Architectural Support for OS

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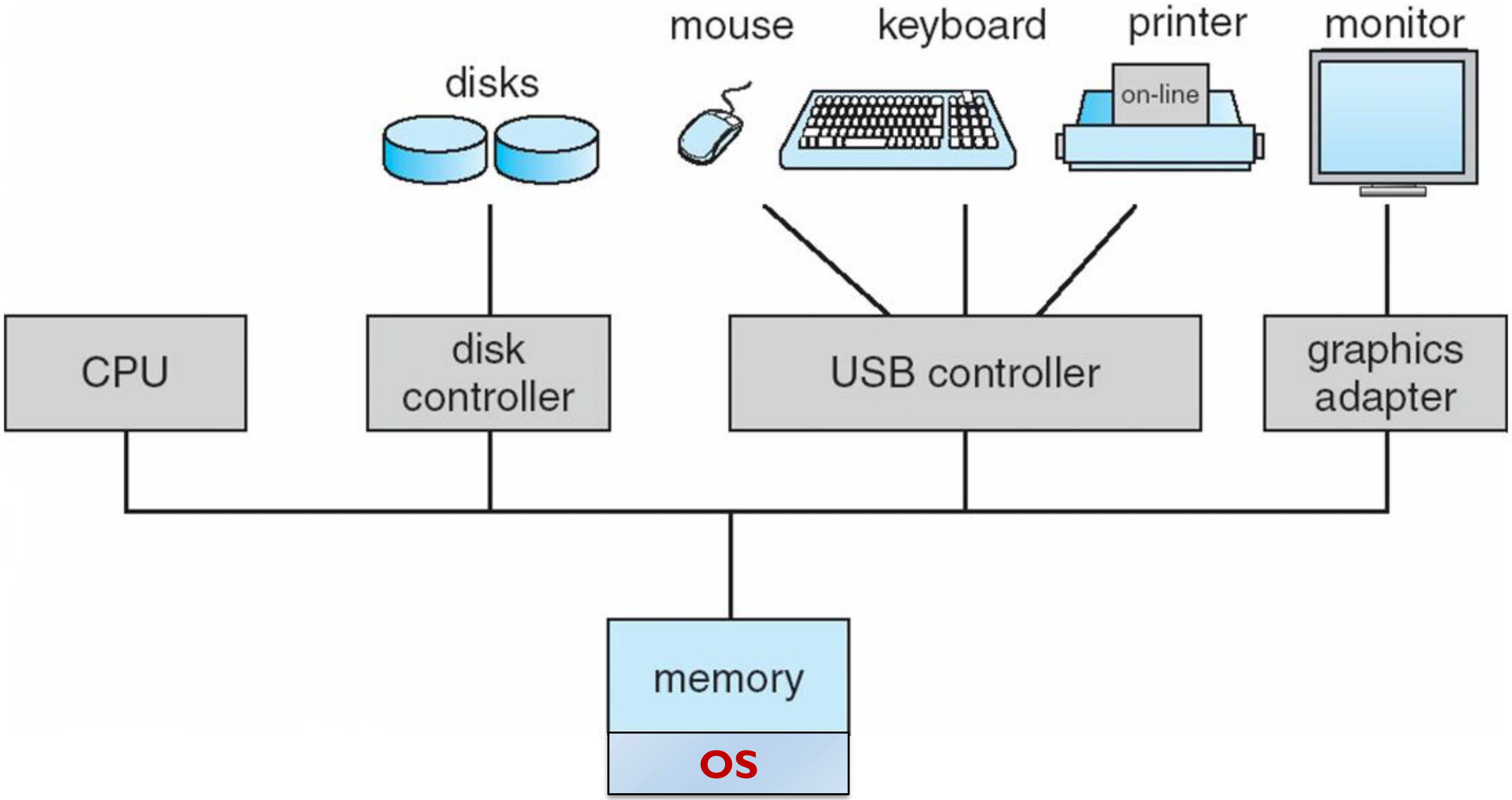
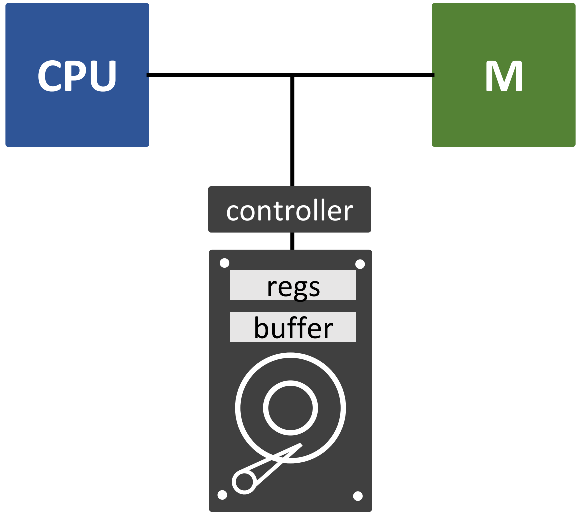
Computer System Organization



