Chap.6
Limited Direct Execution

Problems of Direct Execution

- The OS must virtualize the CPU in an efficient manner while retaining control over the system.

OS	Program
Create entry for process list	
Allocate memory for program	
Load program into memory	
Set up stack with argc/argv	
Clear registers	
Execute **call** main()	
	Run main()
	Execute **return** from main
Free memory of process	
Remove from process list	

- Problems
  - how can the OS make sure the program doesn't do anything that we don't want it to do, while still running it efficiently?
    - such as issuing an I/O request to a disk, or gaining access to more system resources such as CPU or memory
  - how does the OS stop the process from running and switch to another process, thus implementing the time sharing?

Problem #1: Restricted Operations

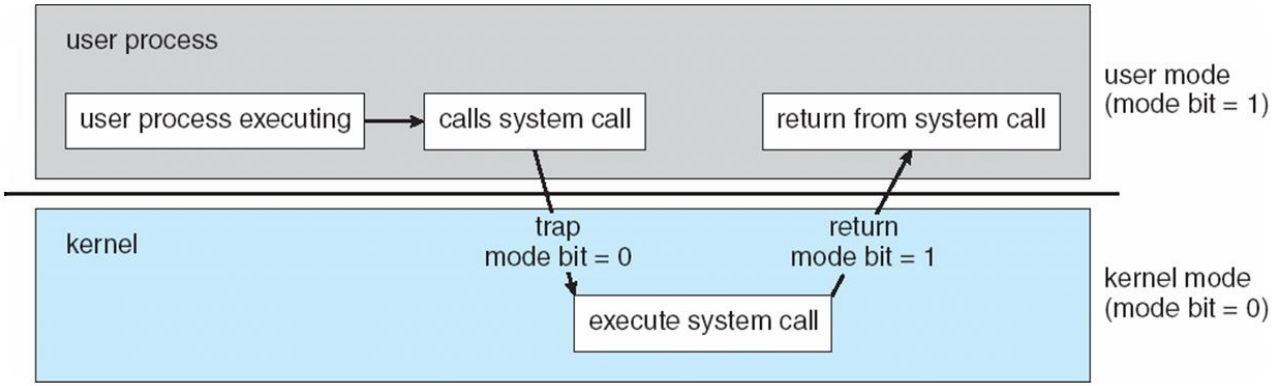
- Without limits on running programs, the OS wouldn't be in control of anything and thus would be "just a library"
- Two different privileged modes
  - user mode
    - code that runs in user mode is restricted in what it can do.
    - For example, when running in user mode, a process can't issue I/O requests; doing so would result in the processor raising an exception;
  - kernel mode
    - the operating system (or kernel) runs in.
    - In this mode, code that runs can do what it likes, including privileged operations such as issuing I/O requests and executing all types of restricted instructions.

Problem #1: Restricted Operations

- System call
  - When a user process wishes to perform some kind of privileged operation
  - a program must execute a special **trap** instruction.
    - Trap must save the caller's registers in order to be able to return correctly to the caller
  - This instruction simultaneously jumps into the kernel and raises the privilege level to **kernel mode**.
    - User code specifies a **system-call number**
    - **Trap table** has the jump address for the system-call number
  - once in the kernel, the system can now perform whatever privileged operations are needed (if allowed), and thus do the required work for the calling process.
  - When finished, the OS calls a special **return-from-trap** instruction, which returns into the calling user program while simultaneously reducing the privilege level back to user mode.

