Exceptions

15-213/18-243: Introduction to Computer Systems

13th Lecture, 25 February 2010

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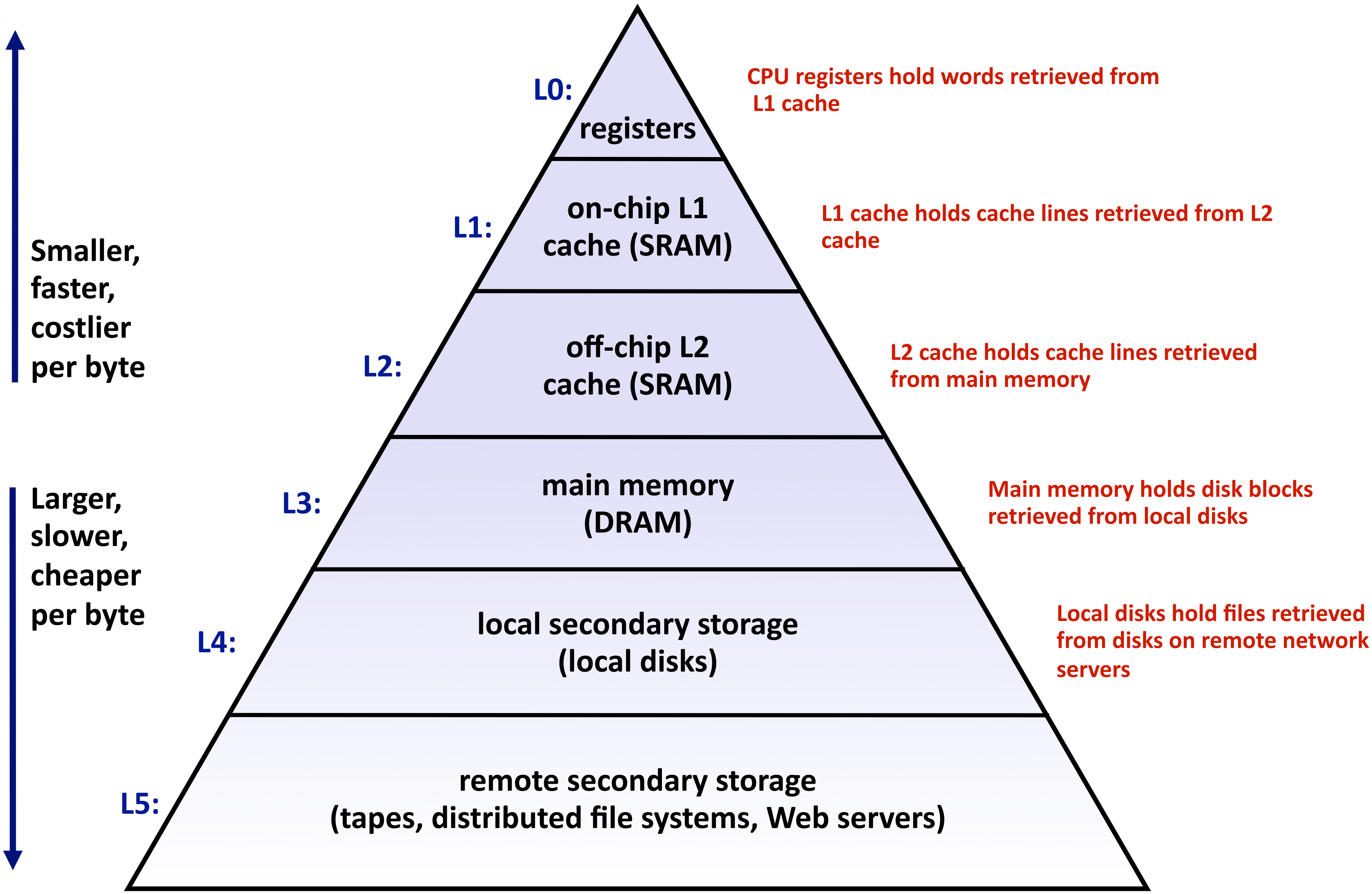
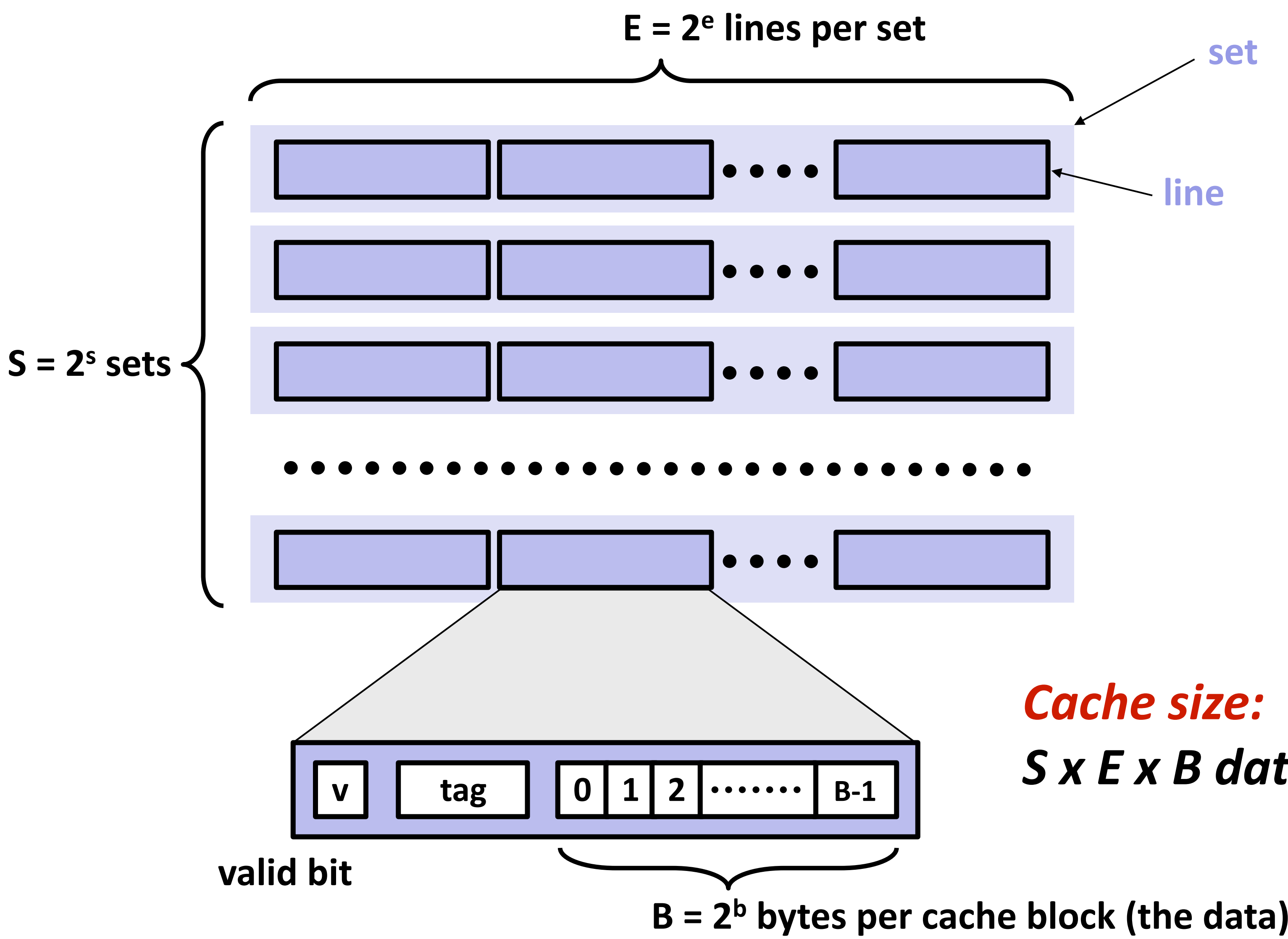
The Exam

