Architectural Support for Operating Systems

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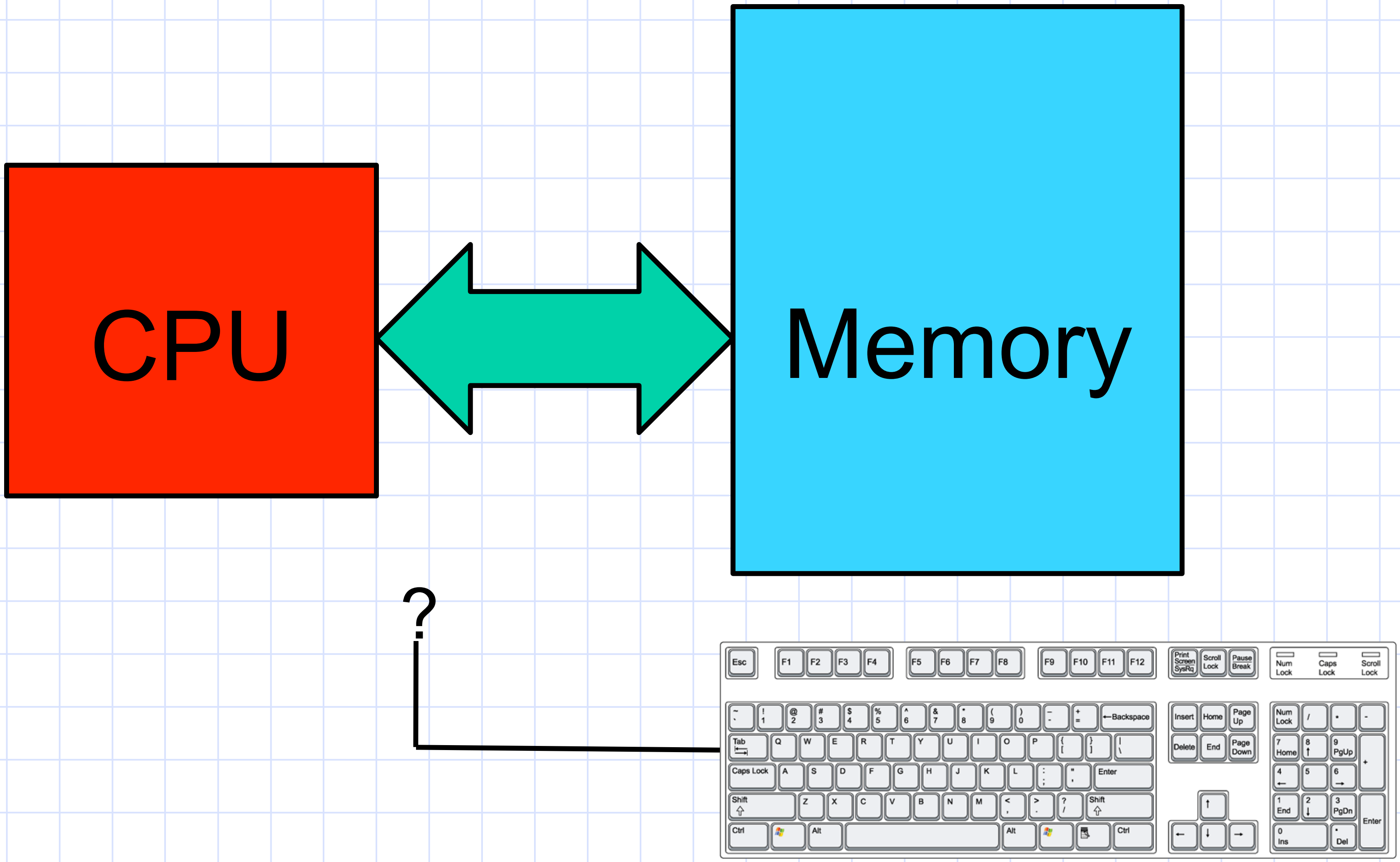
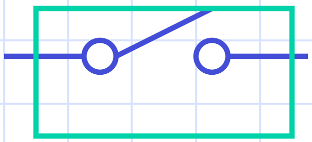
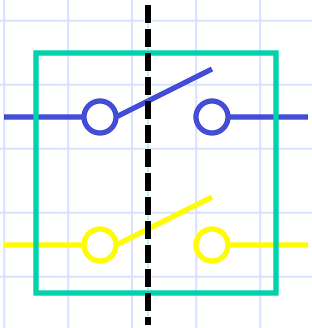
Basic Computer Organization