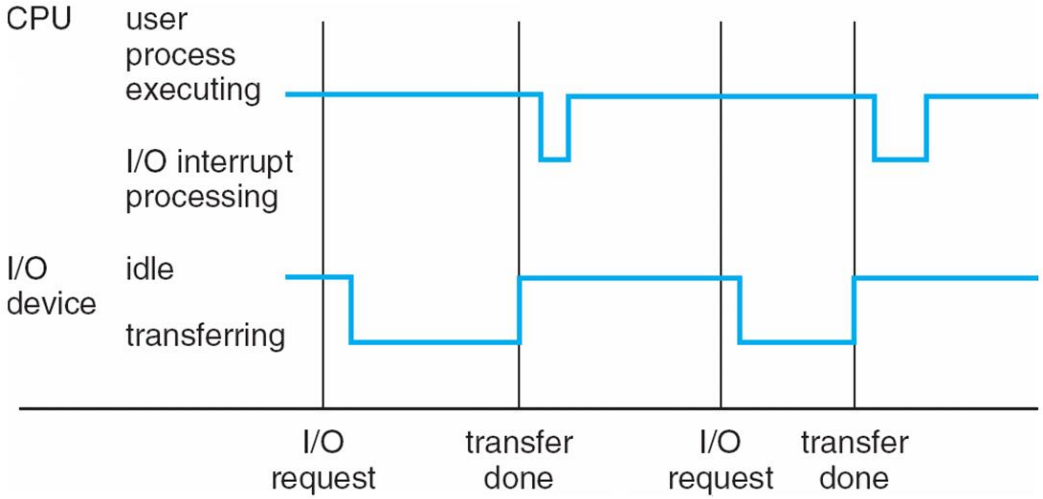
System Mode

- Dual-mode operation allows OS to protect itself and other system components
  - User mode and kernel mode (supervisor mode, privileged mode)
  - Mode bit provided by hardware
  - Some instructions designated as privileged, only executable in kernel mode
- Mode change
  - When a trap or interrupt occurs, the H/W switches from user mode to kernel mode



