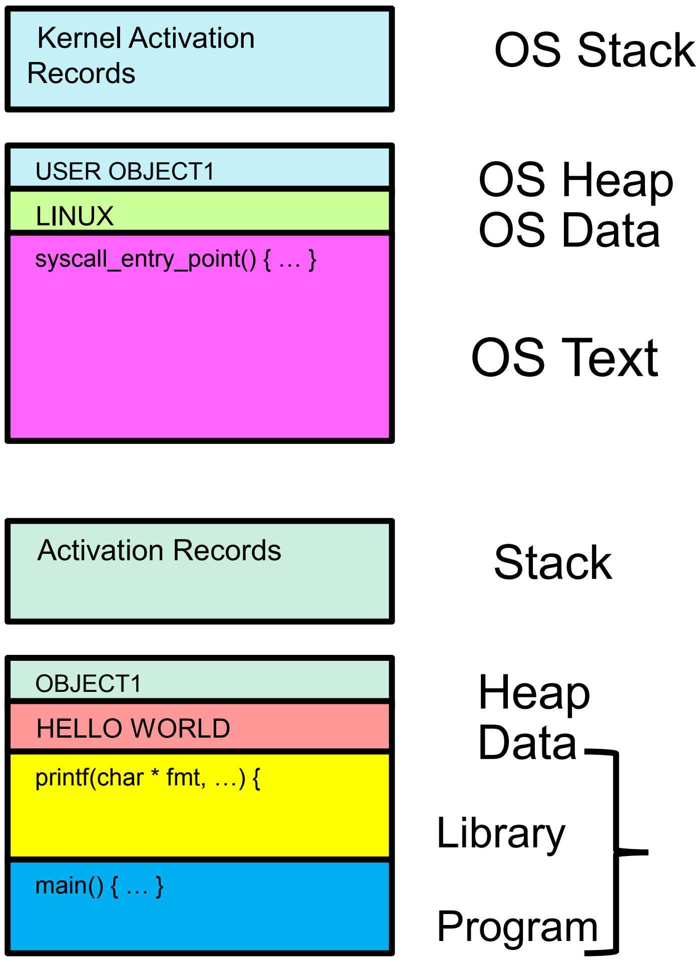
- Libraries provide the glue between user processes and the OS
  - libc linked in with all C programs
  - Provides printf, malloc, and a whole slew of other routines necessary for programs



Full System Layout

- The **OS** is **omnipresent** and steps in where necessary to aid application execution
  - Typically resides in high memory

- When an **application** needs to perform a **privileged operation**, it needs to **invoke the OS**



Exceptional Situations

- **System calls** are **control transfers** to the **OS**, performed under the control of the user application

- Sometimes, need to transfer control to the OS at a time when the user program least expects it

  - Division by zero,
  - Alert from the power supply that electricity is about to go out,
  - Alert from the network device that a packet just arrived,
  - Clock notifying the processor that the clock just ticked,

- Some of these causes for interruption of execution have nothing to do with the user application

- Need a (slightly) different mechanism, that allows resuming the user application

Interrupts & Exceptions

- On an interrupt or exception
  - Switches the sp to the kernel stack
  - Saves the old (user) SP value
  - Saves the old (user) PC value
  - Saves the old privilege mode
  - **Saves cause of the interrupt/exception**
  - Sets the new privilege mode to 1
  - Sets the new PC to the kernel **interrupt/exception handler**
- Kernel **interrupt/exception handler** handles the event
  - Saves **all** registers
  - Examines the **cause**
  - Performs operation required
  - **Restores all registers**
  - Performs a **“return from interrupt”** instruction, which restores the privilege mode, SP and PC

Syscall vs. Interrupt

- The differences lie in how they are initiated, and how much state needs to be saved and restored

- Syscall requires much less state saving
  - Caller-save registers are already saved by the application

- Interrupts typically require saving and restoring the full state of the processor
  - Why?
  - Because the application got struck by a lightning bolt without anticipating the control transfer

Terminology

- **Trap**
  - Any kind of a **control transfer** to the **OS**
- **Syscall**
  - **Synchronous**, **program-initiated control transfer** from user to the **OS** to obtain **service** from the OS
  - e.g. SYSCALL
- **Exception**
  - **Asynchronous**, **program-initiated control transfer** from user to the **OS** in response to an **exceptional event**
  - e.g. Divide by zero, segmentation fault
- **Interrupt**
  - **Asynchronous**, **device-initiated control transfer** from device to the **OS**
  - e.g. Clock tick, network packet

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Activity

- If we want to add the System Call "*machine_active_time*" ; how many hours the machine is ON, which SW components do we have to add and where?