Architectural Support for OS

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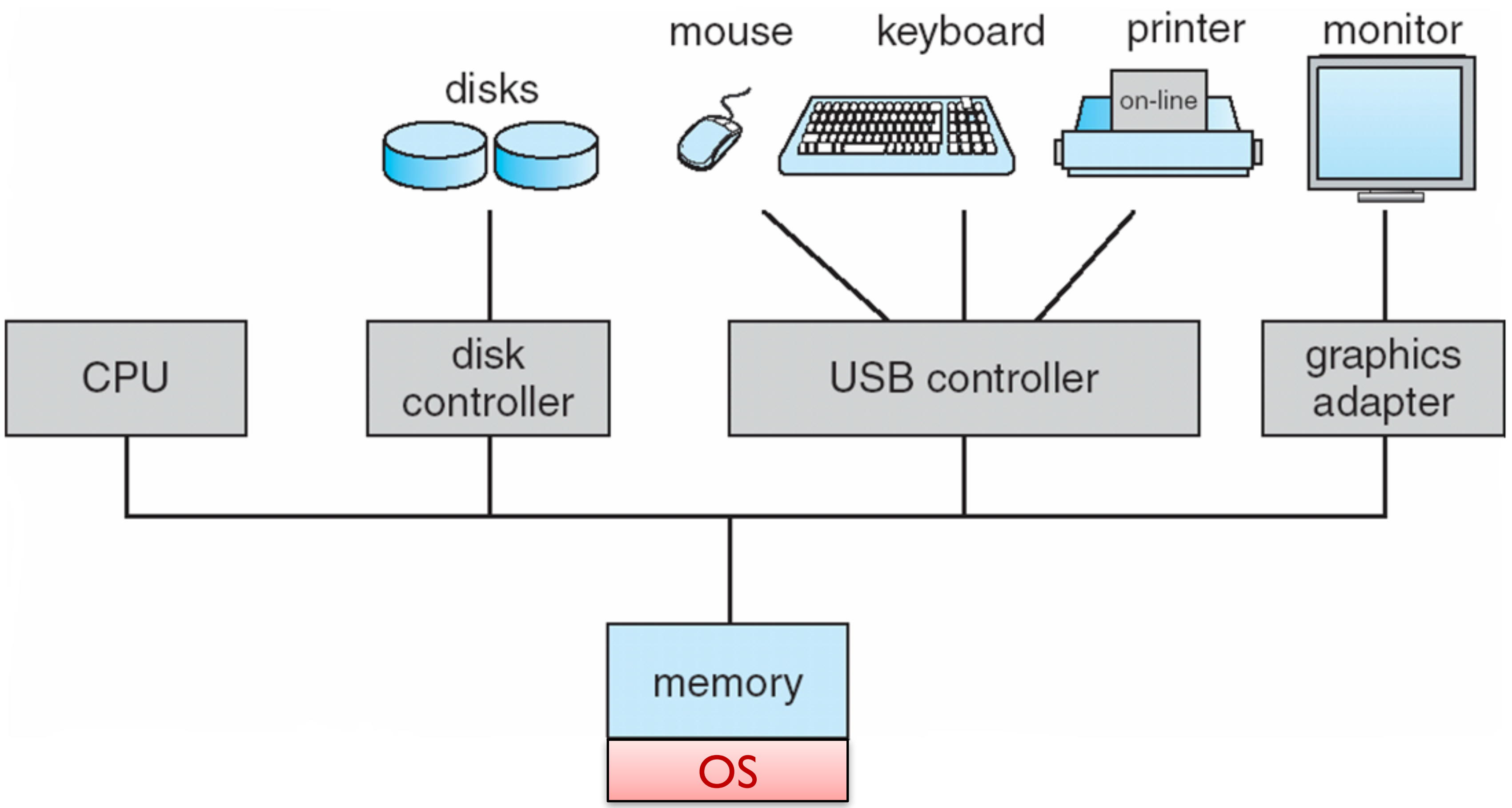
Computer System Organization