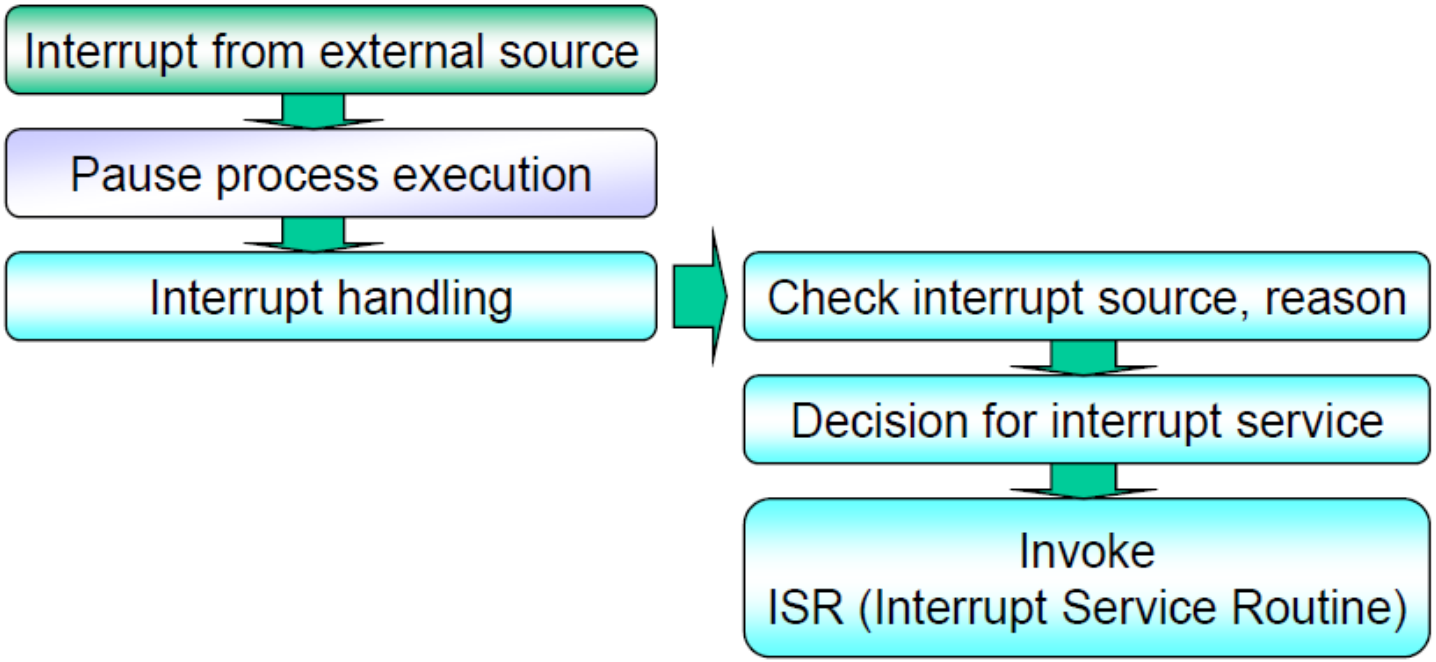
Interrupt and trap

- **Interrupt**
  - Unexpected external event
    - I/O interrupt, Clock interrupt, Console interrupt
    - Machine check interrupt, Inter-process communication interrupt, etc
  - From either the H/W or the S/W
    - H/W may trigger an interrupt by sending a signal to the CPU
- **Trap**
  - Software-generated interrupt caused by
    - Exception: An error of the running program (div by zero)
    - System call: A specific request from a user program:



Interrupts

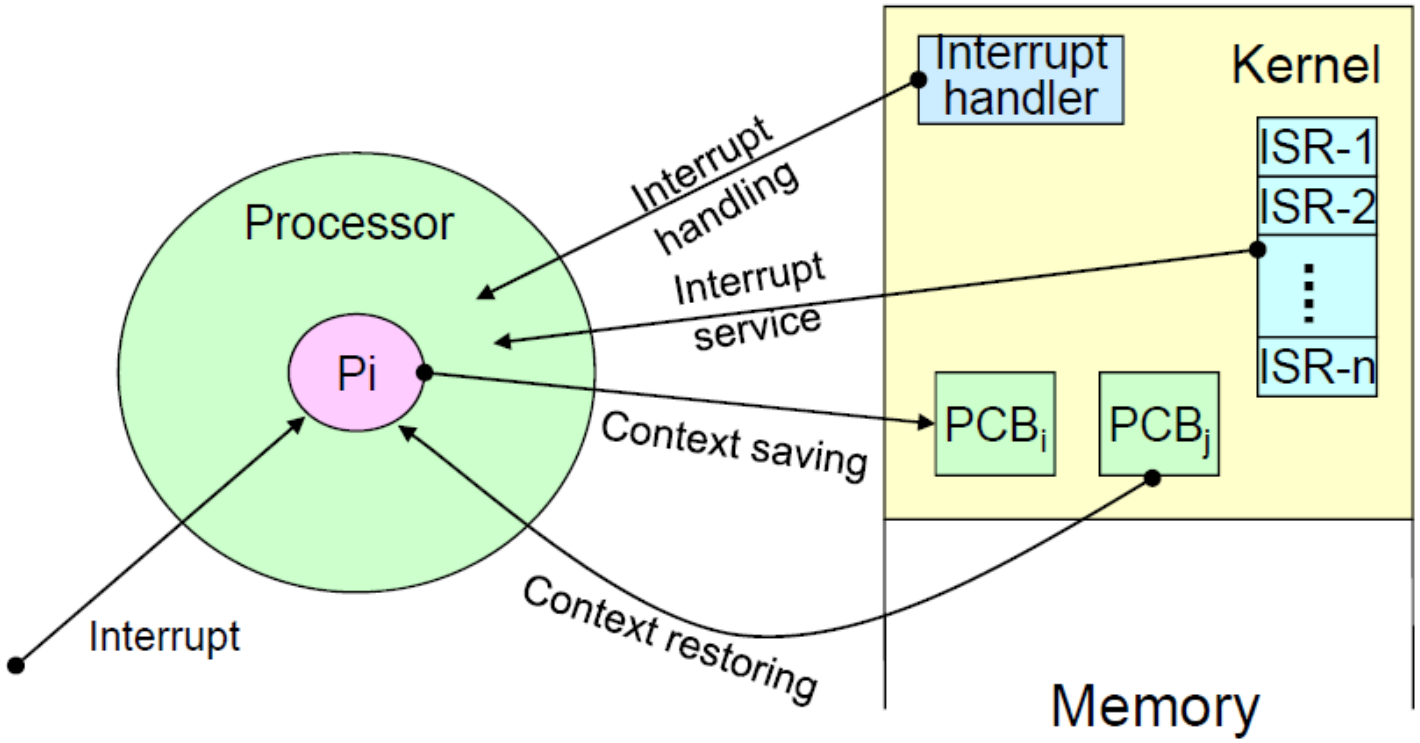
- **Interrupt handling process**



- kernel: Intervene whenever interrupt occurs and control interrupt handling and service process

Interrupts

Interrupt handling



Privileged instructions

- Machine instructions that can be executed only in kernel mode
- Examples
  - I/O control
  - Timer management
  - Interrupt management
  - Switching to user mode
  - Etc

Intel privileged instructions

CLTS - Clear Task-Switched Flag
HLT - Halt Processor
LGDT - Load GDT Register
LIDT - Load IDT Register
LLDT - Load LDT Register
LMSW - Load Machine Status
LTR - Load Task Register
MOV CRn - Move Control Register
MOV DRn - Move Debug Register
MOV TRn - Move Test Register

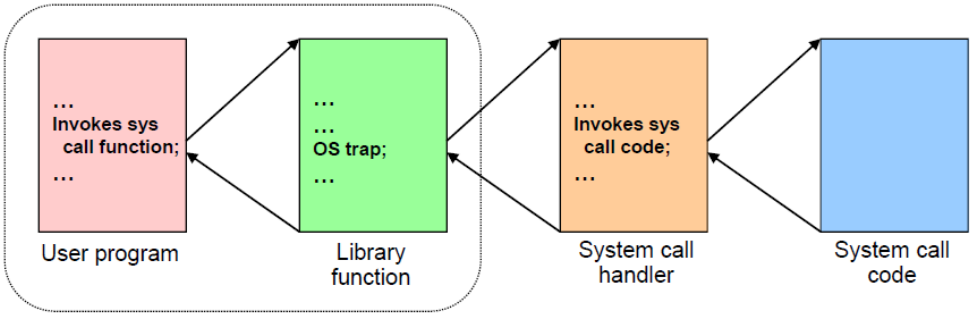
System Call Interface

- Interface between applications/processes and the OS
- Services that OS provides to applications/processes
  - Means for a user program to ask the OS to perform tasks reserved for OS on the user program's behalf
  - Means used by a process to request action by the OS
- Generally, programs uses a high-level Application Programming Interface (API) rather than direct system call
  - POSIX API
- Executed by a generic trap instruction
  - syscall instruction in MIPS R2000
  - swi instruction in ARM
  - INT/SYSENTER in x86

```
#include <unistd.h>

ssize_t     read(int fd, void *buf, size_t count)
```