Issue #1: I/O

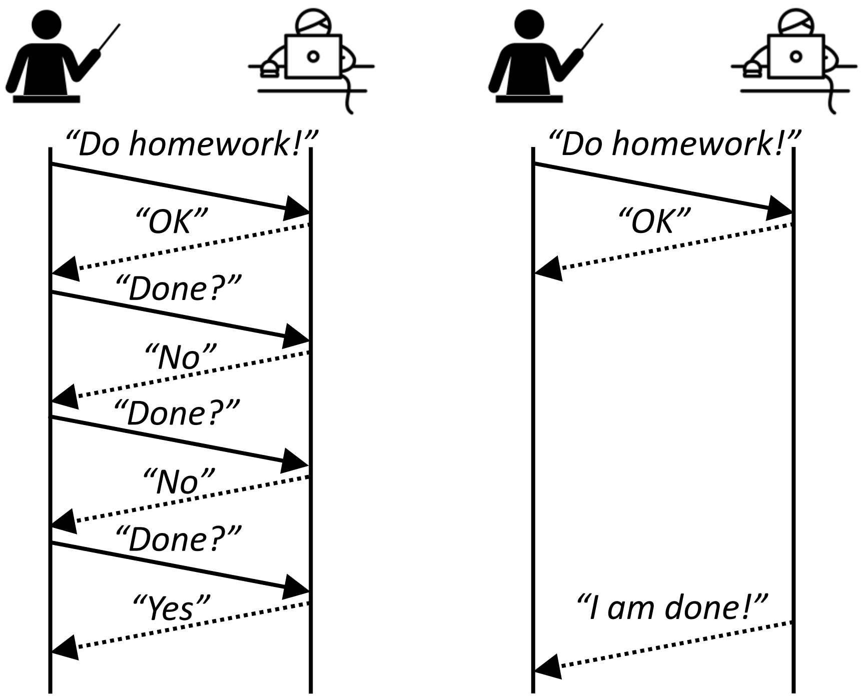
- How to perform I/Os efficiently?
  - I/O devices and CPU can execute concurrently
  - Each device controller is in charge of a particular device type
  - Each device has a local buffer
  - CPU issues specific commands to I/O devices
  - CPU moves data between main memory and local buffers

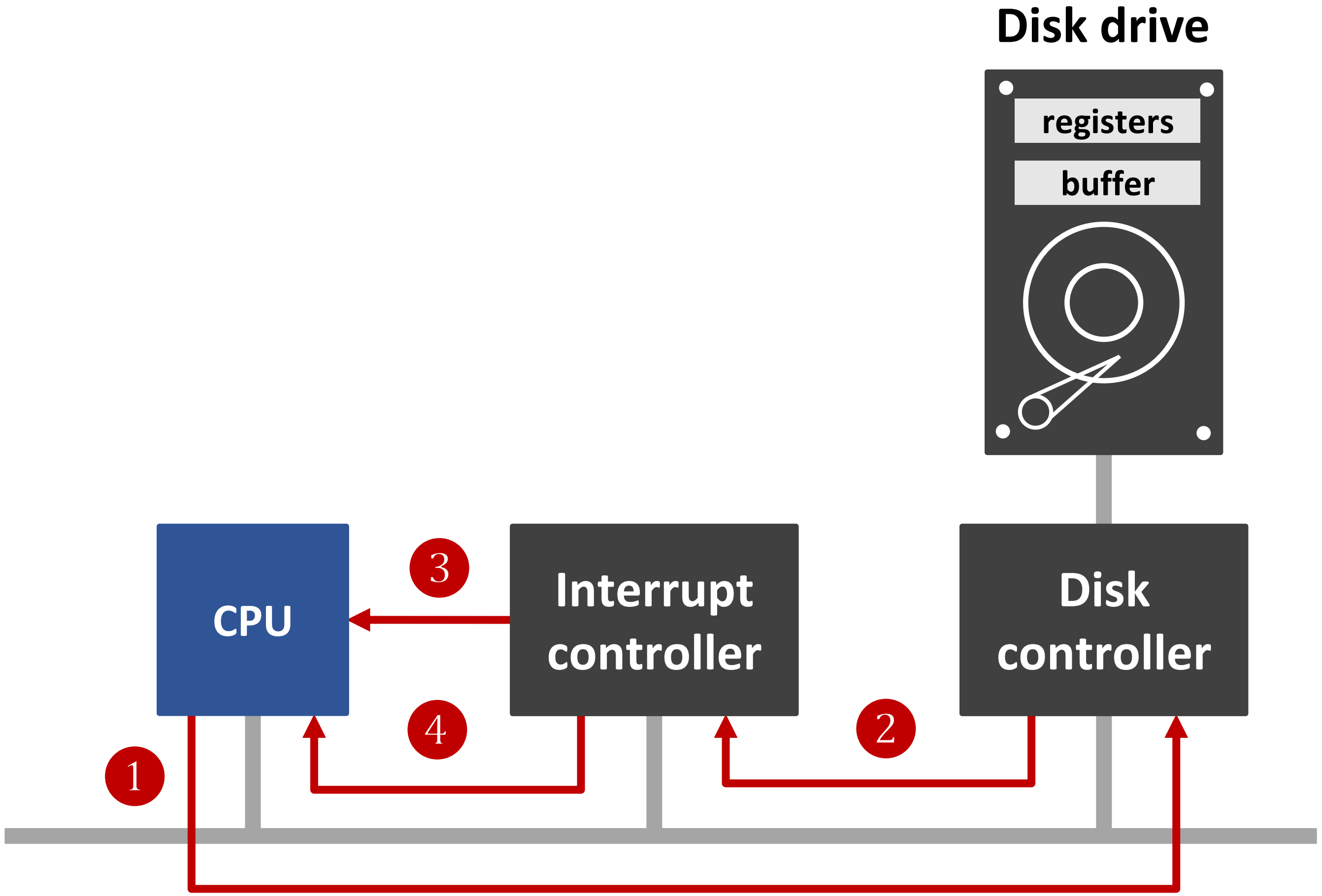


- CPU is a precious resource; it should be freed from time-consuming tasks
  - Checking whether the issued command has been completed or not
  - Moving data between main memory and device buffers

