# Princeton University

Computer Science 217: Introduction to Programming Systems

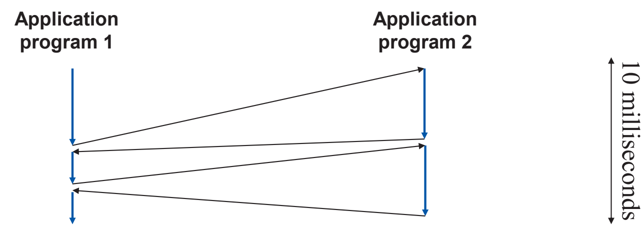
## Exceptions and Processes

Much of the material for this lecture is drawn from
*Computer Systems: A Programmer's Perspective* (Bryant & O'Hallaron) Chapter 8



## Time sharing

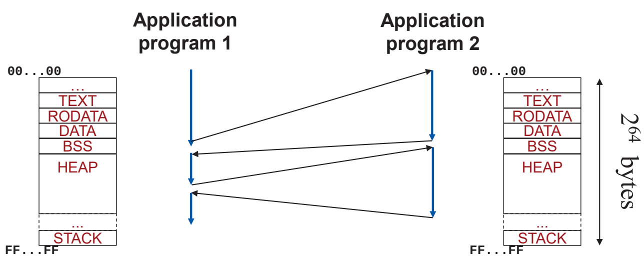
Just one CPU, but each program appears to have its own CPU






## Memory sharing

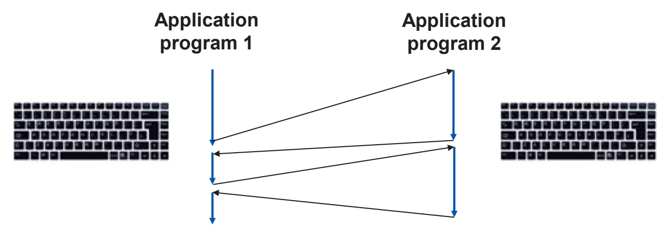
Just one memory, but each program appears to have its own memory






## Device sharing

Just one keyboard, but each program appears to have its own keyboard






## Goals of this Lecture

Help you learn about:

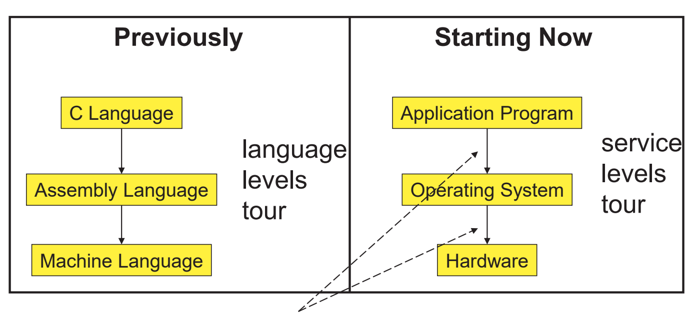
- **Exceptions**
- The **process** concept
- … and thereby…
- How operating systems work
- How application programs interact with operating systems and hardware

The **process** concept is one of the most important concepts in system programming