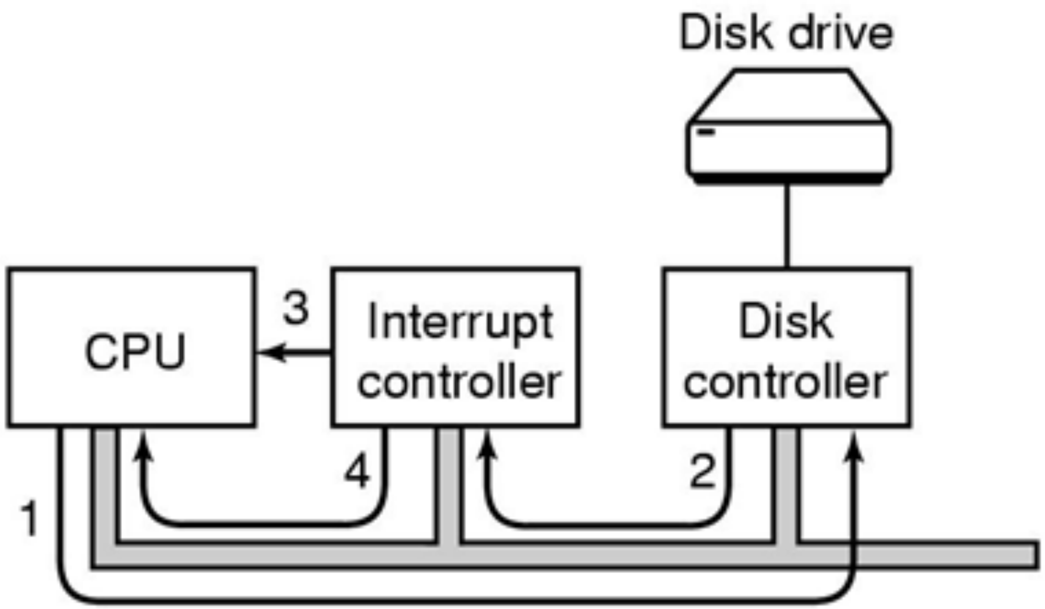
Issue #1

- 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 controller has a local buffer
  - CPU issues specific commands to I/O devices
  - CPU moves data from/to main memory to/from local buffers