- **Tuesday, 2 March**
  - Attend your assigned Lecture section
- **Closed book, closed notes, closed friend, open mind**
  - We will provide reference material
- **Quite unlike past exams**
- **Material from Lectures 1 - 9, Labs 1 & 2**
  - Representation of Integers, Floats
  - Machine code for control structures, procedures
    - Stack discipline
  - Layout of Arrays, Structs, Unions in memory
  - Floating point operations

Last Time: Memory Hierarcy



Last Time: General Cache Org (S, E, B)



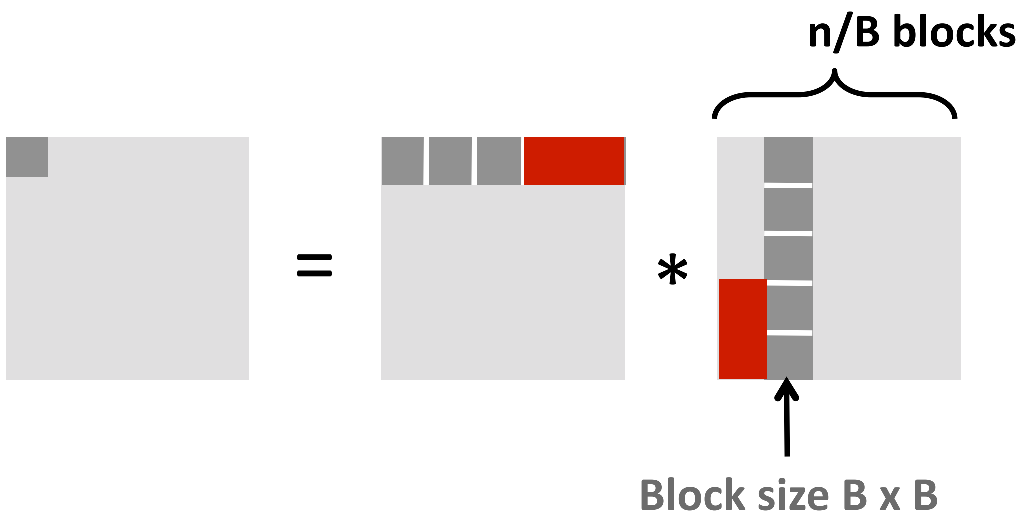
Cache size:

S x E x B data bytes

Last Time: Optimizing for Cache Accesses

- **Assume:**
  - Cache block = 8 doubles
  - Cache size C << n (much smaller than n)
  - Three blocks ■ fit into cache: $3B^2 < C$

- **Second (block) iteration:**
  - Same as first iteration
  - $2n/B * B^2/8 = nB/4$



- **Total misses:**
  - $nB/4 * (n/B)^2 = n^3/(4B)$

Today

- **Exceptional Control Flow**
- **Processes**

Control Flow

- **Processors do only one thing:**
  - From startup to shutdown, a CPU simply reads and executes (interprets) a sequence of instructions, one at a time
  - This sequence is the CPU's *control flow* (or *flow of control*)

Physical control flow

Time

<startup>
$inst_1$
$inst_2$
$inst_3$
…
$inst_n$
<shutdown>

Altering the Control Flow

- **Up to now: two mechanisms for changing control flow:**
  - Jumps and branches
  - Call and return

  Both react to changes in ***program state***

- **Insufficient for a useful system:**
  Difficult to react to changes in *system state*
  - data arrives from a disk or a network adapter
  - instruction divides by zero
  - user hits Ctrl-C at the keyboard
  - System timer expires

