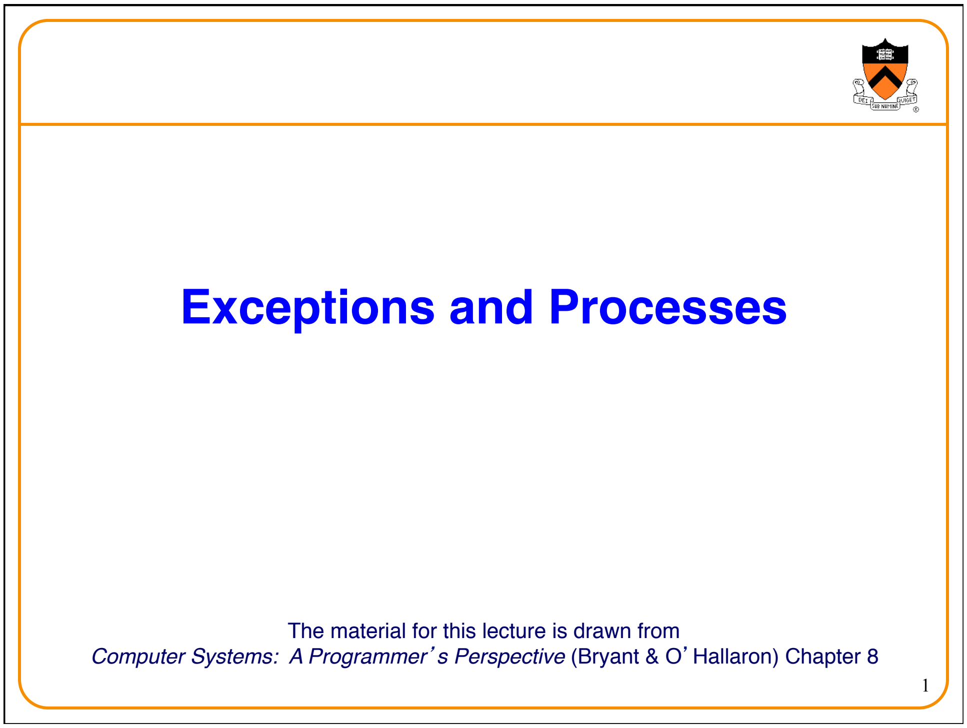
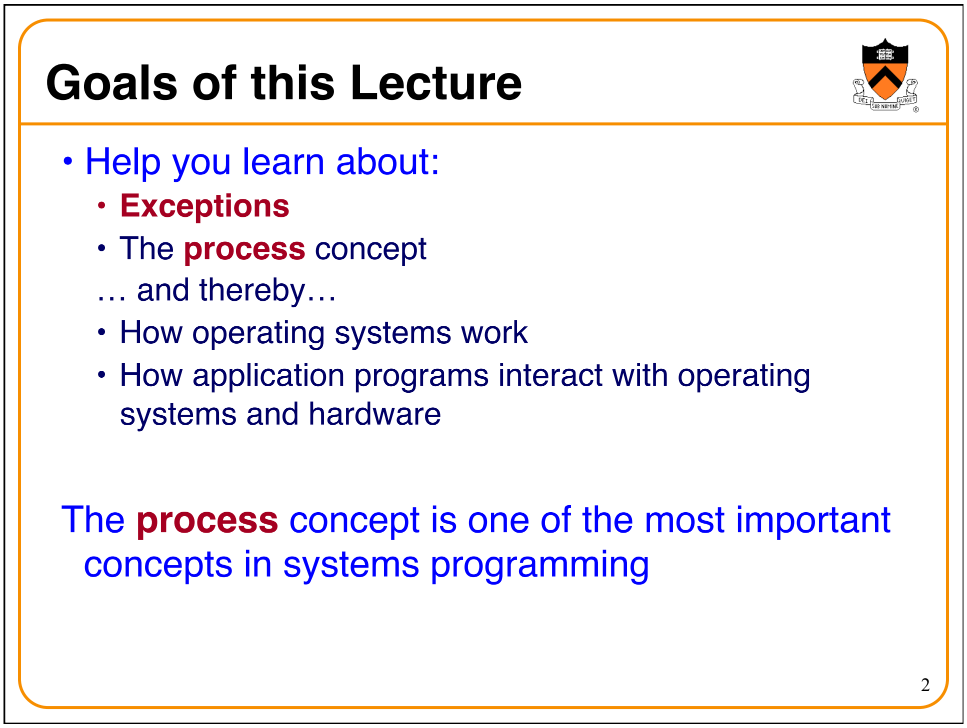