## Context of this Lecture

Second half of the course




Application programs, OS, and hardware interact via **exceptions**

# Agenda

**Exceptions**

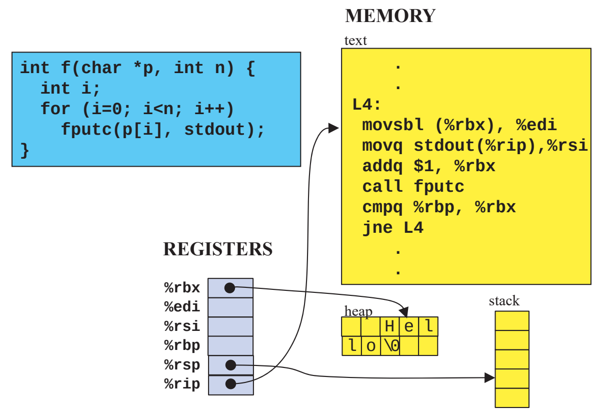
Processes

Illusion: Private address space

Illusion: Private control flow

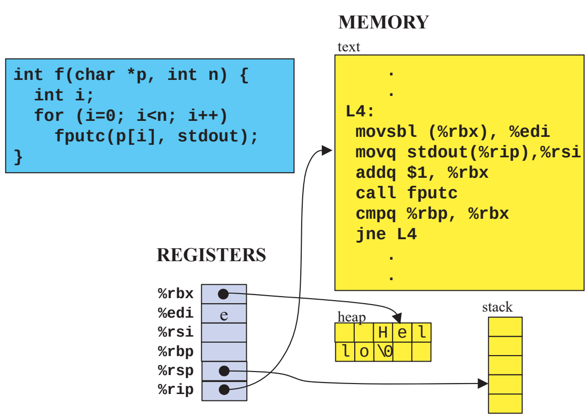


# Example Program



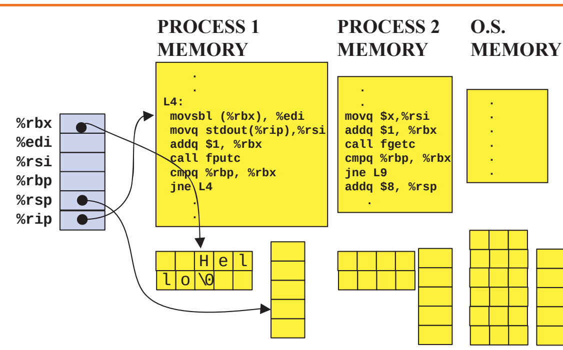



# Example Program



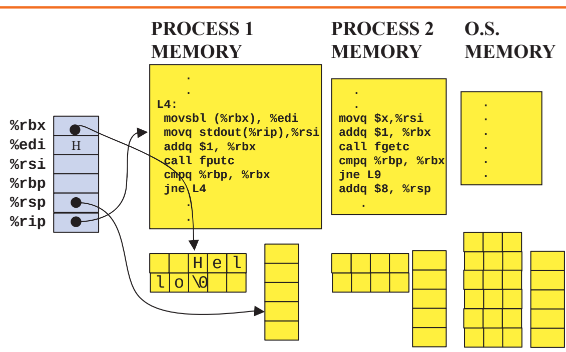



# Multiple processes but only 1 register bank!



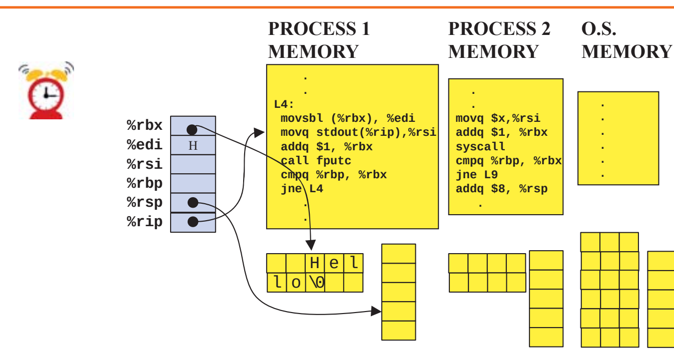



# Normal execution

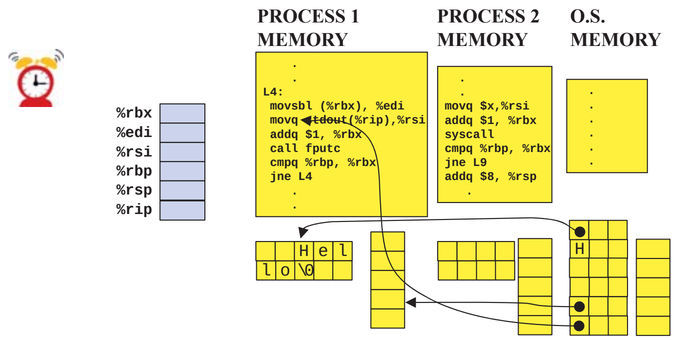





# Exception! (timer interrupt)

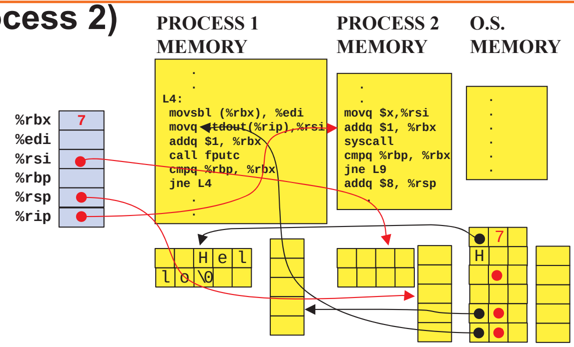


## Copy registers to OS memory





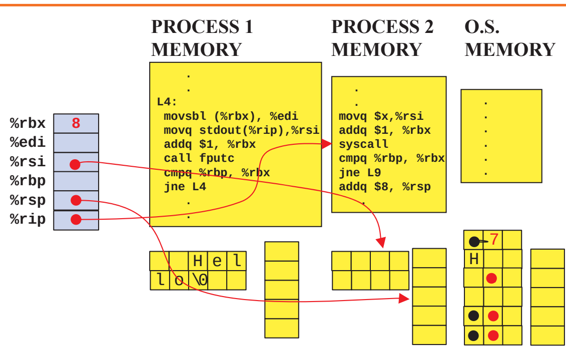

## Copy registers from OS memory (for process 2)




. . . then resume normal execution



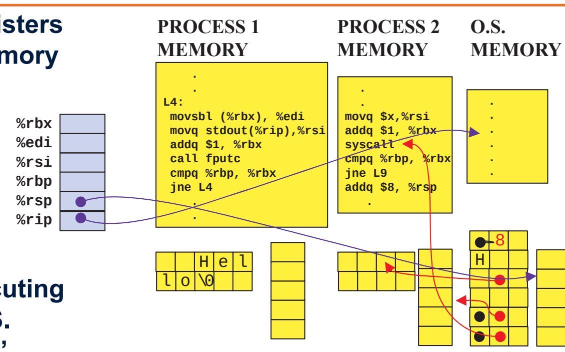
## System call!






## System call!

**Copy registers to OS memory**




**Now executing in the O.S. "process"**



## Exceptions

**Exception**

- An abrupt change in control flow in response to a change in processor state



## Synchronous Exceptions

Some exceptions are **synchronous**

- Occur as result of actions of executing program
- Examples:
  - **System call:** Application requests I/O
  - **System call:** Application requests more heap memory
  - Application pgm attempts integer division by 0
  - Application pgm attempts to access privileged memory