Interrupts

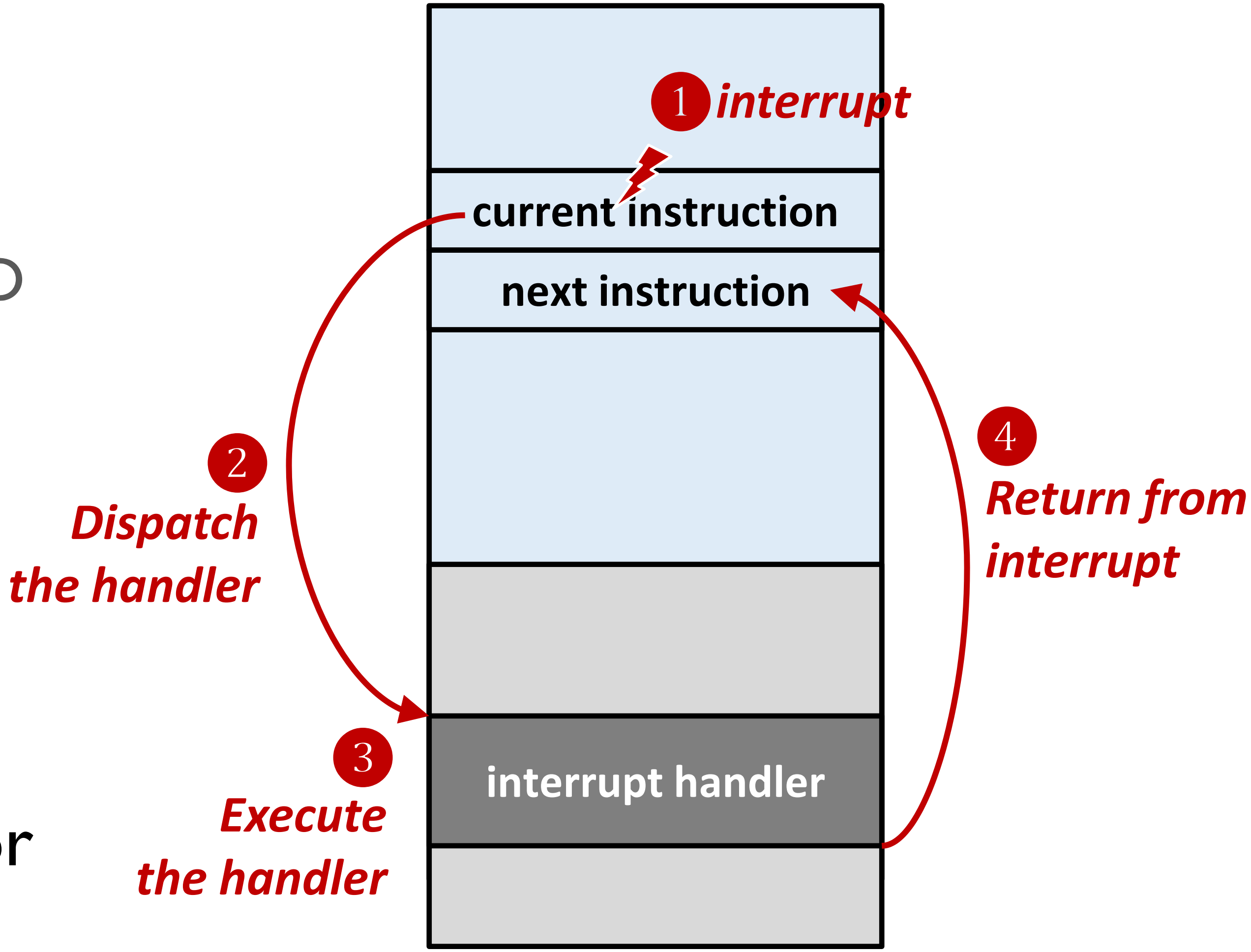
- How does the kernel notice an I/O has finished?
  - ______________
  - Hardware interrupt





Interrupt Handling

- Preserves the state of the CPU
  - In a fixed location
  - In a location indexed by the device ID
  - On the system stack
- Determines the type
  - Polling
  - Vectored interrupt system
- Transfers control to the interrupt service routine (ISR) or interrupt handler