Exceptions and Processes

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



Goals of this Lecture

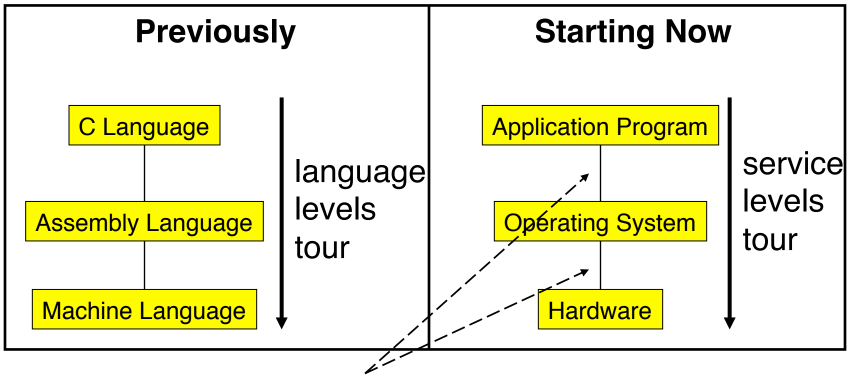
- Help you learn about:
  - **Exceptions**
  - The **process** concept

  … 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

Context of this Lecture

Second half of the course



Previously

C Language

Assembly Language

Machine Language

language levels tour

Starting Now

Application Program

Operating System

Hardware

service levels tour

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

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 and Processes

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

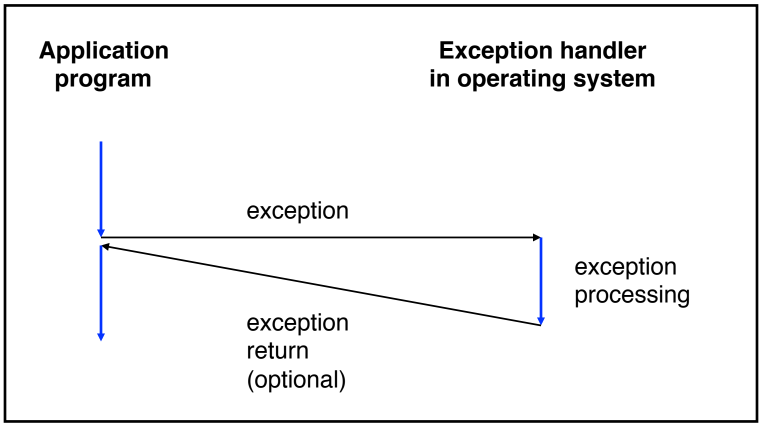
Exceptions Note

- Note:

Exceptions in OS ≠ exceptions in Java

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

Exception Control Flow



Application program

Exception handler in operating system

exception

exception processing

exception return (optional)

Exceptions vs. Function Calls

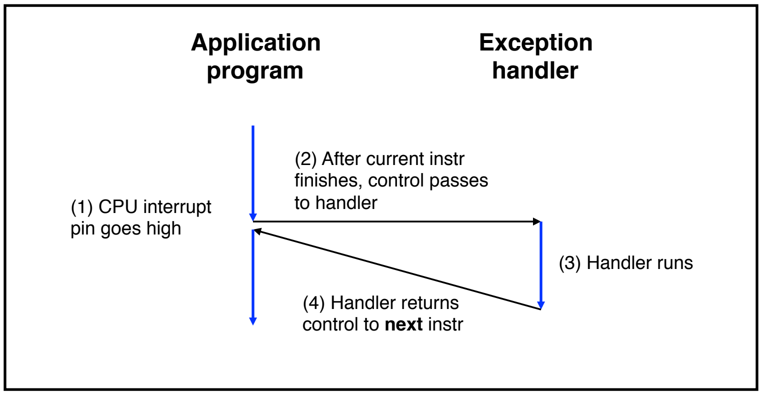
- Exceptions are **similar to** function calls
  - Control transfers from original code to other code
  - Other code executes
  - Control returns to original code
- Exceptions are **different from** function calls
  - Processor pushes **additional state** onto stack
    - E.g. values of all registers
  - Processor pushes data onto **OS's stack**, not application program'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