Keyboard



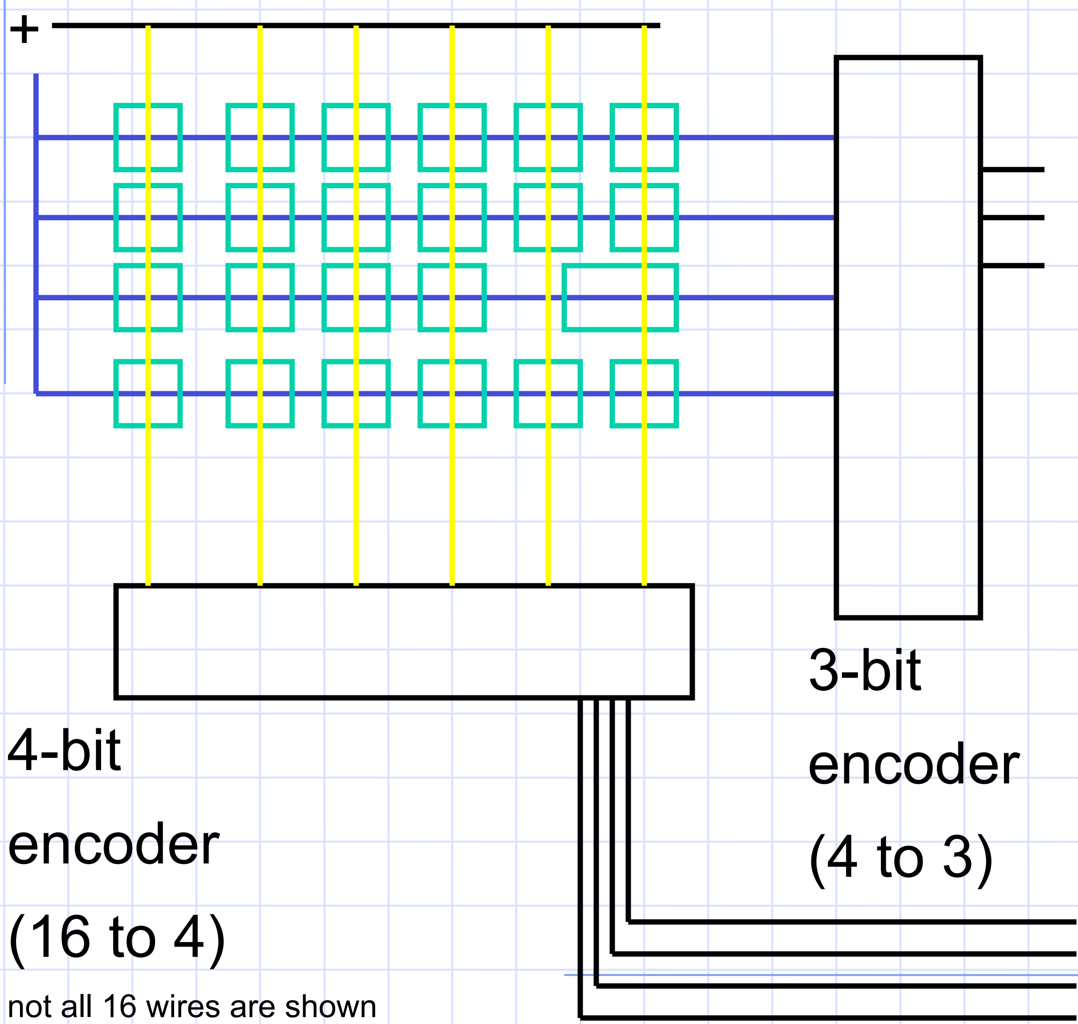
SPST



DPST

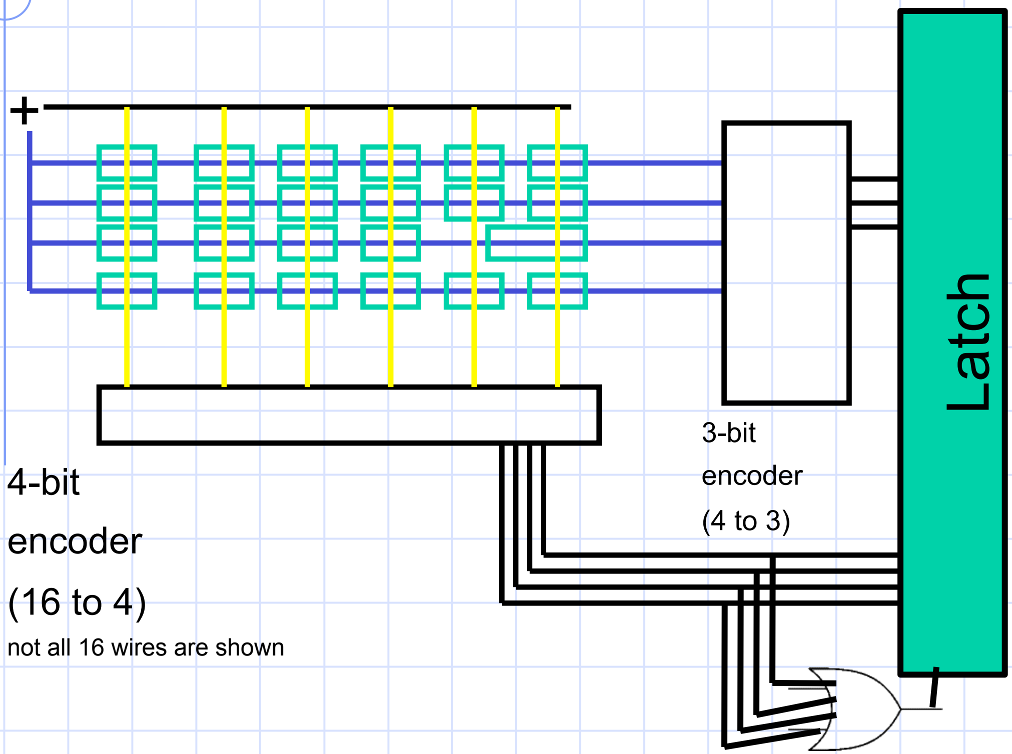
- Let's build a keyboard
- Reading input
  - Mechanical switches
  - Single pole, single throw
  - Double pole, single throw