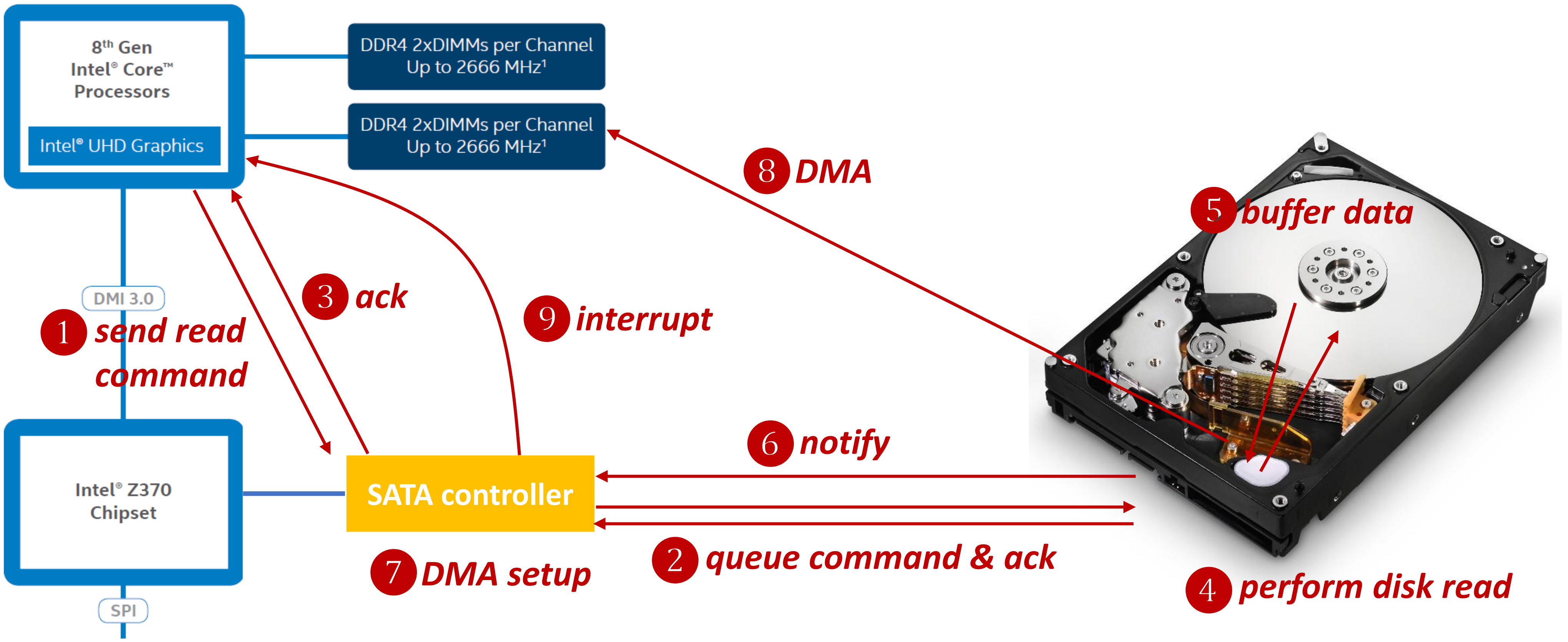


Data Transfer Modes

- ______________________ (PIO)
  - CPU is involved in moving data between I/O devices and memory
  - By special I/O instructions vs. by memory-mapped I/O
  - e.g., keyboard, mouse, …

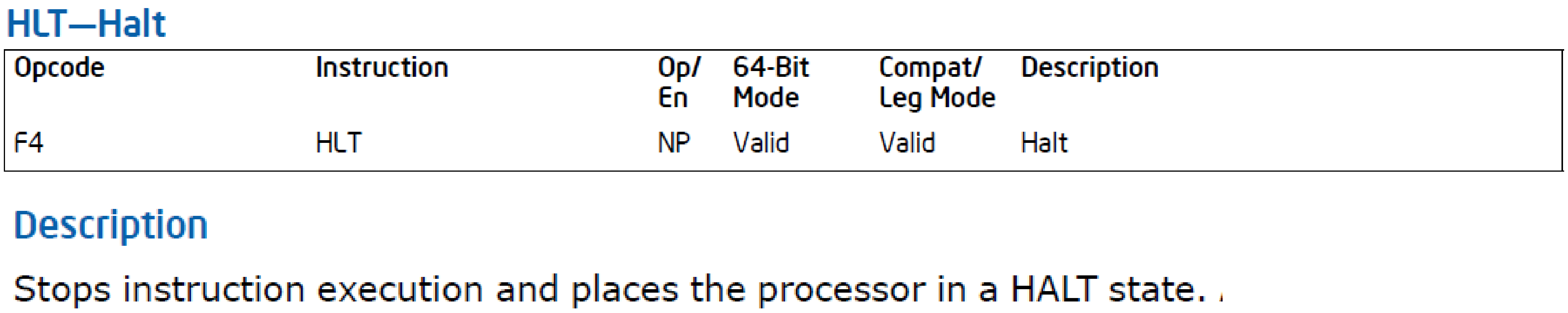
- DMA (Direct Memory Access)
  - Used for high-speed I/O devices to transmit information at close to memory speeds
  - Device controller transfers blocks of data from the local buffer directly to main memory (or vice versa) without CPU intervention
  - DMA controller oversees the overall data transfer
  - Only an interrupt is generated per request

Disk I/O Example



Issue #2: Protection

- How to prevent user applications from harming the system?
  - What if an application accesses disk drives directly?
  - What if an application executes the HLT instruction?



HLT—Halt

Opcode	Instruction	Op/ En	64-Bit Mode	Compat/ Leg Mode	Description
F4	HLT	NP	Valid	Valid	Halt

Description

Stops instruction execution and places the processor in a HALT state.

