Inf2C - Computer Systems
Lecture 20
Exceptions and Processor Management

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Previous lecture: Virtual memory

- Solves two problems:
  - Capacity (physical memory is limited)
  - Safety (physical memory must be shared by multiple programs and the OS)
- Virtual vs physical address space
  - Each program "sees" a full 32-bit address space
  - Actual physical memory managed by the OS
- Address translation
  - Page table – all translations, but slow (in memory)
  - TLB – recent entries only, but fast (cache)

Exceptions

- What happens when a TLB miss happens?
- How can a program display stuff on monitor?
- What happens when the restart button is hit?

Exceptions – definition

- Exceptional events that interrupt normal program flow and require attention of the operating system
- External ("interrupts")
  – Not caused by program execution
  – E.g., I/O interrupt (e.g., network packet arrived)
- Internal ("traps")
  – Caused by program execution
  – E.g., `syscall`, TLB miss

What is the Operating System really?

- System software that manages resources
- Kernel: Nucleus of the OS
  - First to be loaded when system boots
  - Manages interrupts, fork processes, schedules processes, manages memory.

Internal intentional exceptions

- Use exception mechanism to request some OS functions
  - I/O (e.g., print to screen), memory allocation, etc
- MIPS: user program uses `syscall` instruction
  - Register ($v0) is set with a special value to identify the type of syscall exception
  - OS exception handler invoked when the `syscall` instruction executes
- Parameters are passed to the OS through agreed upon registers (usually $a0, $a1, ..)

Syscall example

The following will print the integer in register $t0 to the screen.

```
li  $v0, 1     # service 1 is "print integer"
add $a0, $t0, $zero  # load integer into $a0
syscall
```

Exception mechanism

- Step 1: Save the address of current instruction
  – into a special register, the exception program counter (EPC)
  – Note: Might need to resume the interrupted instruction (not PC+4)
- Step 2: Transfer control to the OS at a known address (i.e., exception handler PC)
- Step 3: Handle the exception
  – Deal with the cause of the exception
  – All registers must be preserved: callee saves everything!
- Step 4: Return to user program execution
  – Handler restores user program's registers and jumps back using EPC
  – Relies on special instruction **`eret`**

Finding the exception handler

- Approach 1:
  – Jump to a predefined address (e.g., 0x800000180 in MARS)
  – Use the Cause register to then branch to the right handler
    E.g. for `syscall` – cause register set to indicate it is syscall

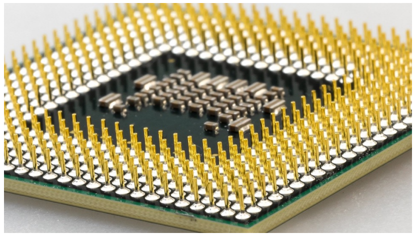
Examples of system calls:

- `putc()` – print character to screen (multiple processes need to display things on the screen)
- `send()` – send a packet over the network
- `sbrk()` – allocate memory

Finding the exception handler

- Approach 2
  - Directly jump to a specific handler depending on the exception (**vectored interrupt**)
  - Eg:

Undefined opcode:	0x8000 0000
Overflow:	0x8000 0020
…:	0x8000 0040



Handling the exception

- Determine action required
  - By inspecting the Cause register or by virtue of being at the right handler (e.g., undefined opcode)
- If restartable:
  - Take corrective action, then use EPC to return to program
- Otherwise:
  - Terminate program and report error using EPC, cause, …
- For a critical time while the interrupt is being handled, certain other interrupts should not happen
  - Otherwise the EPC, Cause will be overwritten
  - This is forced by masking interrupts → by setting the exception level (EXL) bit in the status register

Question

- Why this elaborate rule? Syscall, eret etc?

- Why not simply use jumps and jr instructions like normal procedures?

Protecting system resources

- The OS must guarantee safe and orderly access to critical system resources
  - Hardware (processor, networking, I/O)
  - Program memory (including page tables)
- The OS is the ultimate arbiter of what's allowed
  - TLB miss → OK (but must access page table to service)
  - Arithmetic overflow → may be OK (depends on what we're doing)
  - Illegal opcode → not OK (kill the program)
- Exceptions are used to hand control over to the OS
  - Need a separate mechanism to limit capabilities of user programs

Kernel vs. User Mode Protection

- Exceptions (including system calls) are handled by the OS
  - CPU has two modes of operation: **user** and **kernel** (OS)
  - Current mode identified by a bit in the process status register
- **Privileged** instructions only executed in kernel mode
  - E.g. accessing I/O devices, handling page table accesses and TLB updates, halt or reset the processor or change its voltage
- Kernel mode can only be entered through an exception
  - User programs cannot jump to OS instruction space
- `eret` instruction sets mode back to previous mode