  - Application pgm accesses variable that is not in physical memory
    - See later in this lecture
    - See upcoming ***Virtual Memory*** lecture

## Asynchronous Exceptions

Some exceptions are **asynchronous**

- Do not occur (directly) as result of actions of executing program
- Examples:
  - User presses key on keyboard 
  - Disk controller finishes reading data 
  - Hardware timer expires 



## Exceptions Note

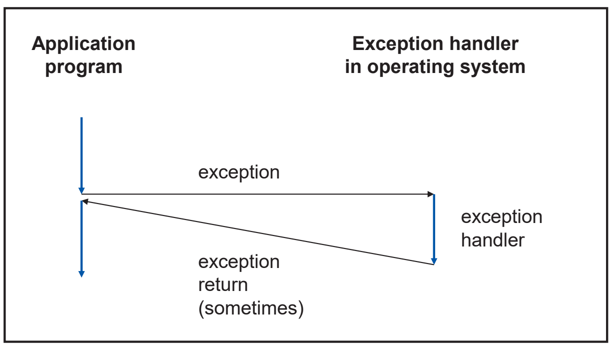
Note:

Exceptions in OS ≠ exceptions in Java

Implemented using **`try/catch`** and **`throw`** statements



## Exceptional Control Flow






## Exceptions vs. Function Calls

Handling an exception is **similar to** calling a function

- CPU pushes arguments onto stack
- Control transfers from original code to other code
- Other code executes
- Control returns to some instruction in original code

Handling an exception is **different from** calling a function

- CPU pushes **additional data** onto stack
  - E.g. values of all registers
- CPU pushes data onto **OS's stack**, not application pgm's stack
- Handler runs in **kernel/privileged mode**, not in **user mode**
  - Handler can execute all instructions and access all memory
- Control **might return** to some instruction in original code
  - Sometimes control returns to **next** instruction
  - Sometimes control returns to **current** instruction
  - Sometimes control does not return at all!