- Digital processing
  - Encoders, decoders, muxes, latches, tristate buffers, logic gates, …

Keyboard



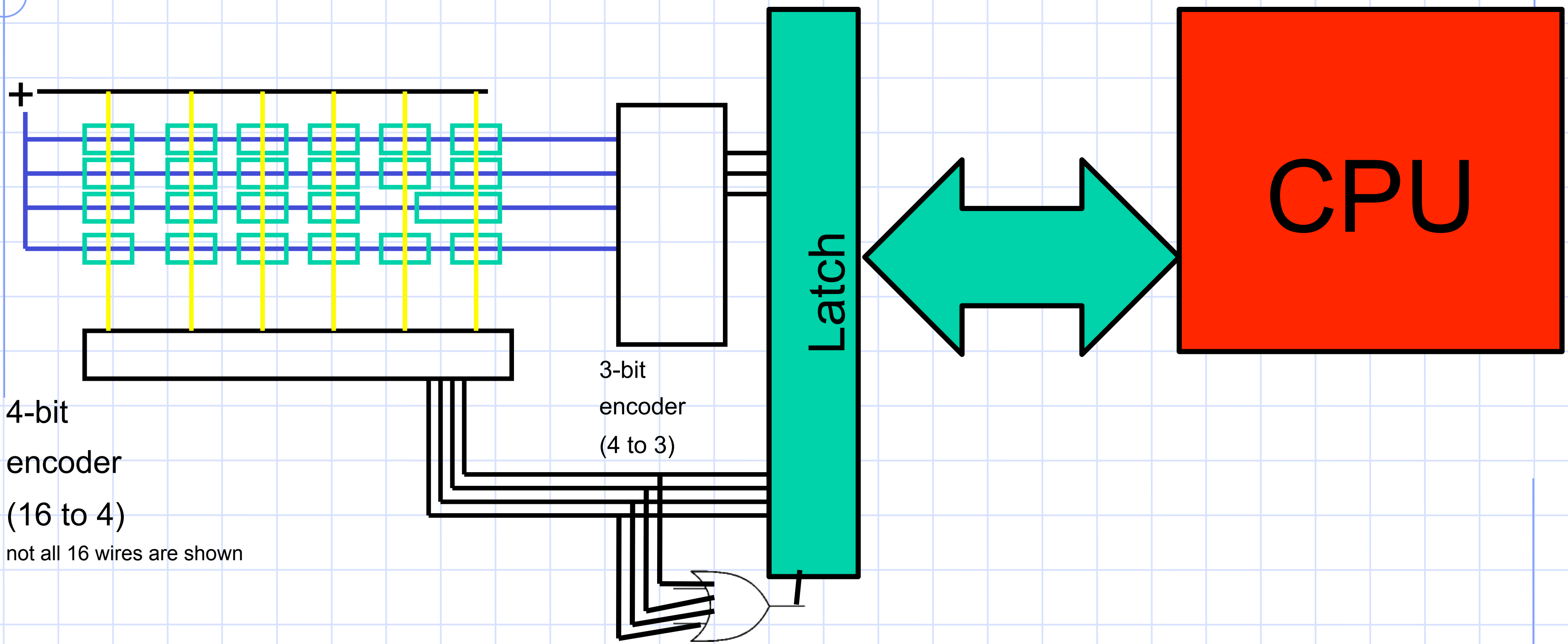
- When a key is pressed, a 7-bit key identifier is computed