Advantages of Dual Mode architecture

- Guarantees that control is transferred to OS when user programs attempt to perform potentially dangerous tasks
- Allows OS to ensure that programs do not interfere with each other
  - e.g., each program is able to get its share of physical memory
- Allows OS to ensure that programs do not have access to resources for which they do not have permission
  - e.g., files, another program's memory
- Ensures that user programs do not have indefinite control of the processor
  - Time-sharing of the CPU

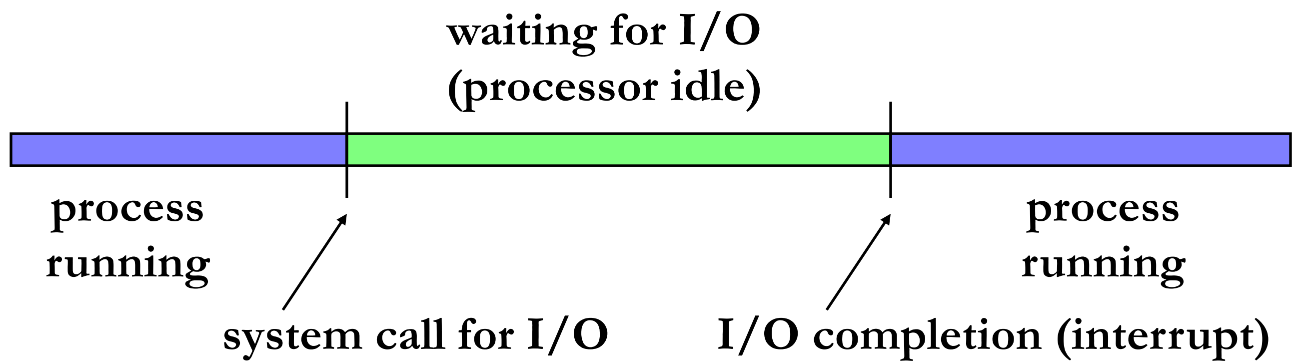
Time-Sharing the CPU

- Issues:
  - Multiple programs, one computer
  - I/O takes too long → processor idle
  - User programs can crash or monopolize the CPU (either unintentionally or maliciously)
- Solution:
  - Multiplex or **time-share** the CPU and other resources among several user processes
  - Switch from one process to another when it performs I/O, or when its time allocation (time slice) expires

Process: "a program in execution" [Silberschatz, Galvin, Gagne]

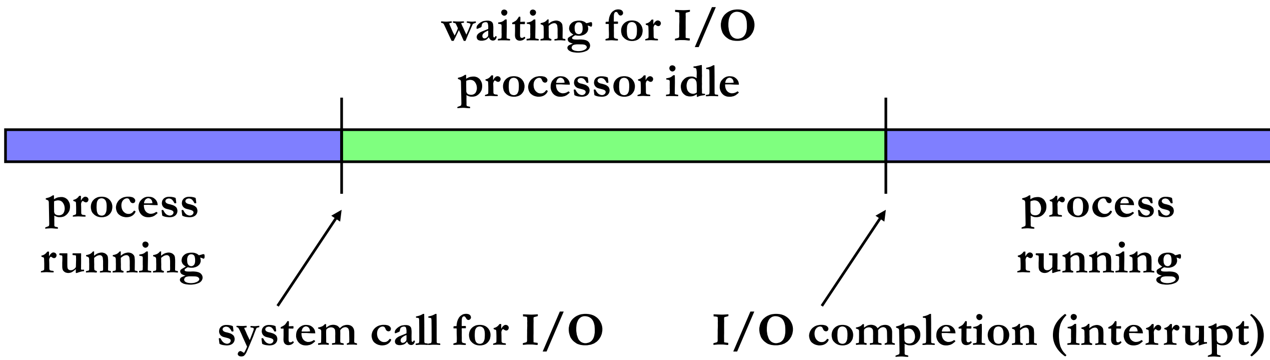
Multi-tasking

- Single-task system:

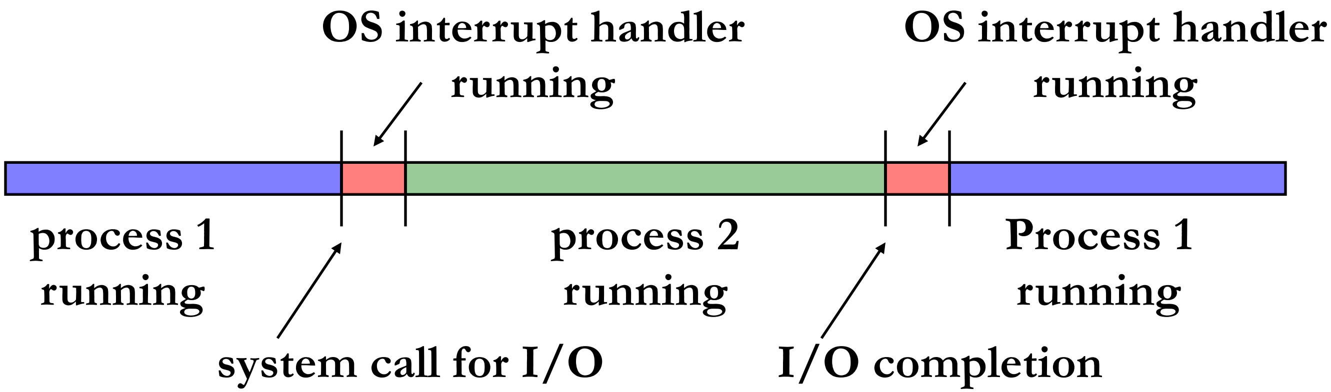


Multi-tasking

- Single-task system:



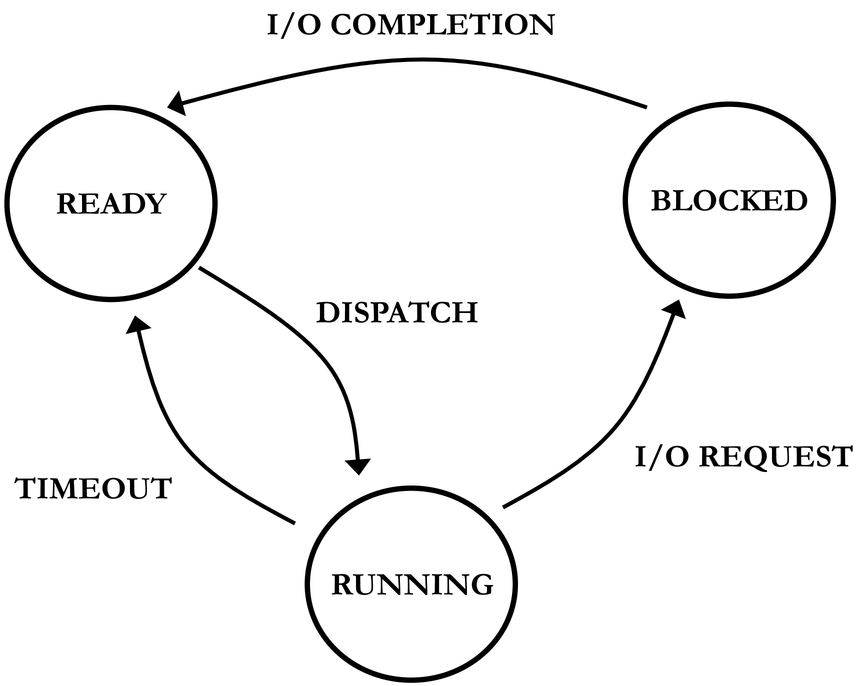
- Multi-tasking system:



Managing Processes

- Processes are managed by the OS **kernel**
  - Kernel: the core of the operating system that controls all software and hardware resources
    - First to be loaded when the computer boots
    - Manages interrupts, processes, memory, I/O
  - The kernel's scheduler chooses which process to run next from the pool of active processes
- New processes can be explicitly created by the user, or implicitly by another process (through forking)
  - Original process → parent
  - New process → child

Process States



States:

RUNNING: process is currently running in the CPU
READY: process is not running, but could run if brought into CPU
BLOCKED: process is not able to run because it is waiting for I/O to finish

Transitions:

I/O REQUEST: process initiates I/O
I/O COMPLETION: I/O finishes
DISPATCH: OS moves process into CPU and it starts executing
TIMEOUT: process's timeslice is over

Process States

- Step 1: process calls (or traps into) the OS, or interrupt occurs (e.g. because of timer)
- Step 2: OS's dispatcher performs **context switch**:
  - Process's context is saved (registers, PC, etc) in process control block (PCB)
  - Dispatcher chooses new process to run
  - Processes' states are updated

PCB: OS data structure containing each process's information:
  - Process id (PID)
  - Process state (blocked, running, etc)
  - Process priority
  - Process permissions
  - Etc

Suspending and Resuming Processes

- Problem:
  - Might not have enough physical memory for all processes
  - Some processes have higher priority and must get more processor & memory resources (e.g., high-res game)
- Solution:
  - Processes can be "swapped out" from memory to disk
  - Such processes are moved into an "inactive" state
    - 2 new process states
  - PCB of inactive processes are still kept in OS memory
  - Inactive processes are resumed by "swapping in" the data from disk back to memory

Suspending and Resuming Processes