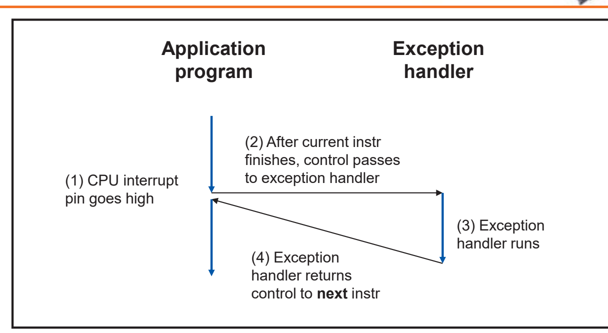
## Classes of Exceptions

There are 4 classes of exceptions…



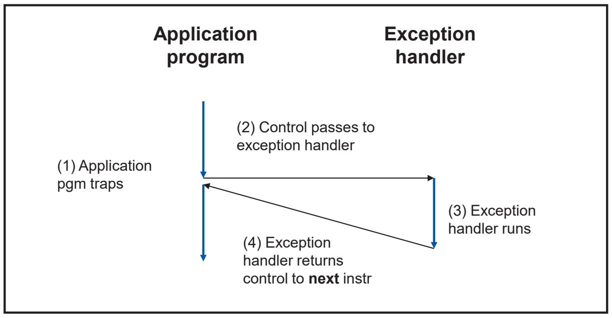
## (1) Interrupts




**Occurs when**: External (off-CPU) device requests attention
**Examples**:
User presses key
Disk controller finishes reading/writing data
Hardware timer expires

# (2) Traps




**Occurs when**: Application pgm requests OS service

**Examples**:

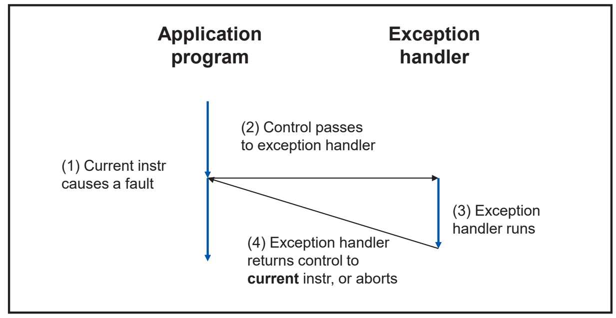
Application pgm requests I/O

Application pgm requests more heap memory

Traps provide a function-call-like interface between application pgm and OS



# (3) Faults




**Occurs when**: Application pgm causes a (possibly recoverable) error

**Examples**:

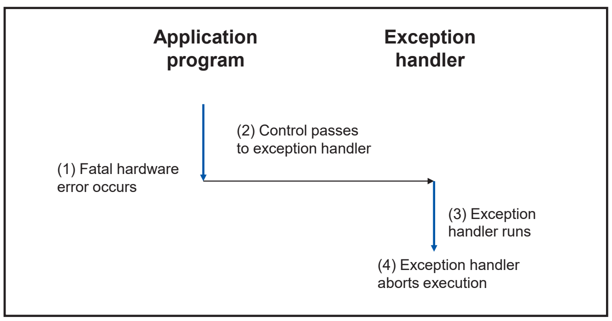
Application pgm divides by 0

Application pgm accesses privileged memory (seg fault)

Application pgm accesses data that is not in physical memory (page fault)



# (4) Aborts




**Occurs when**: HW detects a non-recoverable error

**Example:**

Parity check indicates corruption of memory bit (overheating, cosmic ray!, etc.)



