



# Exceptions and Processes

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

1



## 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

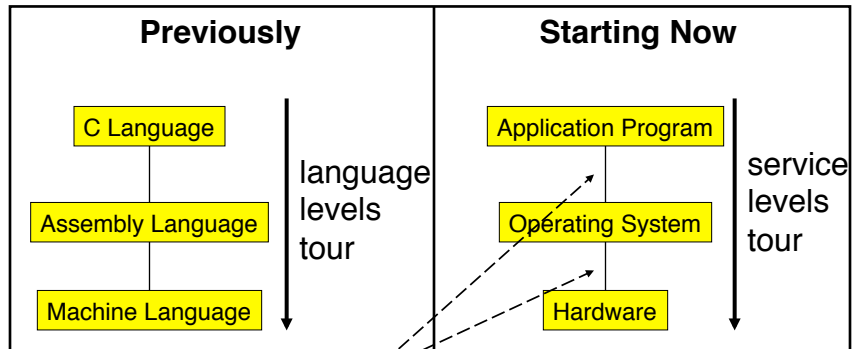
The **process** concept is one of the most important concepts in systems programming

2

## Context of this Lecture



### Second half of the course



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

3

## Motivation



### Question:

- Executing program thinks it has exclusive control of the CPU
- But multiple executing programs must share one CPU (or a few CPUs)
- How is that illusion implemented?

### Question:

- Executing program thinks it has exclusive use of all of memory
- But multiple executing programs must share one memory
- How is that illusion implemented?

Answers: Exceptions...

4

# Exceptions



- **Exception**

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

- **Examples:**

- Application program:
    - Requests I/O
    - Requests more heap memory
    - Attempts integer division by 0
    - Attempts to access privileged memory
    - Accesses variable that is not in real memory (see upcoming "Virtual Memory" lecture)
  - User presses key on keyboard
  - Disk controller finishes reading data
- } Synchronous
- } Asynchronous

5

# Exceptions Note



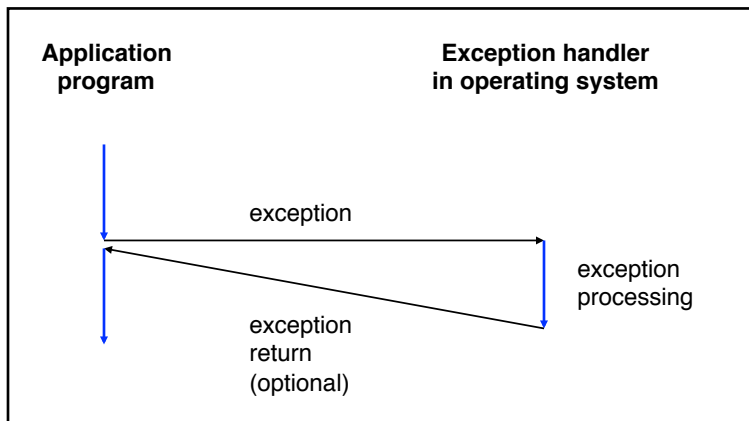
- **Note:**

Exceptions in OS  $\neq$  exceptions in Java

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

6

## Exceptional Control Flow



7

## Exceptions vs. Function Calls



- Exceptions are **similar to function calls**
  - Control transfers from original code to other code
  - Other code executes
  - Control returns to original code
- Exceptions are **different from function calls**
  - Processor pushes **additional state** onto stack
    - E.g. values of all registers
  - Processor pushes data onto **OS' s stack**, not application pgm' s stack
  - Handler runs in **privileged mode**, not in **user mode**
    - Handler can execute all instructions and access all memory
  - Control **might return** to next instruction
    - Control sometimes returns to **current** instruction
    - Control sometimes does not return at all!

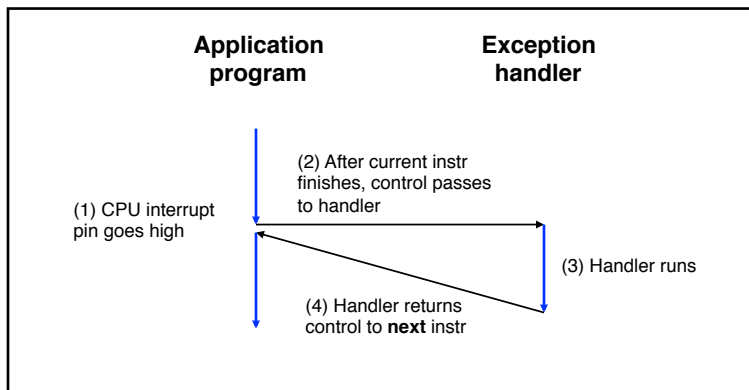
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# Classes of Exceptions



- There are 4 classes of exceptions...