return value | function name | parameters

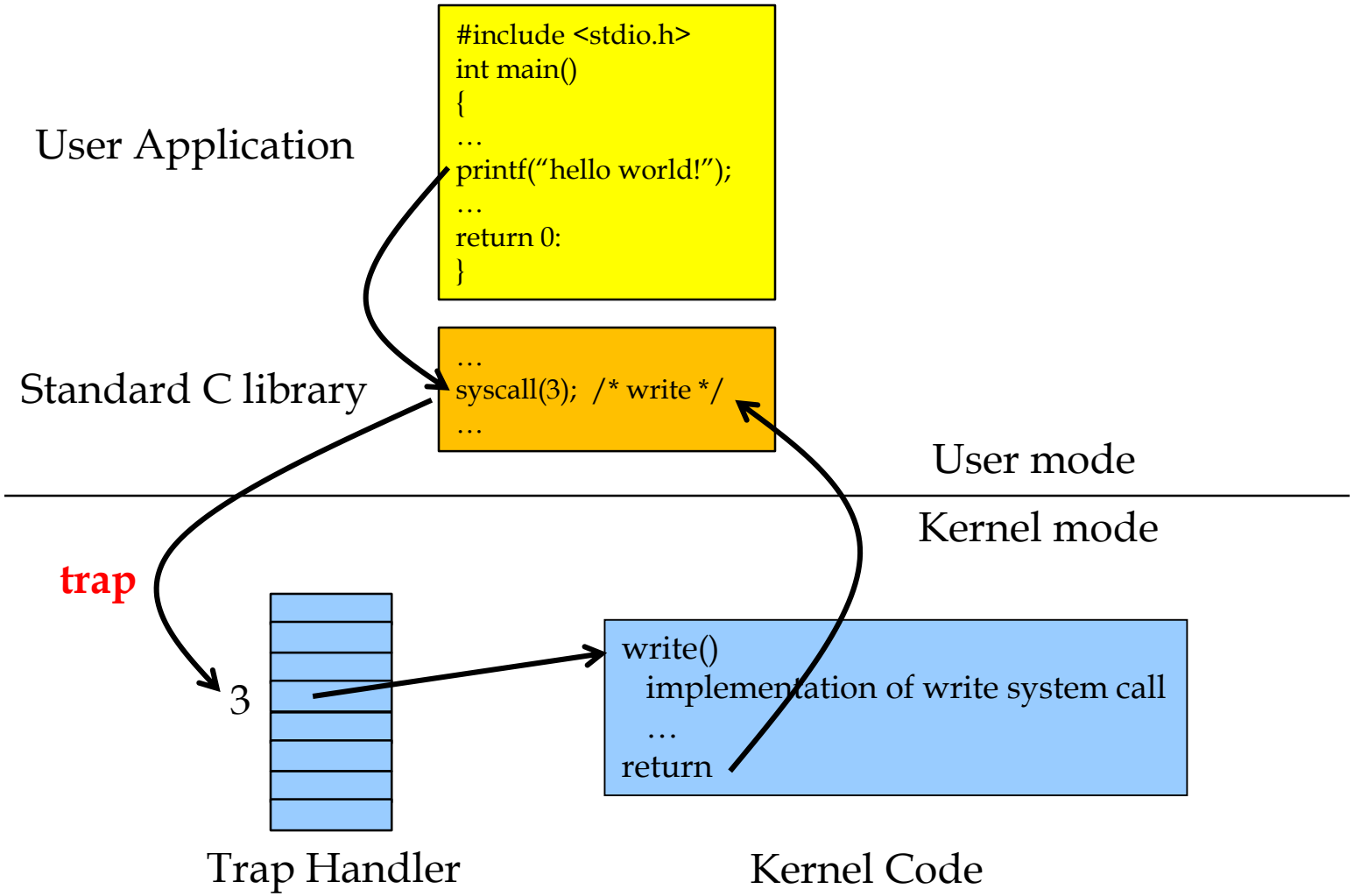


Limited Direct Execution

OS @ boot (kernel mode)	Hardware	Program (user mode)
initialize trap table		
	remember address of... syscall handler	
OS @ run (kernel mode)	**Hardware**	**Program (user mode)**
Create entry for process list		
Allocate memory for program		
Load program into memory		
Setup user stack with argv		
Fill kernel stack with reg/PC		
return-from-trap		
	restore regs from kernel stack	
	move to user mode	
	jump to main	
		Run main()
		...
		Call system call
		trap into OS
	save regs to kernel stack	
	move to kernel mode	
	jump to trap handler	
Handle trap		
Do work of syscall		
return-from-trap		
	restore regs from kernel stack	
	move to user mode	
	jump to PC after trap	
		...
		return from main
		trap (via `exit()`)
Free memory of process		
Remove from process list		

each process has a kernel stack where registers are saved to and restored from (by the hardware) when transitioning into and out of the kernel (x86 Architecture)