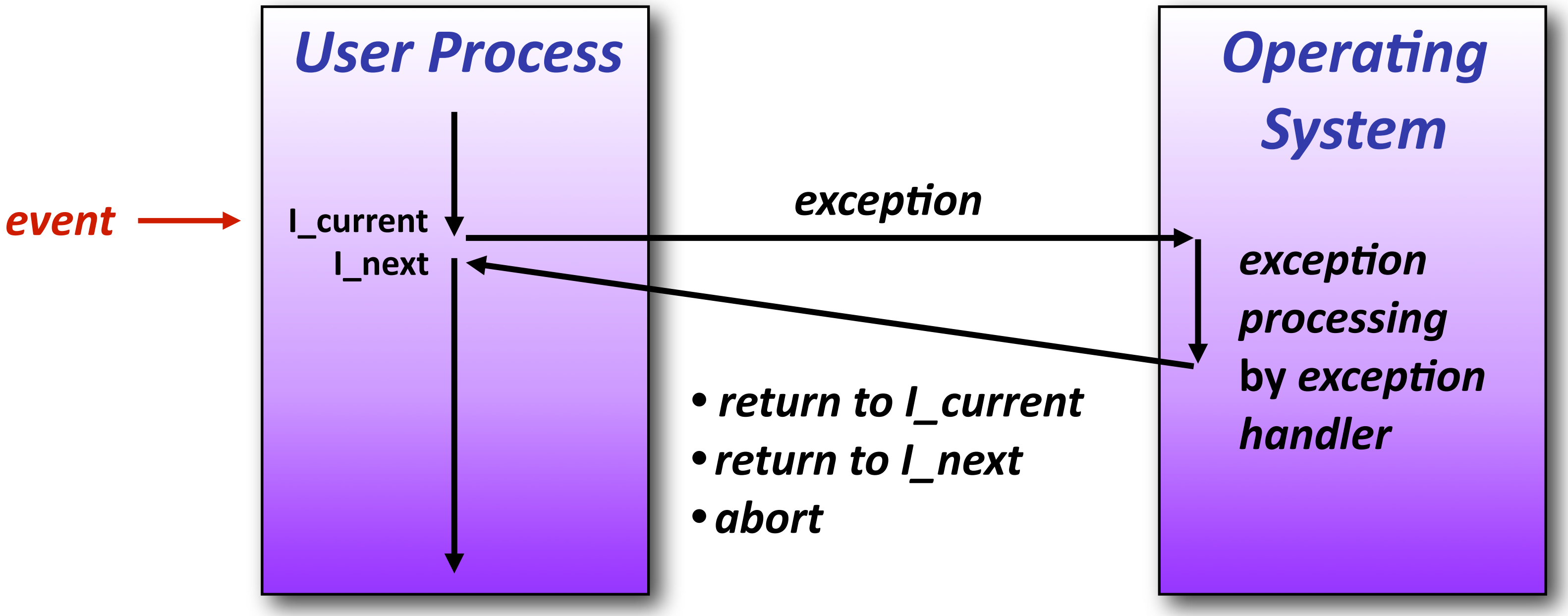
- **System needs mechanisms for "exceptional control flow"**

Exceptional Control Flow

- **Exists at all levels of a computer system**
- **Low level mechanisms**
  - Exceptions
    - change in control flow in response to a system event (i.e., change in system state)
  - Combination of hardware and OS software
- **Higher level mechanisms**
  - Process context switch
  - Signals
  - Nonlocal jumps: setjmp()/longjmp()
  - Implemented by either:
    - OS software (context switch and signals)
    - C language runtime library (nonlocal jumps)