Keyboard



- A latch can store the keystroke indefinitely

Keyboard



- The keyboard can then appear to the CPU as if it is a special memory address

Device Interfacing Techniques

- 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

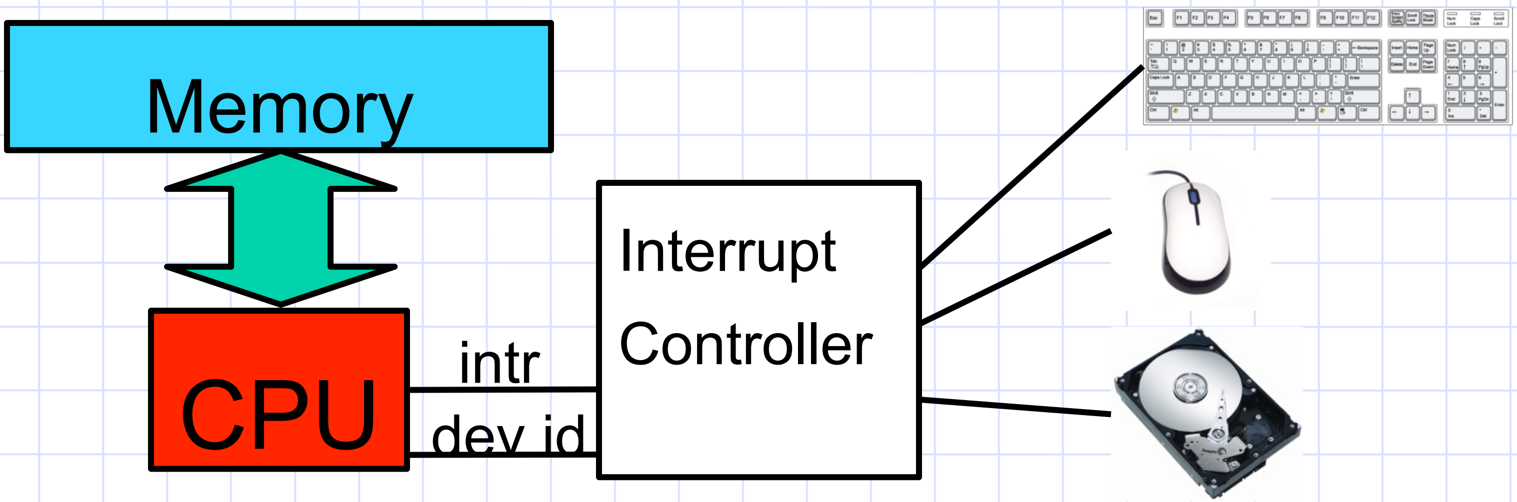
- Programmed I/O
  - CPU has dedicated, special instructions
  - CPU has additional input/output wires (I/O bus)
  - Instruction specifies device and operation