API – System Call – OS Relationship



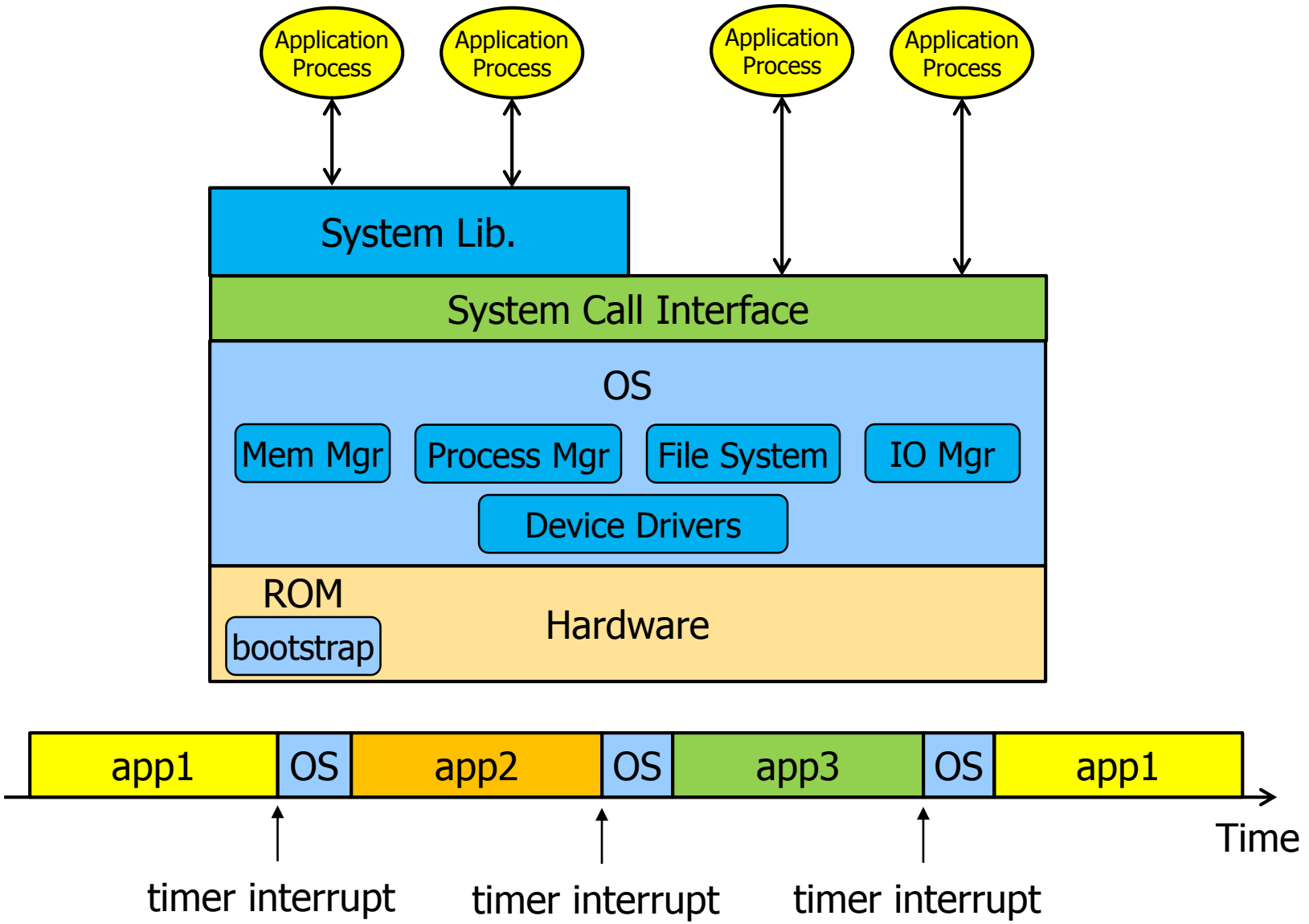
Problem #2: Switching Between Processes

- How can the OS **regain control** of the CPU so that it can switch between processes?
- **A Cooperative Approach: Wait For System Calls**
  - OS trusts the processes of the system to behave reasonably.
  - Processes that run for too long are assumed to periodically give up the CPU so that the OS can decide to run some other task.
  - via system calls (including explicit **yield**), trap by exception
  - Passive approach
    - What happens if a process (whether malicious, or just full of bugs) ends up in an infinite loop, and never makes a system call?

Problem #2: Switching Between Processes

- **A Non-Cooperative Approach: The OS Takes Control**
  - **timer interrupt:** A timer device can be programmed to raise an interrupt every so many milliseconds
  - when the interrupt is raised, the currently running process is halted, and a pre-configured interrupt handler in the OS runs.
    - save the state of the program that was running when the interrupt occurred
  - At this point, the OS has regained control of the CPU, and thus can do what it pleases: stop the current process, and start a different one.

Problem #2: Switching Between Processes



Problem #2: Switching Between Processes

- When OS has regained control, it must decide whether to continue running the currently-running process, or switch to a different one ➔ need **scheduler**
- If the decision is made to switch, the OS then executes a low-level piece of code which we refer to as a **context switch**
- save a few register values for the currently-executing process (onto its kernel stack, for example) and restore a few for the soon-to-be-executing process (from its kernel stack).
- when the return-from-trap instruction is finally executed, instead of returning to the process that was running, the system resumes execution of another process.

Problem #2: Switching Between Processes

OS @ boot (kernel mode)	Hardware
initialize trap table	
	remember addresses of...
	syscall handler
	timer handler
start interrupt timer	
	start timer
	interrupt CPU in X ms

OS @ run (kernel mode)	Hardware	Program (user mode)
		Process A
		...
implicitly saved by H/W →	**timer interrupt**	
	save regs(A) to k-stack(A)	
	move to kernel mode	
	jump to trap handler	
Handle the trap		
Call `switch()` routine		
save regs(A) to proc-struct(A) ← explicitly saved by OS		
restore regs(B) from proc-struct(B)		
switch to k-stack(B)		
return-from-trap (into B)		
	restore regs(B) from k-stack(B)	
	move to user mode	
	jump to B's PC	
		Process B
		...

How long ?