Exceptions

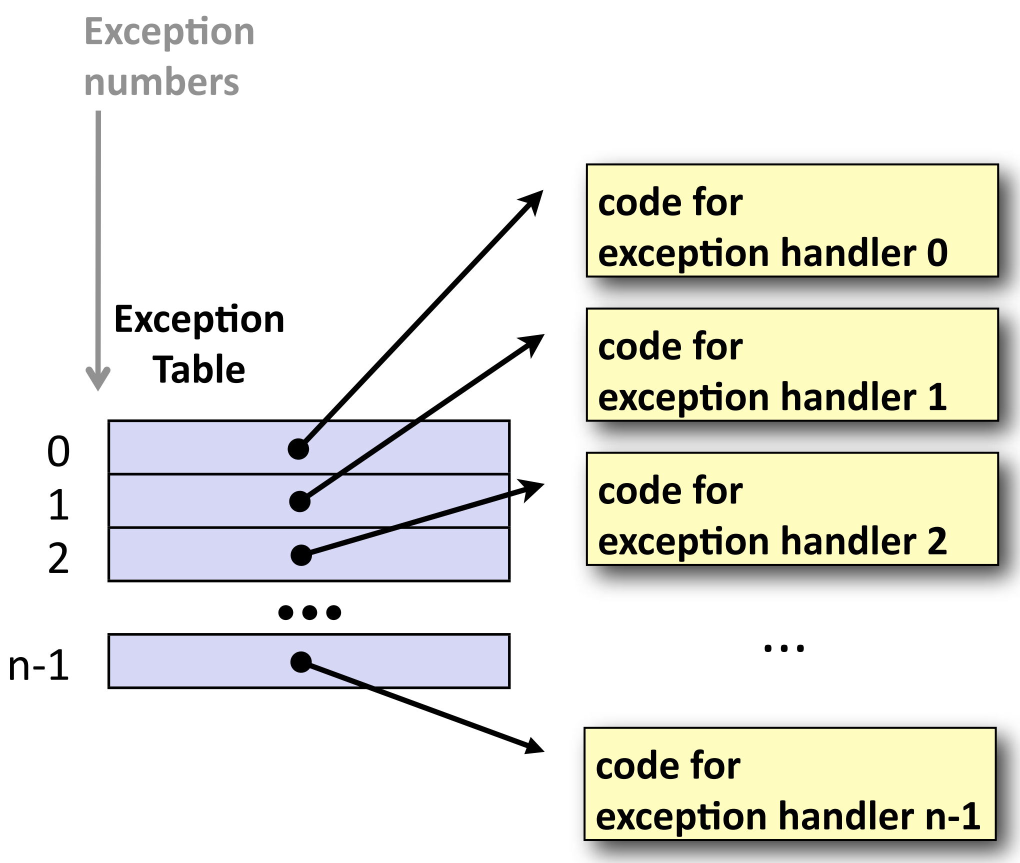
- An *exception* is a transfer of control to the OS in response to some *event* (i.e., change in processor state)



- **Examples:**

  div by 0, arithmetic overflow, page fault, I/O request completes, Ctrl-C

Interrupt Vectors



- **Each type of event has a unique exception number *k***
- ***k* = index into exception table**
  - a.k.a. interrupt vector
- **Handler *k* is called each time exception k occurs**

Asynchronous Exceptions (Interrupts)

- **Caused by events external to the processor**
  - Indicated by setting the processor's interrupt pin
  - Handler returns to "next" instruction

- **Examples:**
  - I/O interrupts
    - hitting Ctrl-C at the keyboard
    - arrival of a packet from a network
    - arrival of data from a disk
  - Hard reset interrupt
    - hitting the reset button
  - Soft reset interrupt
    - hitting Ctrl-Alt-Delete on a PC