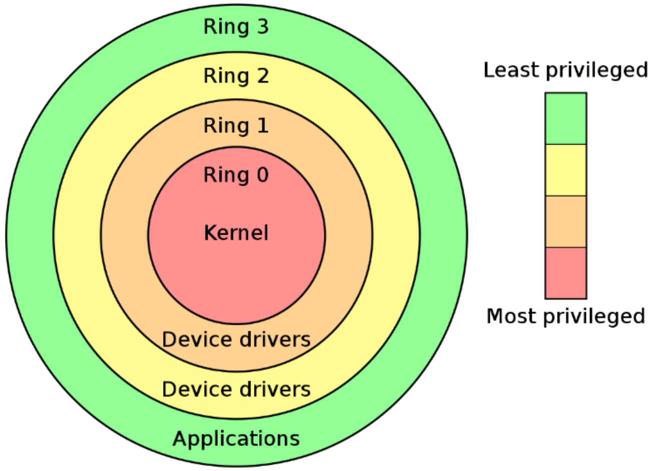
Protected Instructions

- Protected or ______________ instructions
  - The ability to perform certain tasks that cannot be done from user mode

  - Direct I/O access
    - e.g., `in` / `out` instructions in x86
  - Accessing system registers
    - Control and status registers (CSRs)
    - System table locations (e.g., interrupt handler table)
    - Setting special "mode bits", etc.
  - Memory state management
    - Page table updates, page table base address, TLB loads, etc.
  - HLT instruction in x86
  - …

CPU Modes of Operation

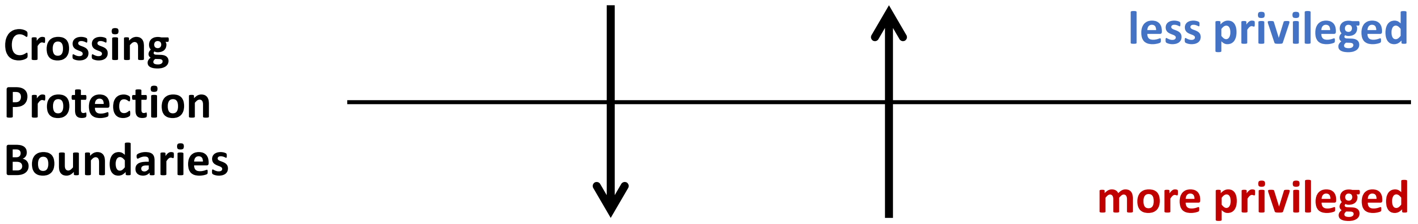
- Kernel mode vs. user mode
  - How does the CPU know if a protected instruction can be executed?
  - The architecture must support at least two modes of operation: kernel and user mode
    - 4 privilege levels in x86_64: Ring 0 > 1 > 2 > 3
    - 4 privilege levels in ARM: EL3 > EL2 > EL1 > EL0
    - 3 privilege levels in RISC-V: Machine > Supervisor > User
  - Mode can be set by a status bit in a protected register
    - IA-32: Current Privilege Level (CPL) in CS register
    - ARM: Mode field in CPSR register



- Protected instructions can only be executed in the corresponding privileged level

Issue #3: Servicing Requests

- How to ask services to the OS?
  - How can an application read a file if it cannot access disk drives?
  - Even a "`printf()`" call requires hardware access
  - User programs must ask the OS to do something privileged



System Calls

- OS defines a set of system calls
  - Programming interface to the services provided by OS
  - OS protects the system by rejecting illegal requests
  - OS may impose a quota on a certain resource
  - OS may consider fairness while sharing a resource

- A system call is a _______________ procedure call
  - System call routines are in the OS code
  - Executed in the kernel mode
  - On entry, user mode → kernel mode switch
  - On exit, CPU mode is changed back to the user mode

System Calls Example

- POSIX vs. Win32

Category	POSIX	Win32	Description
Process Management	`fork`	`CreateProcess`	Create a new process (CreateProcess = fork + exec)
	`waitpid`	`WaitForSingleObject`	Wait for a process to exit
	`execve`	`(none)`	Execute a new program
	`exit`	`ExitProcess`	Terminate execution
	`kill`	`(none)`	Send a signal
File Management	`open`	`CreateFile`	Create a file or open an existing file
	`close`	`CloseHandle`	Close a file
	`read`	`ReadFile`	Read data from a file
	`write`	`WriteFile`	Write data to a file
	`lseek`	`SetFilePointer`	Move the file pointer
	`stat`	`GetFileAttibutesEx`	Get various file attributes
	`chmod`	`(none)`	Change the file access permission
File System Management	`mkdir`	`CreateDirectory`	Create a new directory
	`rmdir`	`RemoveDirectory`	Remove an empty directory
	`link`	`(none)`	Make a link to a file
	`unlink`	`DeleteFile`	Destroy an existing file
	`chdir`	`SetCurrentDirectory`	Change the current working directory
	`mount`	`(none)`	Mount a file system

Exceptional Events

- Interrupts
  - Generated by hardware devices
    - Triggered by a signal in INTR or NMI pins (x86_64)
  - Asynchronous

- Exceptions
  - Generated by software executing instructions
    - Unintentional: Divide-by-zero, …
    - Intentional: **`syscall`** instruction in x86_64 or **`ecall`** instruction in RISC-V
  - Synchronous
  - Exception handling is same as interrupt handling