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



Application program

Exception handler

(1) CPU interrupt pin goes high

(2) After current instr finishes, control passes to handler

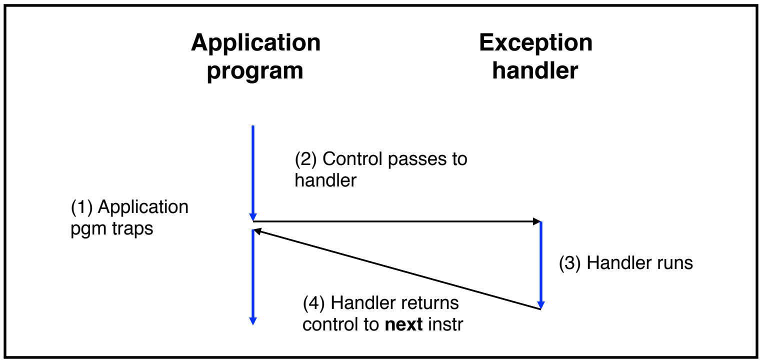
(3) Handler runs

(4) Handler returns control to **next** instr

(2) Traps

Cause: Intentional (application program requests OS service)
Examples:
Application program requests more heap memory
Application program requests I/O

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



Application program

Exception handler

(1) Application pgm traps

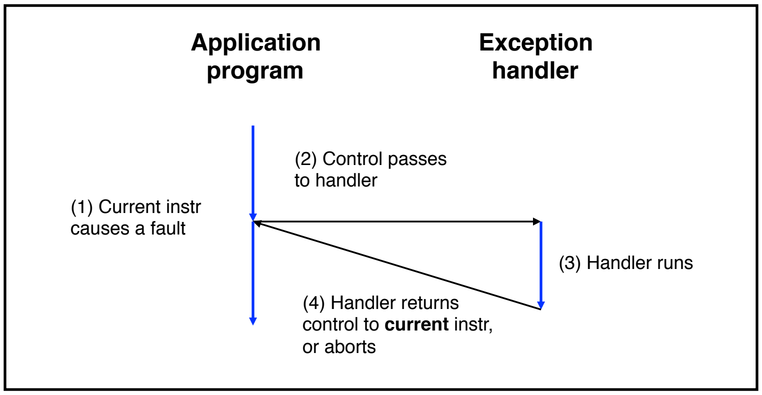
(2) Control passes to handler

(3) Handler runs

(4) Handler returns control to **next** instr

(3) Faults

Cause: Application program causes (possibly) recoverable error
Examples:
Application program accesses privileged memory (seg fault)
Application accesses data that is not in real memory (page fault)



Application program

Exception handler

(1) Current instr causes a fault

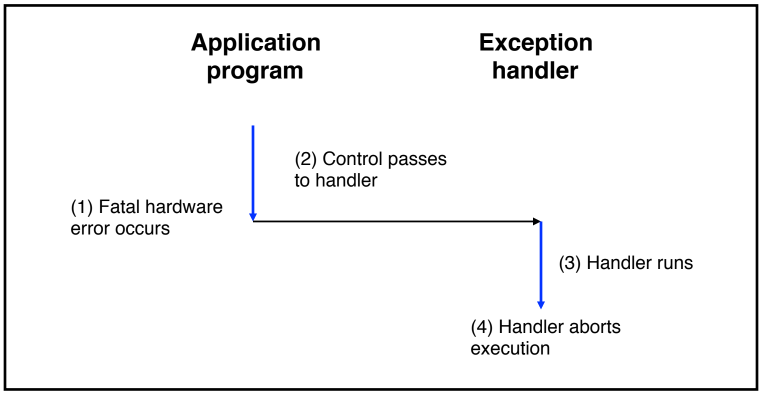
(2) Control passes to handler

(3) Handler runs

(4) Handler returns control to **current** instr, or aborts

(4) Aborts

Cause: Non-recoverable error
Example:
Parity check indicates corruption of memory bit (overheating, cosmic ray, etc.)