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

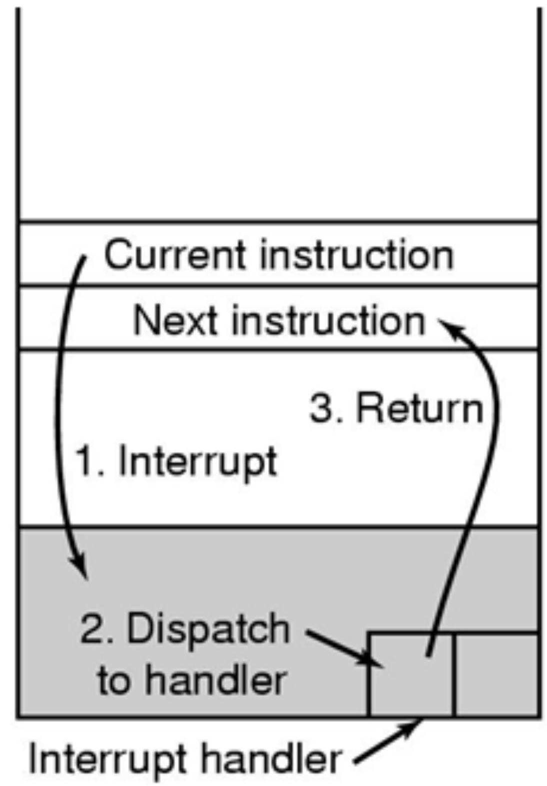
Interrupts

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



Interrupt Handling

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

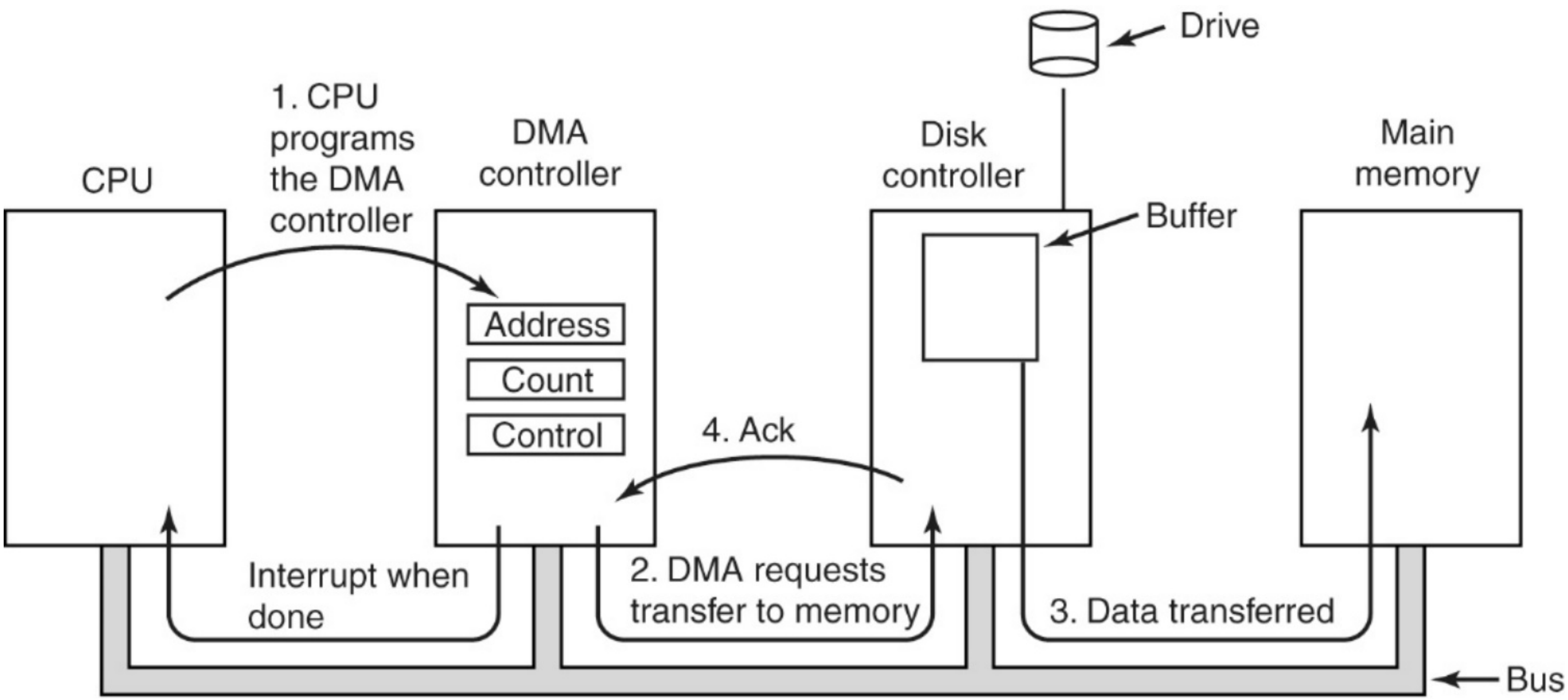


Data Transfer Modes

- Programmed I/O (PIO)
  - CPU is involved in moving data between I/O devices and memory
  - By special I/O instructions vs. by memory-mapped I/O

- 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 without CPU intervention
  - Only an interrupt is generated per block

DMA Example


Drive
1. CPU programs the DMA controller
CPU
DMA controller
Disk controller
Main memory
Buffer
Address
Count
Control
4. Ack
Interrupt when done
2. DMA requests transfer to memory
3. Data transferred
Bus

Issue #2

- 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 privileged instructions
  - The ability to perform certain tasks that cannot be done from user mode
  - Direct I/O access
    - e.g. IN / OUT instructions in IA-32
  - Accessing system registers
    - Control registers
    - System table locations (e.g. interrupt handler table)
    - Setting special "mode bits", etc.
  - Memory state management
    - Page table updates, page table pointers, TLB loads, etc.
  - HLT instruction IA-32

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 IA-32: Ring 0 > 1 > 2 > 3
    - 2 privilege levels in ARM: User vs. Supervisor
  - Mode is 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 privileged level (kernel mode)