## (1) Interrupts



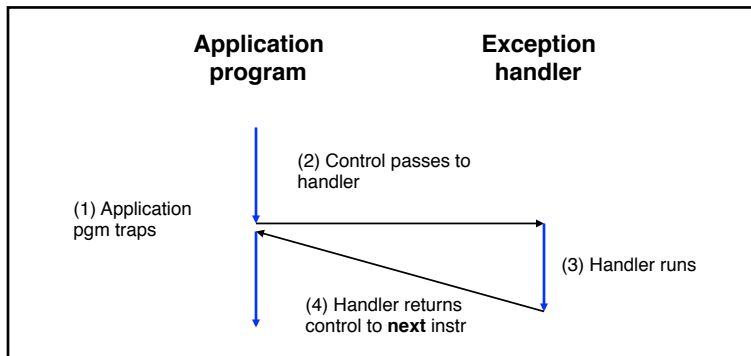
**Cause:** Signal from I/O device

**Examples:**

User presses key

Disk controller finishes reading/writing data

## (2) Traps



**Cause:** Intentional (application pgm requests OS service)

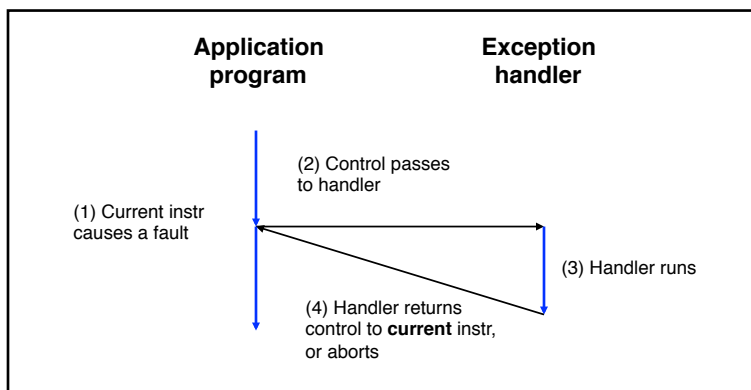
**Examples:**

- Application pgm requests more heap memory
- Application pgm requests I/O

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

11

## (3) Faults



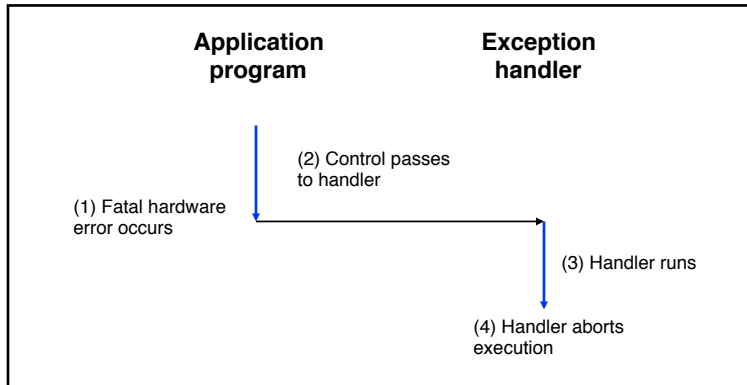
**Cause:** Application pgm causes (possibly) recoverable error

**Examples:**

- Application pgm accesses privileged memory (seg fault)
- Application pgm accesses data that is not in real memory (page fault)

12

## (4) Aborts



**Cause:** Non-recoverable error

**Example:**

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

13

## Summary of Exception Classes



Class	Cause	Asynch/Synch	Return Behavior
<b>Interrupt</b>	Signal from I/O device	Asynch	Return to next instr
<b>Trap</b>	Intentional	Sync	Return to next instr
<b>Fault</b>	(Maybe) recoverable error	Sync	(Maybe) return to current instr
<b>Abort</b>	Non-recoverable error	Sync	Do not return