- Memory-mapped I/O is the predominant device interfacing technique in use

Polling vs. Interrupts

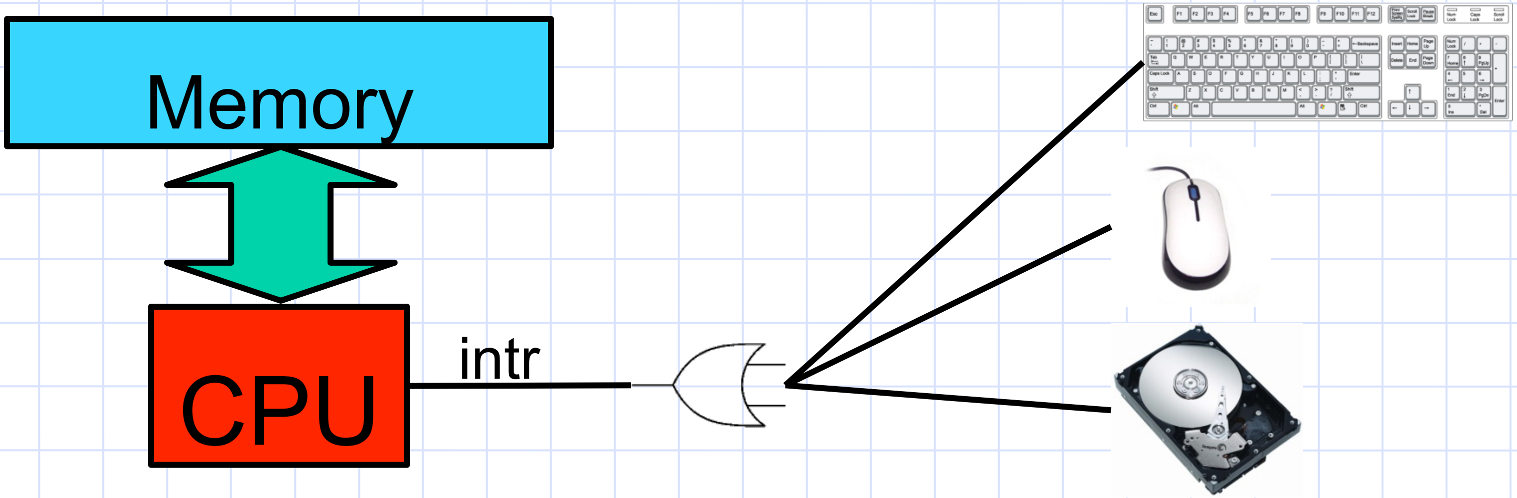
- In our design, the CPU constantly needs to read the keyboard latch memory location to see if a key is pressed
  - Called polling
  - Inefficient
- An alternative is to add extra circuitry so the keyboard can alert the CPU when there is a keypress
  - Called interrupt driven I/O
- Interrupt driven I/O enables the CPU and devices to perform tasks concurrently, increasing throughput
  - Only needs a tiny bit of circuitry and a few extra wires to implement the "alert" operation

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 Driven I/O



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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
  - CPU initiates a device operation (e.g. read from disk) by writing an operation descriptor to a device register
  - CPU continues its regular computation
  - The device asynchronously performs the operation
  - When the operation is complete, interrupts the CPU
- 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

Recap

- We now have a basic computer system to which devices can be connected
- How do we execute applications on this system?
  - Applications are not necessarily trusted!