Exceptions in x86_64

- ________
  - Intentional
  - System call traps, breakpoint traps, special instructions, …
  - Return control to "next" instruction
- Faults
  - Unintentional but possibly recoverable
  - Page faults (recoverable), protection faults (unrecoverable), …
  - Either re-executing faulting ("current") instruction or abort
- ________
  - Unintentional and unrecoverable (parity error, machine check, …)
  - Abort the current program or halt the system

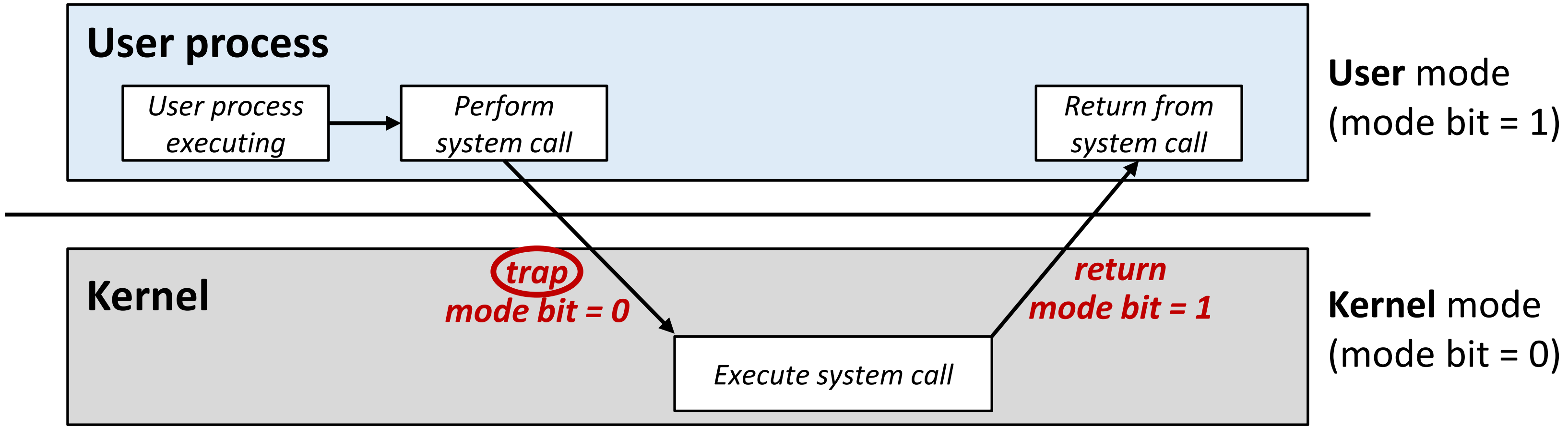
OS Trap

- There must be a special "trap" instruction that:
  - Causes an exception, which invokes a kernel handler
  - Passes a parameter indicating which system call to invoke
  - Saves caller's state (registers, mode bits)
  - Returns to user mode when done with restoring its state
  - OS must verify caller's parameters (e.g., pointers)

Examples:

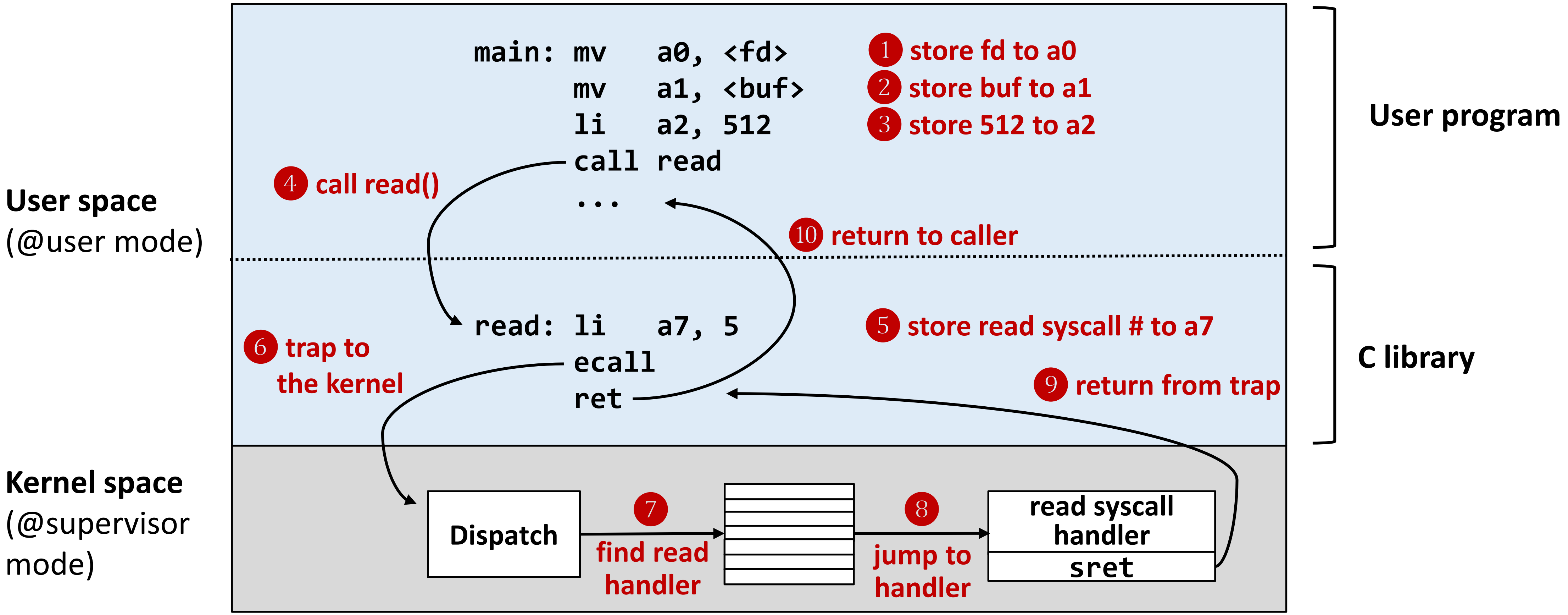
SYSCALL instruction (x86_64)