Issue #3

- 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 protected 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
	waitpid	WaitForSingleObject	Wait for a process to exit
	execve	(none)	CreateProcess = fork + exec
	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

Exceptions

- Interrupts
  - Generated by hardware devices
    - Triggered by a signal in INTR or NMI pins (IA-32)
  - Asynchronous

- Exceptions
  - Generated by software executing instructions
    - Divide-by-zero
    - INT instruction in IA-32
  - Synchronous
  - Exception handling is same as interrupt handling

Exceptions in IA-32

- Traps
  - 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-execute faulting ("current") instruction or abort
- Aborts
  - Unintentional and unrecoverable
  - Parity error, machine check, …
  - Abort the current program

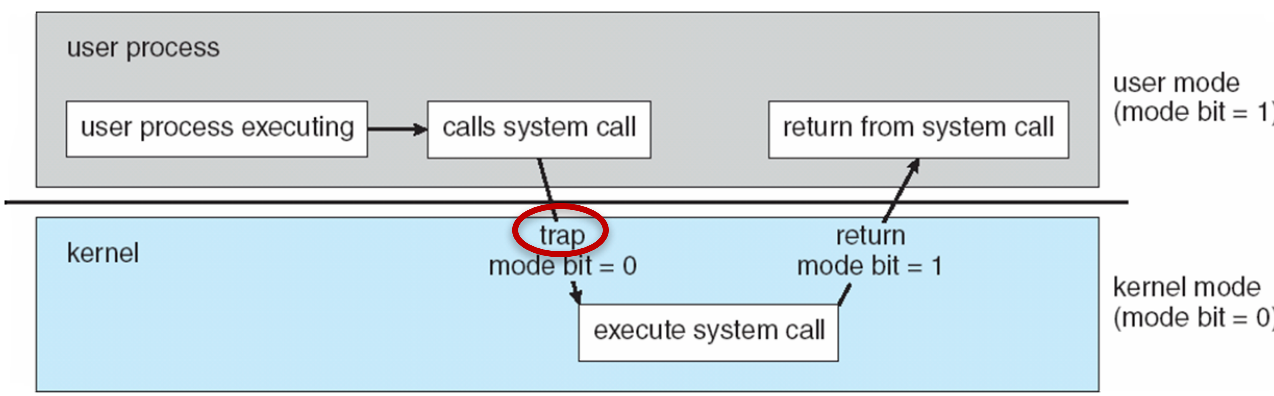
OS Trap

- 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:

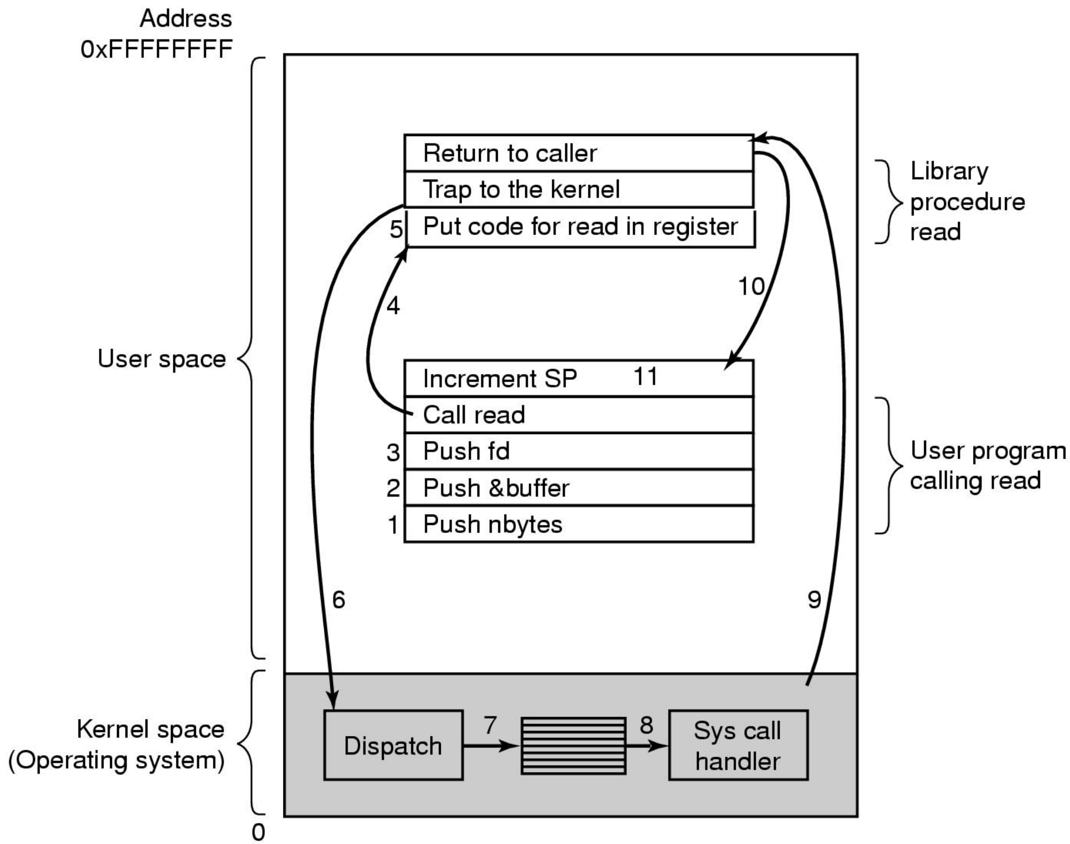
INT instruction (IA-32)