Privilege Levels

- 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)
- Need to delineate between untrusted applications and OS code
  - 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

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

SYSCALL instruction

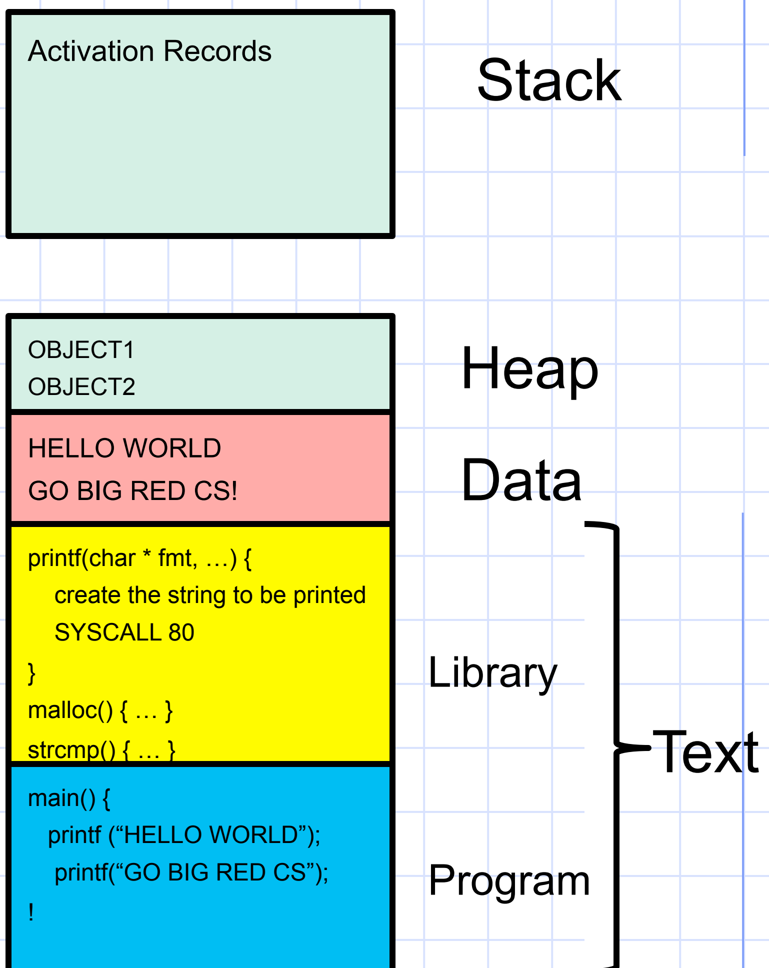
- SYSCALL instruction does an atomic jump to a controlled location
  - Switches the sp to the kernel stack
  - Saves the old (user) SP value
  - Saves the old (user) PC value (= return address)
  - Saves the old privilege mode
  - Sets the new privilege mode to 1
  - Sets the new PC to the kernel syscall 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

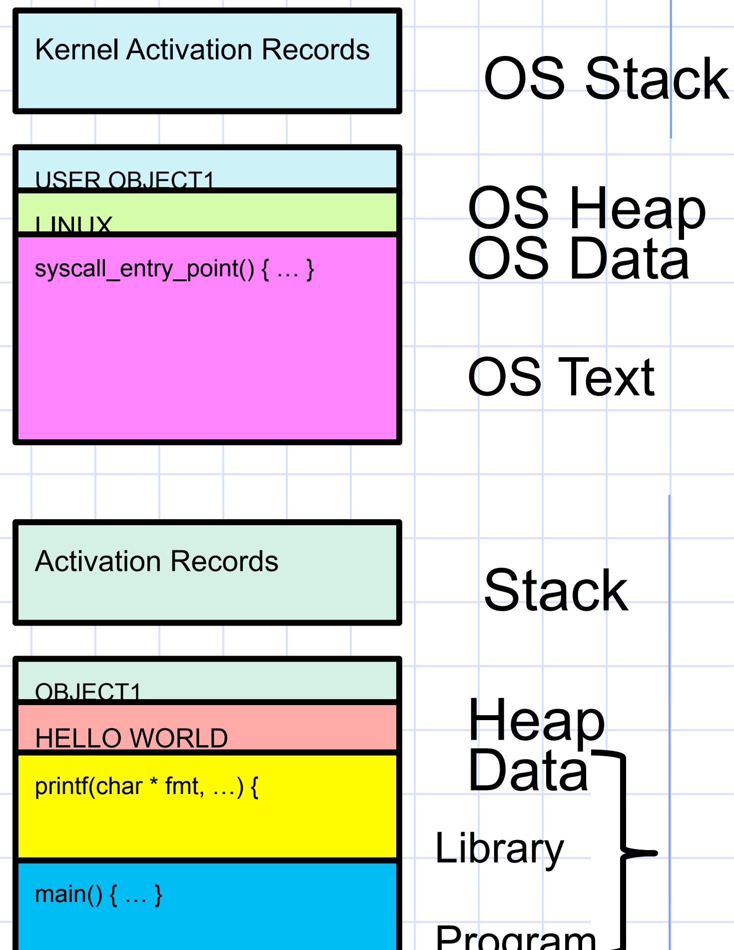
Typical Process Layout

- 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
  - Because the application got struck by a lightning bolt without anticipating the control transfer