ECALL instruction (RISC-V)



Implementing System Calls in RISC-V

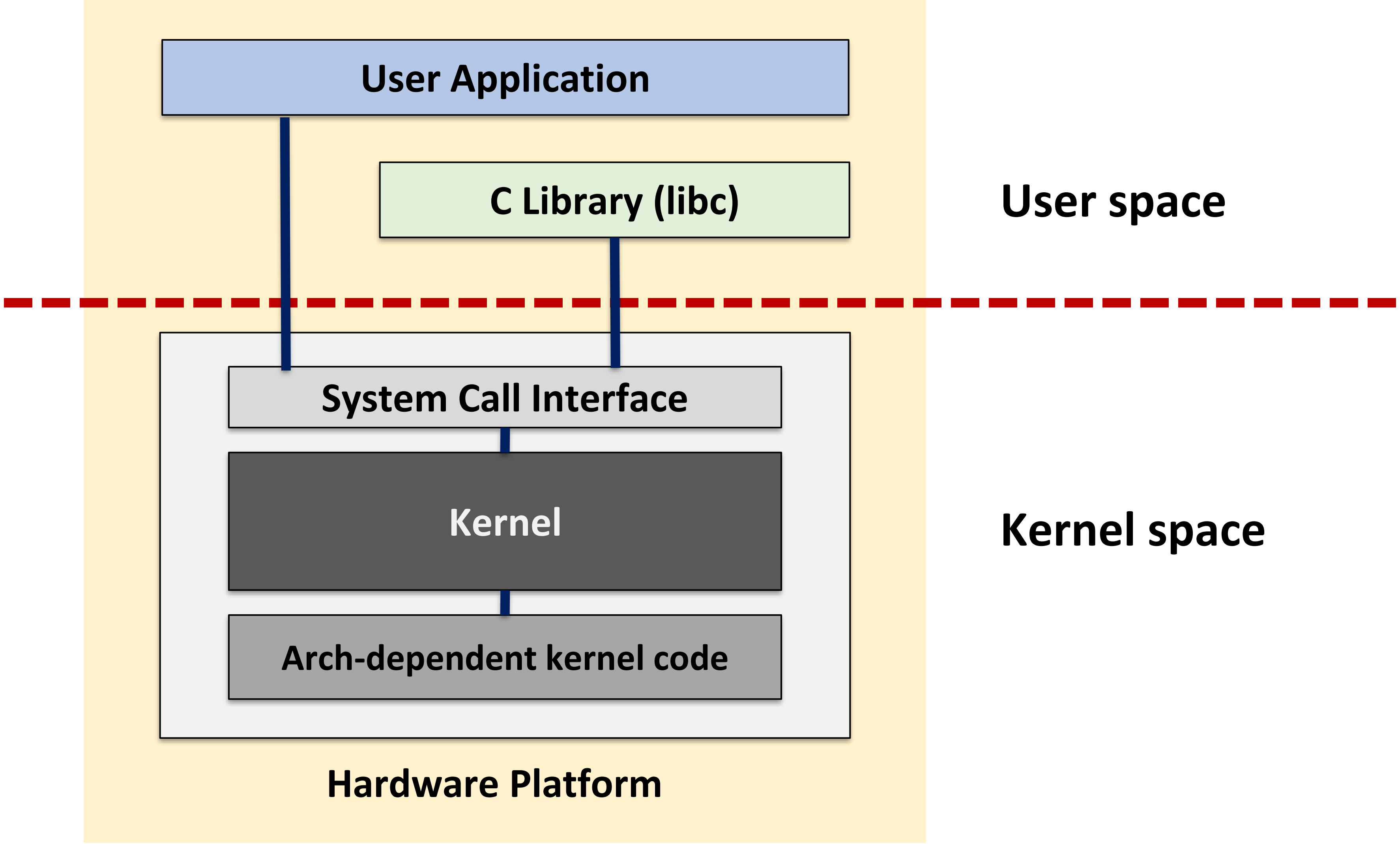
- `count = read(fd, buf, 512);`



```
main: mv   a0, <fd>
      mv   a1, <buf>
      li   a2, 512
      call read
      ...

read: li   a7, 5
      ecall
      ret
```

Typical (Monolithic) OS Structure



Issue #4: Control

- How to take the control of the CPU back from the running program?