# Summary of Exception Classes

| Class | Occurs when | Asynch /Synch | Return Behavior |
| --- | --- | --- | --- |
| **Interrupt** | External device requests attention | Asynch | Return to next instr |
| **Trap** | Application pgm requests OS service | Sync | Return to next instr |
| **Fault** | Application pgm causes (maybe recoverable) error | Sync | Return to current instr (maybe) |
| **Abort** | HW detects non-recoverable error | Sync | Do not return |



# Aside: Traps in x86-64 Processors

To execute a trap, application program should:

- Place number in RAX register indicating desired OS service
- Place arguments in RDI, RSI, RDX, RCX, R8, R9 registers
- Execute assembly language instruction **`syscall`**

Example: To request change in size of heap section of memory (see ***Dynamic Memory Management*** lecture)…

```
movq $12, %rax
movq $newAddr, %rdi
syscall
```

Place 12 (change size of heap section) in RAX

Place new address of end of heap in RDI

Execute trap



# Aside: System-Level Functions

Traps are wrapped in **system-level functions**

Example: To change size of heap section of memory…

```
/* unistd.h */
int brk(void *addr);
```

**`brk()`** is a system-level function

```
/* unistd.s */
brk:    movq $12, %rax
        movq $newAddr, %rdi
        syscall
        ret
```

```
/* client.c */
…
brk(newAddr);
…
```

A call of a system-level function, that is, a **system call**

See Appendix for some Linux system-level functions

## Agenda

Exceptions

**Processes**

Illusion: Private address space

Illusion: Private control flow



## Processes

**Program**

- Executable code
- A static entity

**Process**

- An instance of a program in execution
- A dynamic entity: has a time dimension
- Each process runs one program
  - E.g. process 12345 might be running emacs
- One program can run in multiple processes
  - E.g. Process 12345 might be running emacs, and process 54321 might also be running emacs – for the same user or for different users



## Processes Significance

Process abstraction provides application pgms with two key illusions:

- Private address space
- Private control flow

**Process is a profound abstraction in computer science**



## Agenda

Exceptions

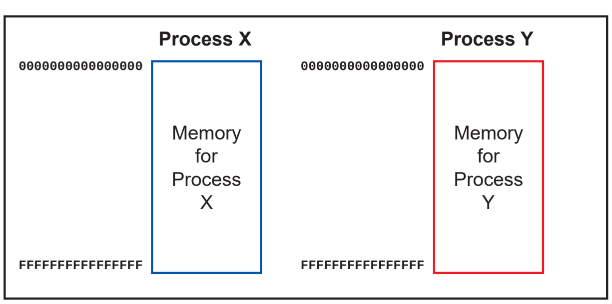
Processes

**Illusion: Private address space**

Illusion: Private control flow



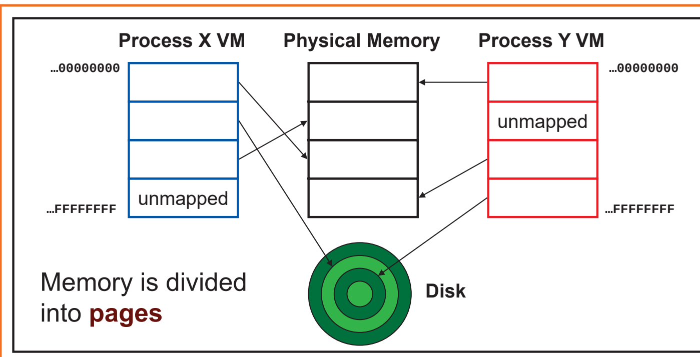
## Private Address Space: Illusion




Hardware and OS give each application process the illusion that it is the only process using memory



## Private Address Space: Reality




All processes use the same physical memory
Hardware and OS provide application pgms with a **virtual** view of memory, i.e. **virtual memory (VM)**

## Private Address Space: Implementation

### Question:
- How do the CPU and OS implement the illusion of private address space?
- That is, how do the CPU and OS implement virtual memory?