14

## Exceptions in Intel Processors



Each exception has a number  
Some exceptions in Intel processors:

Exception #	Exception
0	Fault: Divide error
13	Fault: Segmentation fault
14	Fault: Page fault (see “Virtual Memory” lecture)
18	Abort: Machine check
32-127	Interrupt or trap (OS-defined)
<b>128</b>	<b>Trap</b>
129-255	Interrupt or trap (OS-defined)

15

## Traps in Intel Processors



- To execute a trap, application program should:
  - Place number in EAX register indicating desired functionality
  - Place parameters in EBX, ECX, EDX registers
  - Execute assembly language instruction “int 128”
- Example: To request more heap memory...

```
movl $45, %eax  
movl $1024, %ebx  
int $128
```

In Linux, 45 indicates request for more heap memory

Causes trap

Request is for 1024 bytes

16



## System-Level Functions



- For convenience, traps are wrapped in **system-level functions**
- Example: To request more heap memory...

```
/* unistd.h */  
void *sbrk(intptr_t increment);  
...
```

sbrk () is a  
system-level  
function

```
/* unistd.s */  
Defines sbrk() in assembly lang  
Executes int instruction  
...
```

```
/* client.c */  
...  
sbrk(1024);  
...
```

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

See Appendix for list of some Linux system-level functions<sup>17</sup>

## Processes



- **Program**
  - Executable code
- **Process**
  - An instance of a program in execution
- Each program runs in the **context** of some process
- **Context** consists of:
  - Process ID
  - Address space
    - TEXT, RODATA, DATA, BSS, HEAP, and STACK
  - Processor state
    - EIP, EFLAGS, EAX, EBX, etc. registers
  - Etc.

18

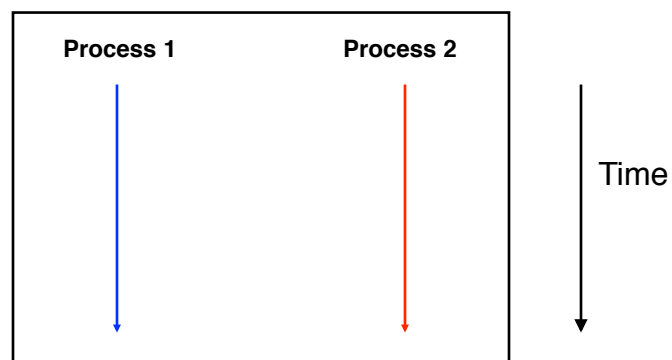
## Significance of Processes



- **Process** is a profound abstraction in computer science
- The process abstraction provides application pgms with two key illusions:
  - Private control flow
  - Private address space

19

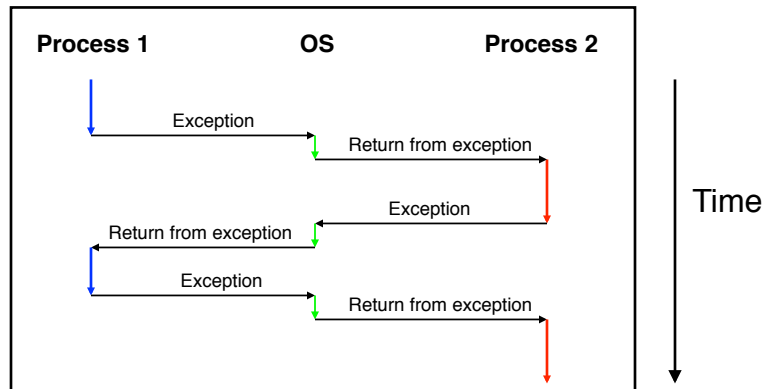
## Private Control Flow: Illusion



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

20

## Private Control Flow: Reality



All application processes -- and the OS process -- share the same CPU(s)

21

## Context Switches



- **Context switch**
  - The activity whereby the OS assigns the CPU to a different process
  - Occurs during exception handling, at discretion of OS
- **Exceptions can be caused:**
  - Synchronously, by application pgm (trap, fault, abort)
  - Asynchronously, by external event (interrupt)
  - **Asynchronously, by hardware timer**
    - So no process can dominate the CPUs
- **Exceptions are the mechanism that enables the illusion of private control flow**