- Cooperative approach
  - Each application periodically transfers the control of the CPU to OS by calling various system calls
  - A special system call can be used just to release the CPU (e.g., `yield()`)
  - Can be used when ______________________________
  - What if a process ends up in an infinite loop?
    (due to a bug or with a malicious intent)

Timers

- A non-cooperative approach
  - Use a hardware timer that generates a periodic interrupt
  - The timer interrupt transfers control back to OS

- The OS preloads the timer with a time to interrupt
  - 10ms for Linux 2.4, 1ms for Linux 2.6, 4ms for Linux 5.5
  - ~~10ms~~ 100ms for xv6

- The timer is privileged
  - Only the OS can load it

Issue #5: Memory Protection

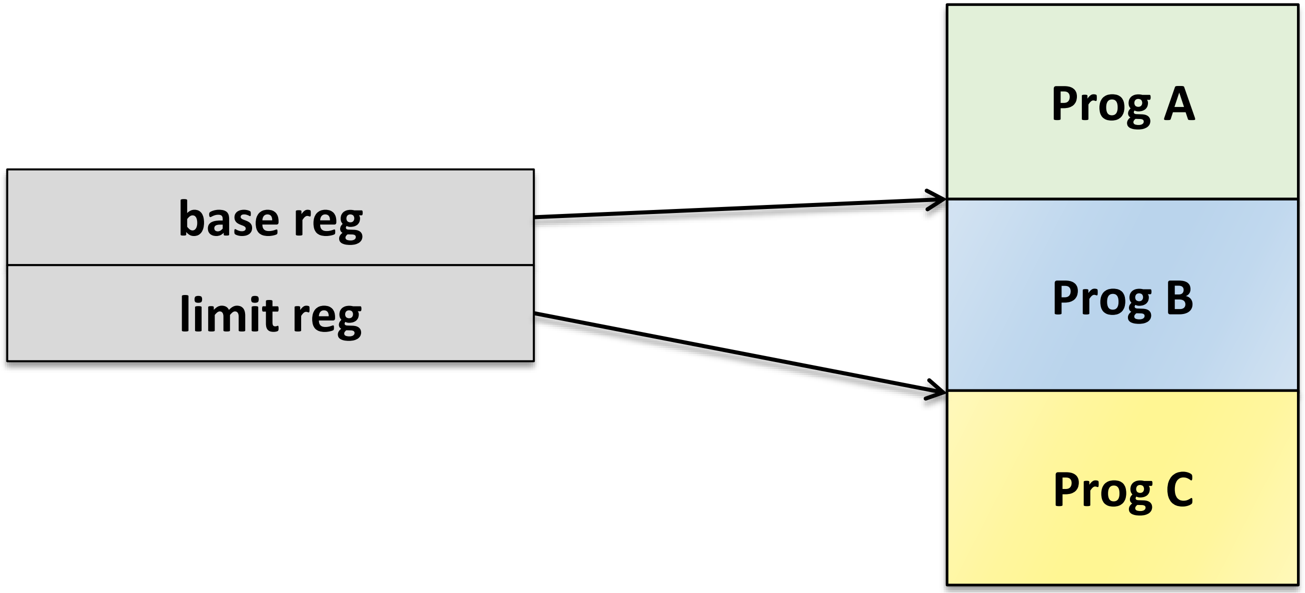
- How can we protect memory?
  - Unlike the other hardware resources, we allow applications to access memory directly without OS intervention. Why?

- From malicious users:
  OS must protect user applications from each other

- For integrity and security:
  OS must also protect itself from user applications

Simplest Memory Protection

- Use base and limit registers
- Base and limit registers are loaded by OS before starting an application
- CPU generates an exception if the memory address is out of bound
- Can be used in a simple embedded environment



Virtual Memory

- Modern CPUs are equipped with memory management hardware
  - MMU (Memory Management Unit)

- MMU provides more sophisticated memory protection mechanisms
  - Virtual memory
  - Paging: page tables, page protection, TLBs
  - Segmentation: segment tables, segment protection

- Manipulation of MMU is a privileged operation

Issue #6: Synchronization

- How to coordinate concurrent activities?
  - What if multiple concurrent streams access the shared data?
  - Interrupt can occur at any time and may interfere with the interrupted code

```
LOAD R1 ← Mem[X]

ADD R1 ← R1, #1

                       LOAD R1 ← Mem[X]

                       ADD R1 ← R1, #1

                       STORE R1 → Mem[X]

STORE R1 → Mem[X]
```

- Turn off/on interrupts?

Atomic Instructions

- Requires special atomic instructions
  - Read-Modify-Write (e.g., INC, DEC)
  - Test-and-Set
  - Compare-and-Swap
  - LOCK prefix in x86_64
  - LL (Load Locked) & SC (Store Conditional) in MIPS

- RISC-V "A" extension
  - LR (Load Reserved) & SC (Store Conditional) instructions
  - AMO (Atomic Memory Operation) instructions
    - Swap, integer add, bitwise AND/OR/XOR, integer max/min (signed/unsigned)

Summary

- The functionality of an OS is limited by architectural features
  - Multiprocessing on MS-DOS/8086?
- The structure of an OS can be simplified by architectural support
  - Interrupt, DMA, atomic instructions, etc.
- Most proprietary OSes were developed with the certain architecture in mind
  - SunOS/Solaris for SPARC
  - IBM AIX for Power/PowerPC
  - HP-UX for PA-RISC