### Answer:
- Exceptions!
- Specifically, **page faults**
- Overview now, details next lecture…



## Private Address Space Example 1

Private Address Space Example 1

```
•  Process executes instruction that references
   virtual memory
•  CPU determines virtual page
•  CPU checks if required virtual page is in
   physical memory: yes
•  CPU does load/store from/to physical memory
```



## Private Address Space Example 2

Private Address Space Example 2

```
•  Process executes instruction that references
   virtual memory
•  CPU determines virtual page
•  CPU checks if required virtual page is in
   physical memory: no!
   •  CPU generates page fault
   •  OS gains control of CPU
   •  OS evicts some page from physical memory
      to disk, loads required page from disk to
      physical memory
   •  OS returns control of CPU to process –
      to same instruction
•  Process executes instruction that references
   virtual memory
•  CPU checks if required virtual page is in
   physical memory: yes
•  CPU does load/store from/to physical memory
```

Exceptions (specifically, **page faults**) enable the illusion of private address spaces



## Agenda

Exceptions

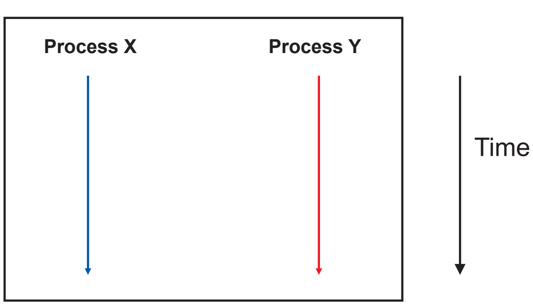
Processes

Illusion: Private address space

**Illusion: Private control flow**



## Private Control Flow: Illusion

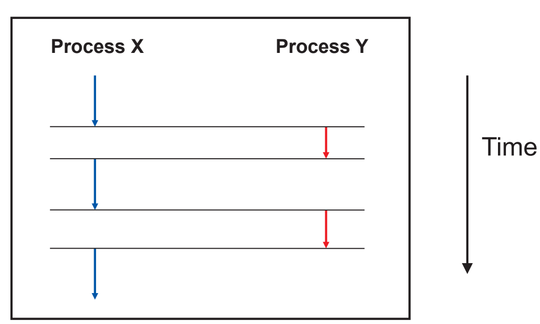



Simplifying assumption: only one CPU

Hardware and OS give each application process the illusion that it is the only process running on the CPU



## Private Control Flow: Reality




Multiple processes share the CPU
Multiple processes run **concurrently**
OS occasionally **preempts** running process

## Process Status

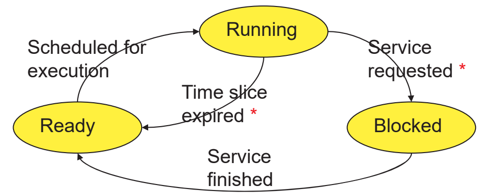
More specifically…

At any time a process has **status**:

- **Running**: CPU is executing process's instructions
- **Ready**: Process is ready for OS to assign it to the CPU
- **Blocked**: Process is waiting for some requested service (typically I/O) to finish



## Process Status Transitions

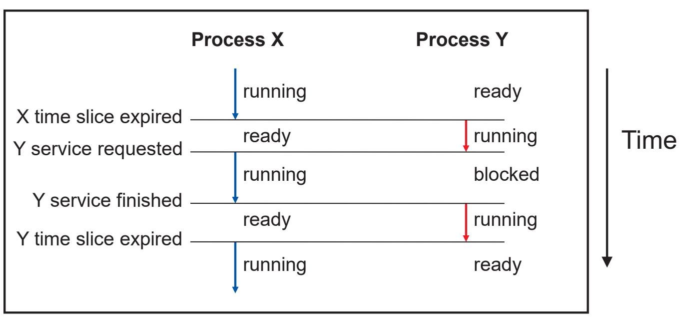



* Preempting transition

**Service requested**: OS moves running process to blocked set because it requested a (time consuming) system service (often I/O)
**Service finished**: OS moves blocked process to ready set because the requested service finished
**Time slice expired**: OS moves running process to ready set because process consumed its fair share of CPU time
**Scheduled for execution**: OS selects some process from ready set and assigns CPU to it



## Process Status Transitions Over Time




Throughout its lifetime a process's status switches between running, ready, and blocked



## Private Control Flow: Implementation (1)

**Question:**

- How do CPU and OS implement the illusion of private control flow?
- That is, how to CPU and OS implement process status transitions?