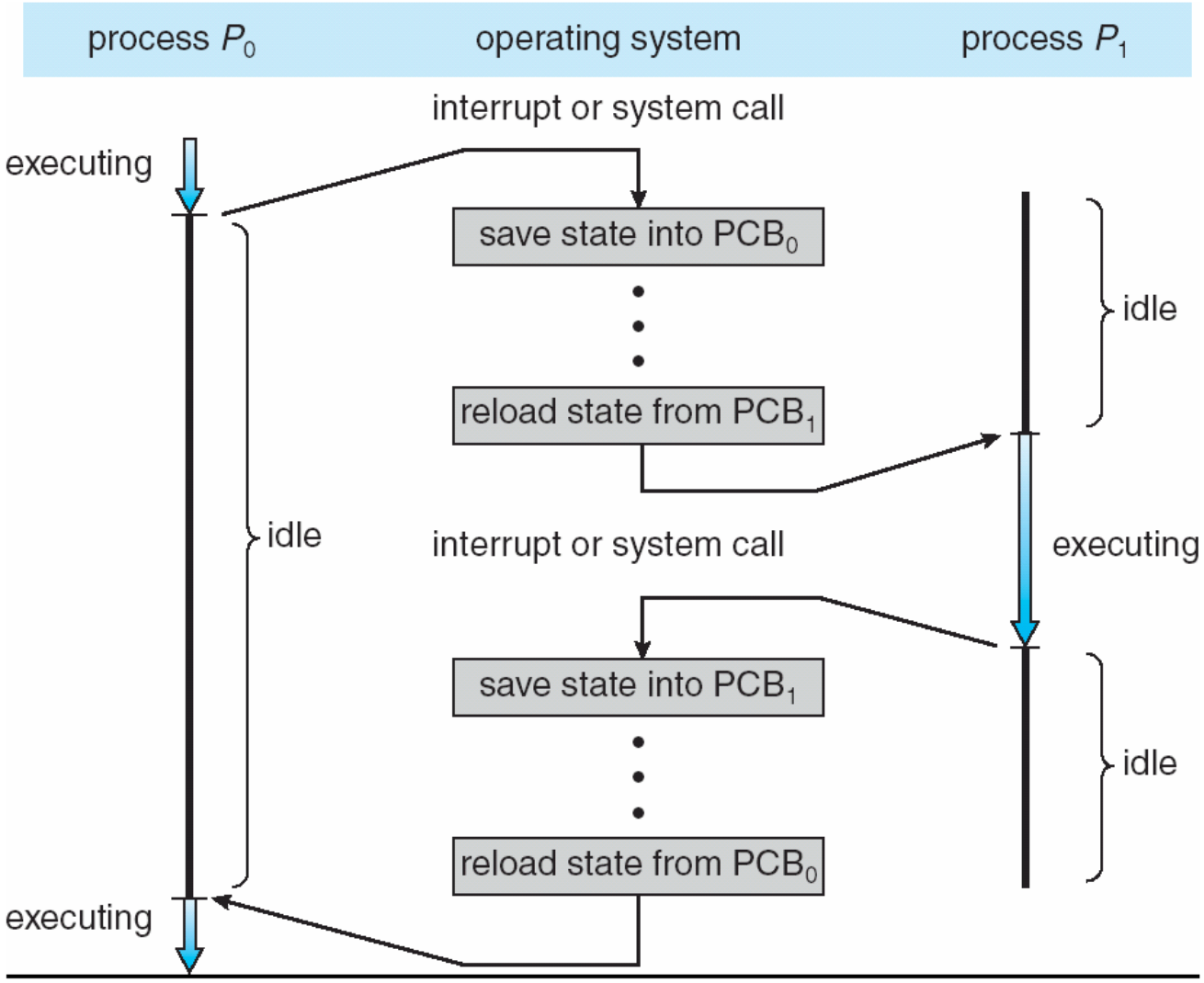
Context Switching

- When CPU switches to another process, the system must save the state of the old process and load the saved state for the new process via a context switch
- **Context**
  - Set of information related to a process
    - User-level context
    - Register context
    - System-level context

Context Switching

- **Context switch**
  - Context saving: Saving the register context of a process when the process releases processor
  - Context restoring: Reloading the register context of a process to continue execution
  - Context switching: Saving the context of a process and restoring the context of another process
- **Context switch time**
  - Pure overhead
    - The more complex the OS and the PCB ➔ the longer the context switch
  - Highly dependent on hardware support
    - Some processors provide multiple sets of registers
      - Context switch by changing the pointer to the current register set
      - Sun UltraSPARC, ARM

Context Switching



Worried About Concurrency?

- **Concurrency Issues**
  - Interrupt during trap handling – "What happens when, during a system call, a timer interrupt occurs?"
  - Interrupt during interrupt handling – "What happens when you're handling one interrupt and another one happens?"
- One simple solution is **disable interrupts** during interrupt processing
  - disabling interrupts for too long could lead to lost interrupts
- More sophisticated approach is **locking**
  - protect concurrent access to internal data structures.
  - enables multiple activities to be on-going within the kernel at the same time, particularly useful on multiprocessors