Application program

Exception handler

(2) Control passes to handler

(1) Fatal hardware error occurs

(3) Handler runs

(4) Handler aborts execution

Summary of Exception Classes

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

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)
128	**Trap**
129-255	Interrupt or trap (OS-defined)

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…

In Linux, 45 indicates request for more heap memory

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

Request is for 1024 bytes

Causes trap

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

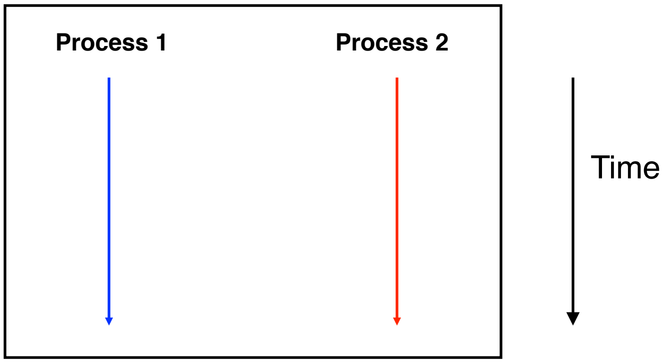
Processes

- **Program**
  - Executable code
- **Process**
  - An instance of a program in execution
- Every 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.

Significance of Processes

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

Private Control Flow: Illusion



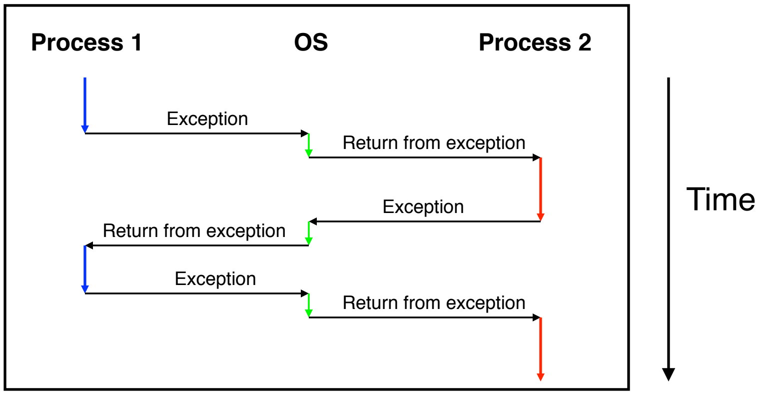
Process 1

Process 2

Time

Hardware and OS give each application process the
illusion that it is the only process running on the CPU
Multiple processes appear to run “at the same time”

Private Control Flow: Reality



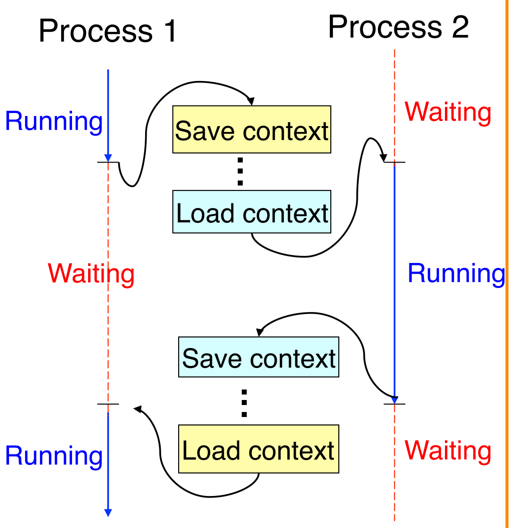
All application processes -- and the OS process -- share the same CPU(s)
Only one process can run on the CPU at any instant

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 and context switches are mechanisms that enable the illusion of private control flow

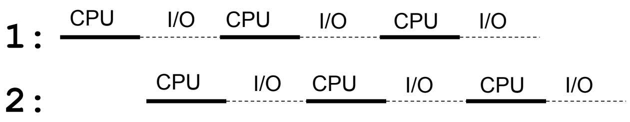
Context Switch Details

- 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



When Should OS Do Context Switch?