**Answer (Part 1):**

- Contexts and context switches…



## Process Contexts

Each process has a **context**

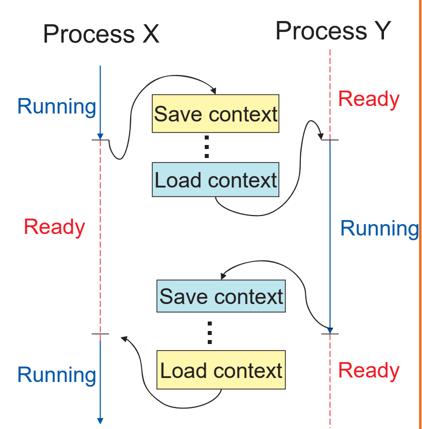
- The process's state, that is…
- Register contents
  - RIP, EFLAGS, RDI, RSI, etc. registers
- Memory contents
  - TEXT, RODATA, DATA, BSS, HEAP, and STACK



## Context Switch

**Context switch**:

- OS saves context of running process
- OS loads context of some ready process
- OS passes control to newly restored process



## Aside: Process Control Blocks

**Question:**
- Where does OS save a process's context?

**Answer:**
- In its **process control block (PCB)**

**Process control block (PCB)**
- A data structure
- Contains all data that OS needs to manage the process



## Aside: Process Control Block Details

Process control block (PCB):

| Field | Description |
| --- | --- |
| ID | Unique integer assigned by OS when process is created |
| Status | Running, ready, or waiting |
| Hierarchy | ID of parent process<br>ID of child processes (if any)<br>(See ***Process Management*** Lecture) |
| Priority | High, medium, low |
| Time consumed | Time consumed within current time slice |
| **Context** | **When process is not running…**<br>**Contents of all registers**<br>**(In principle) contents of all of memory** |
| Etc. | |



## Context Switch Efficiency

**Observation**:
- During context switch, OS must:
  - Save context (register and memory contents) of running process to its PCB
  - Restore context (register and memory contents) of some ready process from its PCB

**Question**:
- Isn't that **very** expensive (in terms of time and space)?



## Context Switch Efficiency

**Answer**:
- Not really!
- During context switch, OS **does** save/load **register** contents
  - But there are few registers
- During context switch, OS **does not** save/load **memory** contents
  - Each process has a **page table** that maps virtual memory pages to physical memory pages
  - During context switch, need only deactivate process X page table and activate process Y page table
  - See ***Virtual Memory*** lecture



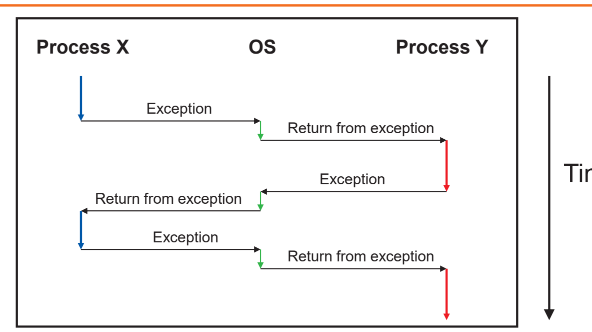
## Private Control Flow: Implementation (2)

**Question:**
- How do CPU and OS implement the illusion of private control flow?
- That is, how do CPU and OS implement process status transitions?
- That is, how do CPU and OS implement context switches?

**Answer (Part 2):**
- Exceptions!
- Context switches occur while the OS handles exceptions…



## Exceptions and Context Switches




Context switches occur
while OS is handling exceptions

## Exceptions and Context Switches

Exceptions occur frequently
- Process explicitly requests OS service (trap)
- Service request fulfilled (interrupt)
- Process accesses VM page that is not in physical memory (fault)
- Etc.
- … And if none of them occur for a while …
- Expiration of hardware timer (interrupt)

Whenever OS gains control of CPU via exception…

It has the option of performing context switch



## Private Control Flow Example 1

Private Control Flow Example 1

- Process X is running
- Hardware clock generates interrupt
- OS gains control of CPU
- OS examines "time consumed" field of process X's PCB
- OS decides to do context switch
  - OS saves process X's context in its PCB
  - OS sets "status" field in process X's PCB to *ready*
  - OS adds process X's PCB to the ready set
  - OS removes process Y's PCB from the ready set
  - OS sets "status" field in process Y's PCB to running
  - OS loads process Y's context from its PCB
- Process Y is running