22

## Context Switch Details

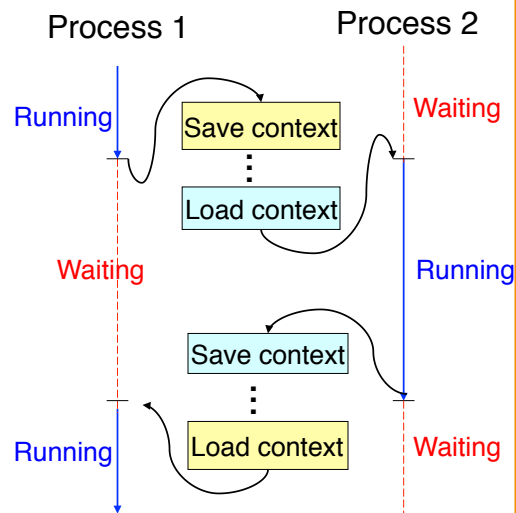


- **Context**

- State the OS needs to restart a preempted process

- **Context switch**

- Save the context of current process
- Restore the saved context of some previously preempted process
- Pass control to this newly restored process



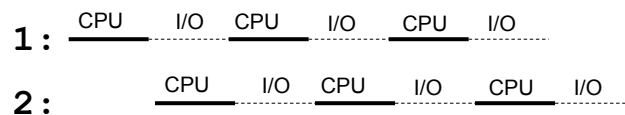
23

## When Should OS Do Context Switch?



- **When a process is stalled waiting for I/O**

- Better utilize the CPU, e.g., while waiting for disk access



- **When a process has been running for a while**

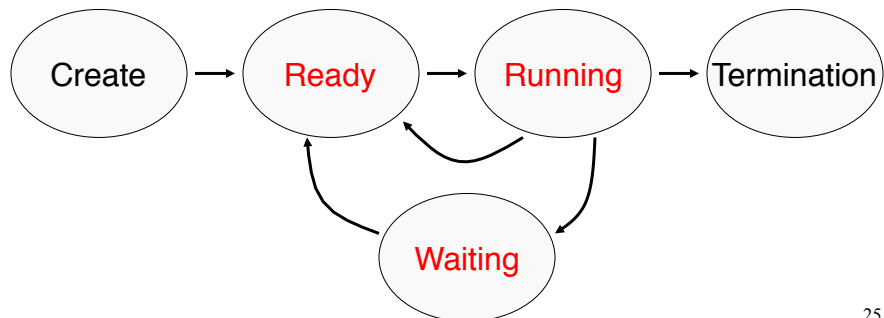
- Sharing on a fine time scale to give each process the illusion of running on its own machine
- Trade-off efficiency for a finer granularity of fairness

24

## Life Cycle of a Process



- **Running**: instructions are being executed
- **Waiting**: waiting for some event (e.g., I/O finish)
- **Ready**: ready to be assigned to a processor



25

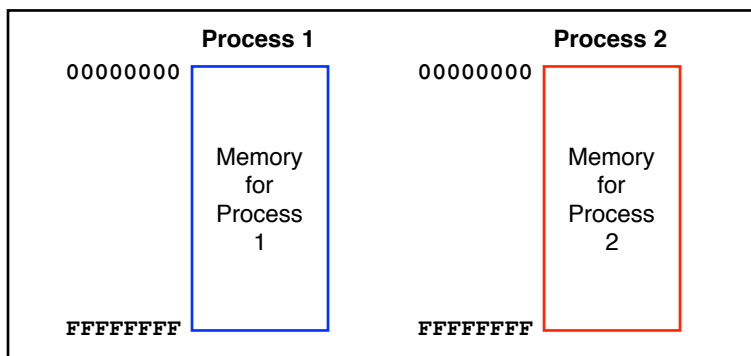
## Context Details



- What does the OS need to save/restore during a context switch?
  - Process state
    - New, ready, waiting, terminated
  - CPU registers
    - EIP, EFLAGS, EAX, EBX, ...
  - I/O status information
    - Open files, I/O requests, ...
  - Memory management information
    - Page tables (see “Virtual Memory” lecture)
  - Accounting information
    - Time limits, group ID, ...
  - CPU scheduling information
    - Priority, queues