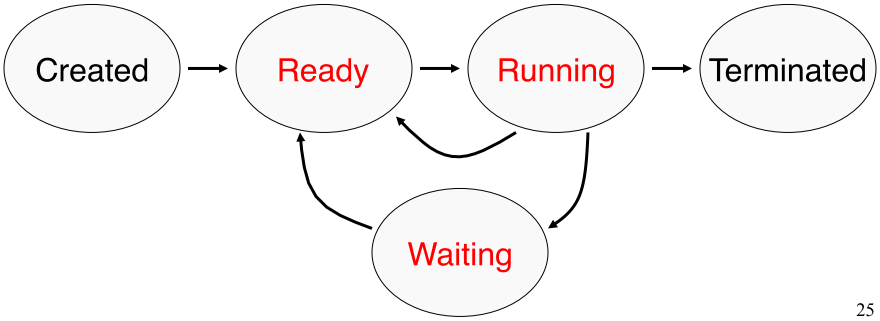
- When a process is stalled waiting for I/O
  - Better utilize the CPU, e.g., while waiting for disk access



- 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

Life Cycle of a Process

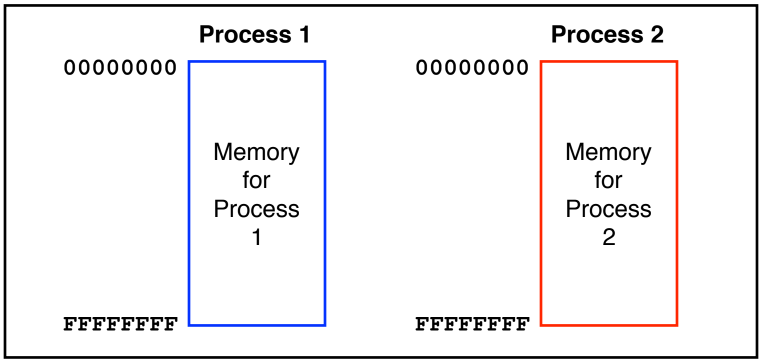
- **Running**: instructions are being executed
- **Waiting**: waiting for some event (e.g., I/O finish)
- **Ready**: ready to be assigned to a processor



Context Details

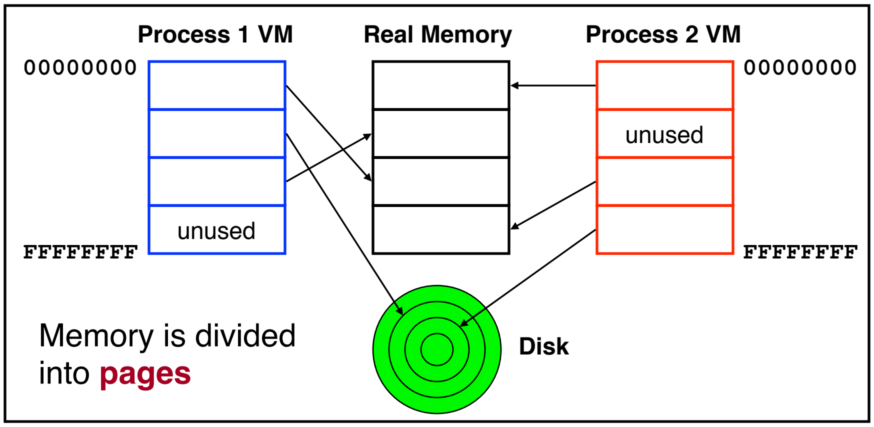
- What does the OS need to save/restore during a context switch?
  - Process state
    - New, ready, waiting, terminated
  - CPU registers
    - EIP, EFLAGS, EAX, EBX, …
  - I/O status information
    - Open files, I/O requests, …
  - Memory management information
    - Page tables (see “Virtual Memory”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

Private Address Space: Illusion



- Hardware and OS give each application process the illusion that it is the only process using memory
- Addresses start at 0 and go to FFFFFF…

Private Address Space: Reality



Memory is divided into **pages**

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

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

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**)

Appendix: System-Level Functions

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

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

Described in **I/O Management** lecture

Appendix: System-Level Functions

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

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

Described in **Process Management** lecture

Appendix: System-Level Functions

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

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

Described in **Process Management** lecture

Appendix: System-Level Functions

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

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

Described in **Dynamic Memory Management** lectures

Appendix: System-Level Functions

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

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

Described in **Signals** lecture