## Private Control Flow Example 2

Private Control Flow Example 2

- Process Y is running
- Process Y executes trap to request read from disk
- OS gains control of CPU
- OS decides to do context switch
  - OS saves process Y's context in its PCB
  - OS sets "status" field in process Y's PCB to blocked
  - OS adds process Y's PCB to the blocked set
  - OS removes process X's PCB from the ready set
  - OS sets "status" field in process X's PCB to running
  - OS loads process X's context from its PCB
- Process X is running



## Private Control Flow Example 3

Private Control Flow Example 3

- Process X is running
- Read operation requested by process Y completes => disk controller generates interrupt
- OS gains control of CPU
- OS sets "status" field in process Y's PCB to ready
- OS moves process Y's PCB from the blocked list to the ready list
- OS examines "time consumed within slice" field of process X's PCB
- OS decides not to do context switch
- Process X is running



## Private Control Flow Example 4

Private Control Flow Example 4

- Process X is running
- Process X accesses memory, generates page fault
- OS gains control of CPU
- OS evicts page from memory to disk, loads referenced page from disk to memory
- OS examines "time consumed" field of process X's PCB
- OS decides not to do context switch
- Process X is running

Exceptions enable the illusion of private control flow



## Summary

**Exception**: an abrupt change in control flow
- **Interrupt**: asynchronous; e.g. I/O completion, hardware timer
- **Trap**: synchronous; e.g. app pgm requests more heap memory, I/O
- **Fault**: synchronous; e.g. seg fault, page fault
- **Abort**: synchronous; e.g. failed parity check

**Process**: An instance of a program in execution
- CPU and OS give each process the illusion of:
  - Private address space
    - Reality: **virtual memory**
  - Private control flow
    - Reality: **Concurrency**, **preemption**, and **context switches**
- Both illusions are implemented using exceptions

## Appendix: System-Level Functions

Linux system-level functions for **I/O management**

| Number | Function | Description |
| --- | --- | --- |
| 0 | read() | Read data from file descriptor; called by getchar(), scanf(), etc. |
| 1 | write() | Write data to file descriptor; called by putchar(), printf(), etc. |
| 2 | open() | Open file or device; called by fopen() |
| 3 | close() | Close file descriptor; called by fclose() |
| 85 | creat() | Open file or device for writing; called by fopen(…, "w") |
| 8 | lseek() | Position file offset; called by fseek() |

Described in ***I/O Management*** lecture



## Appendix: System-Level Functions

Linux system-level functions for **process management**

| Number | Function | Description |
| --- | --- | --- |
| 60 | exit() | Terminate the current process |
| 57 | fork() | Create a child process |
| 7 | wait() | Wait for child process termination |
| 11 | execvp() | Execute a program in the current process |
| 20 | getpid() | Return the process id of the current process |

Described in ***Process Management*** lecture



## Appendix: System-Level Functions

Linux system-level functions for **I/O redirection** and **inter-process communication**

| Number | Function | Description |
| --- | --- | --- |
| 32 | dup() | Duplicate an open file descriptor |
| 22 | pipe() | Create a channel of communication between processes |

Described in ***Process Management*** lecture



## Appendix: System-Level Functions

Linux system-level functions for **dynamic memory management**

| Number | Function | Description |
| --- | --- | --- |
| 12 | brk() | Move the program break, thus changing the amount of memory allocated to the HEAP |
| 12 | sbrk() | (Variant of previous) |
| 9 | mmap() | Map a virtual memory page |
| 11 | munmap() | Unmap a virtual memory page |

Described in ***Dynamic Memory Management*** lecture



## Appendix: System-Level Functions

Linux system-level functions for **signal handling**

| Number | Function | Description |
| --- | --- | --- |
| 37 | alarm() | Deliver a signal to a process after a specified amount of wall-clock time |
| 62 | kill() | Send signal to a process |
| 13 | sigaction() | Install a signal handler |
| 38 | setitimer() | Deliver a signal to a process after a specified amount of CPU time |
| 14 | sigprocmask() | Block/unblock signals |

Described in ***Signals*** lecture