26

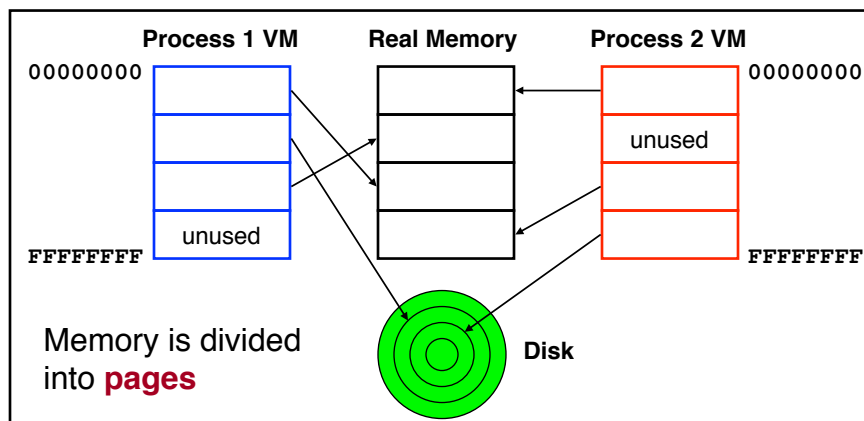
## Private Address Space: Illusion



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

27

## Private Address Space: Reality



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

28

## Private Address Space Details



- Exceptions (specifically, page faults) are the mechanism that enables the illusion of private address spaces
- See the **Virtual Memory** lecture for details

29

## Summary



- **Exception**: an abrupt change in control flow
  - **Interrupts**: asynchronous; e.g. I/O completion, hardware timer
  - **Traps**: synchronous; e.g. app pgm requests more heap memory, I/O
  - **Faults**: synchronous; e.g. seg fault
  - **Aborts**: synchronous; e.g. parity error
- **Process**: An instance of a program in execution
  - Hardware and OS use exceptions to give each process the illusion of:
    - Private control flow (reality: **context switches**)
    - Private address space (reality: **virtual memory**)

30

## Appendix: System-Level Functions



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

Number	Function	Description
3	<code>read()</code>	Read data from file descriptor Called by <code>getchar()</code> , <code>scanf()</code> , etc.
4	<code>write()</code>	Write data to file descriptor Called by <code>putchar()</code> , <code>printf()</code> , etc.
5	<code>open()</code>	Open file or device Called by <code>fopen()</code>
6	<code>close()</code>	Close file descriptor Called by <code>fclose()</code>
8	<code>creat()</code>	Open file or device for writing Called by <code>fopen(..., "w")</code>

Described in **I/O Management** lecture

31

## Appendix: System-Level Functions



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

Number	Function	Description
1	<code>exit()</code>	Terminate the process
2	<code>fork()</code>	Create a child process
7	<code>waitpid()</code>	Wait for process termination
7	<code>wait()</code>	(Variant of previous)
11	<code>exec()</code>	Execute a program in current process
20	<code>getpid()</code>	Get process id

Described in **Process Management** lecture

32



## Appendix: System-Level Functions



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

Number	Function	Description
41	<code>dup ()</code>	Duplicate an open file descriptor
42	<code>pipe ()</code>	Create a channel of communication between processes
63	<code>dup2 ()</code>	Close an open file descriptor, and duplicate an open file descriptor

Described in **Process Management** lecture

33

## Appendix: System-Level Functions



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

Number	Function	Description
45	<code>brk ()</code>	Move the program break, thus changing the amount of memory allocated to the HEAP
45	<code>sbrk ()</code>	(Variant of previous)
90	<code>mmap ()</code>	Map a virtual memory page
91	<code>munmap ()</code>	Unmap a virtual memory page

Described in **Dynamic Memory Management** lectures

34

## Appendix: System-Level Functions



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

Number	Function	Description
27	<code>alarm()</code>	Deliver a signal to a process after a specified amount of wall-clock time
37	<code>kill()</code>	Send signal to a process
67	<code>sigaction()</code>	Install a signal handler
104	<code>setitimer()</code>	Deliver a signal to a process after a specified amount of CPU time
126	<code>sigprocmask()</code>	Block/unblock signals

Described in **Signals** lecture

35