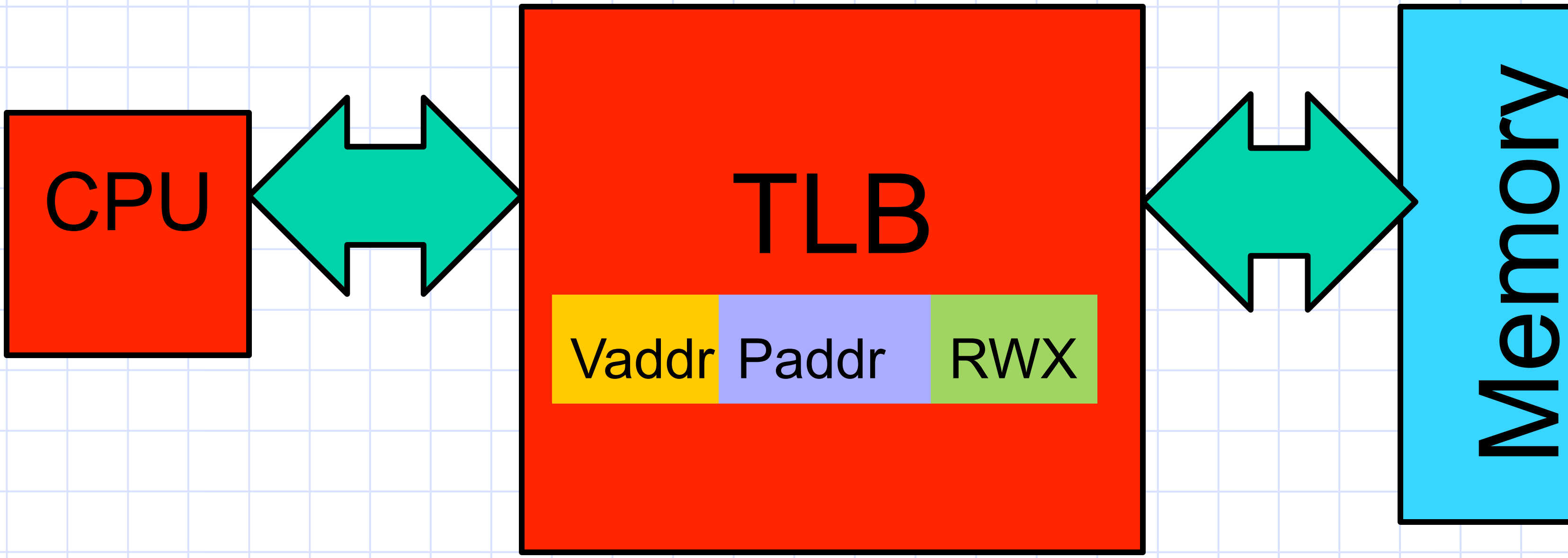
Terminology

- 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 user to the OS
  - e.g. Clock tick, network packet

Memory Protection

- Some memory addresses need protection
  - The OS text, data, heap and stack need to be protected from untrusted applications
  - Some devices should be out of reach of applications
- Memory Management Unit (MMU) aids with memory management
  - Provides a virtual to physical address translation
  - Examines every load/store/jump and ensures that applications remain within bounds using protection (RWX) bits associated with every page of memory
- Modern architectures use a Translation Lookaside Buffer (TLB) for keeping track of virtual to physical mappings
  - Software is invoked on a miss

TLB Operation



- TLB examines every virtual address uttered by the CPU, and if there is a match, and the permissions are appropriate, replaces the virtual page number with the physical page number

Atomic Instructions

- Hardware needs to provide special instructions to enable concurrent programs to operate correctly