SVC instruction (ARM)

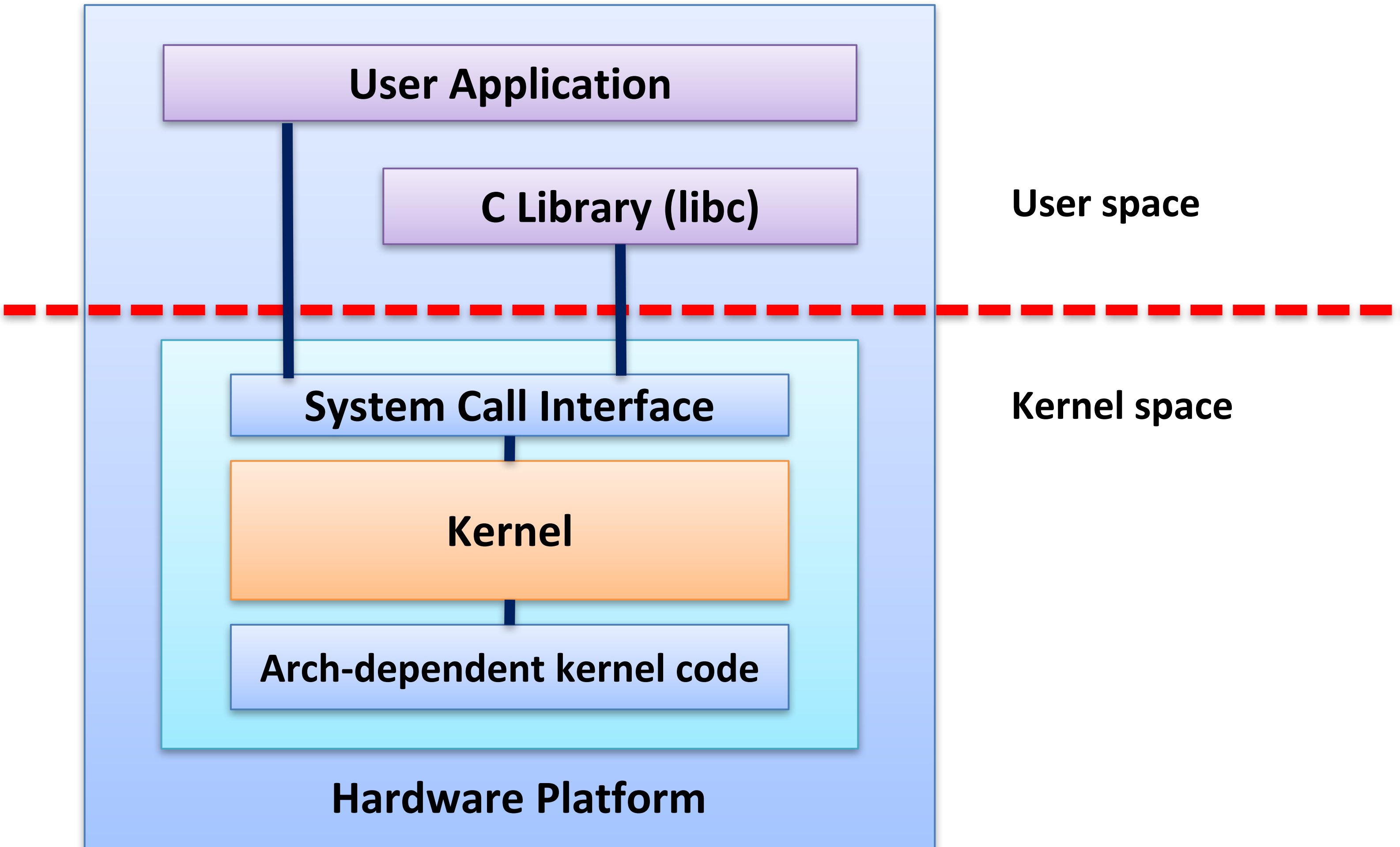


Implementing System Calls

```
count = read (fd, buffer, nbytes);
```



Typical OS Structure



Issue #4

- 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 OS trusts user applications
  - What if a process ends up in an infinite loop? (due to a bug or with a malicious intent)

Timers

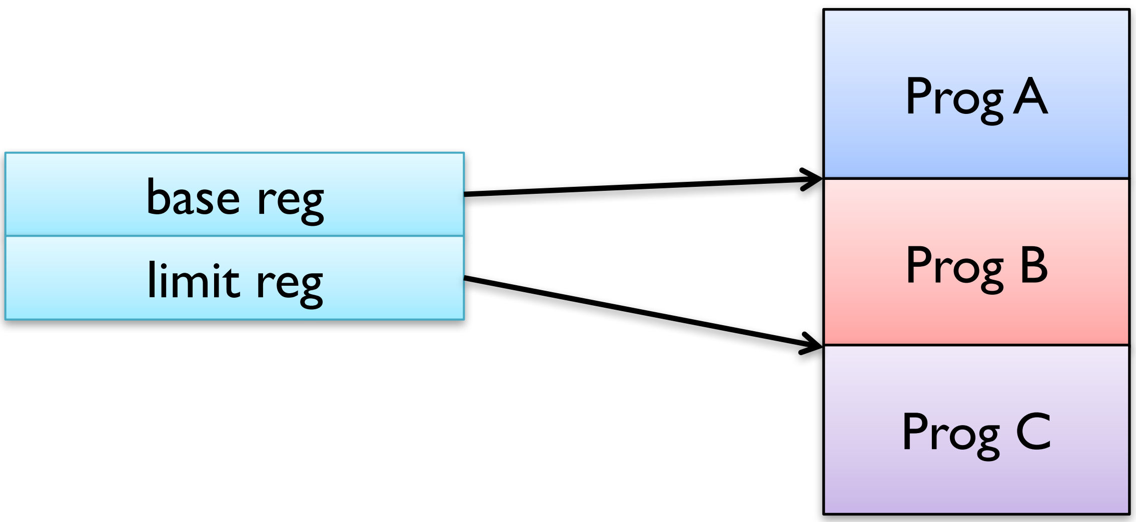
- A non-cooperative approach
  - User a hardware timer that generates a periodic interrupt
  - The timer interrupt transfers control back to OS
- The OS preloads the timer with a time to interrupt
  - 10ms for Linux 2.4, 1ms for Linux 2.6, 4ms for Linux 4.1
  - 10ms for xv6
- The timer is privileged
  - Only the OS can load it

Issue #5

- 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



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 table pointers, page protection, TLBs
  - Segmentation: segment table pointers, segment protection
- Manipulation of MMU is a privileged operation

Issue #6

- 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***]	

Synchronization

- Turn off/on interrupts

- Use a special atomic instruction
  - Read-Modify-Write (e.g. INC, DEC)
  - Test-and-Set
  - Compare-and-Swap
  - LOCK prefix in IA-32
  - LL (Load Locked) & SC (Store Conditional) in MIPS

OS and Architecture

- 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