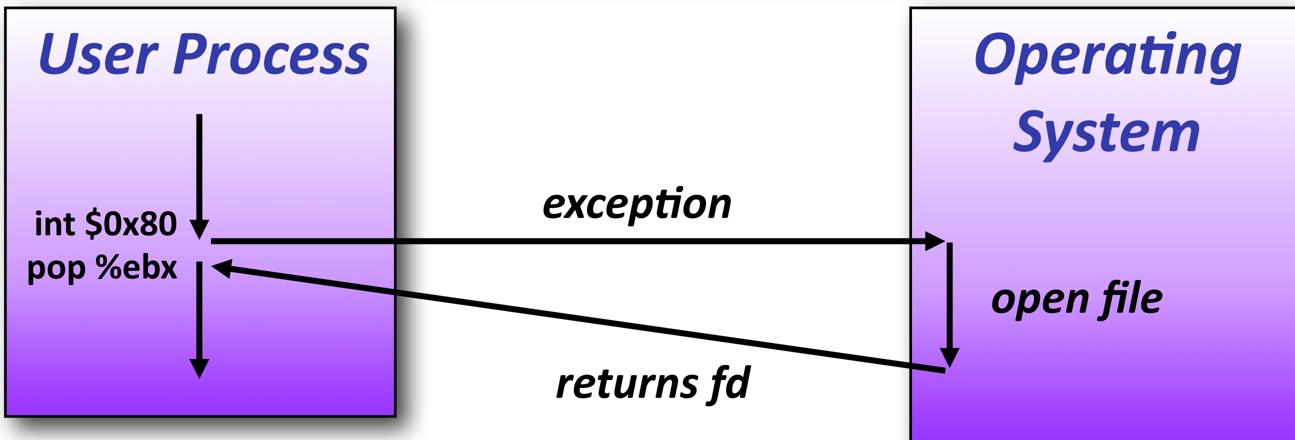
Synchronous Exceptions

- **Caused by events that occur as a result of executing an instruction:**
  - ***Traps***
    - Intentional
    - Examples: system calls, breakpoint traps, special instructions
    - Returns control to “next” instruction
  - ***Faults***
    - Unintentional but possibly recoverable
    - Examples: page faults (recoverable), protection faults (unrecoverable), floating point exceptions
    - Either re-executes faulting (“current”) instruction or aborts
  - ***Aborts***
    - unintentional and unrecoverable
    - Examples: parity error, machine check
    - Aborts current program

Trap Example: Opening File

- User calls: `open(filename, options)`
- Function `open` executes system call instruction `int`

```
0804d070 <__libc_open>:
 . . .
 804d082: cd 80                    int    $0x80
 804d084: 5b                       pop    %ebx
 . . .
```



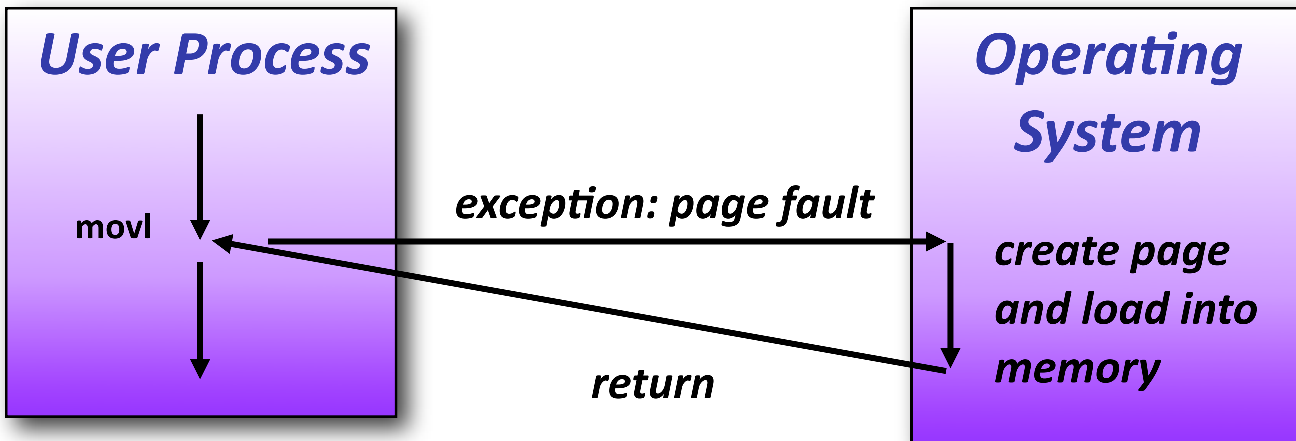
- OS must find or create file, get it ready for reading or writing
- Returns integer file descriptor

Fault Example: Page Fault

- User writes to memory location
- That portion (page) of user's memory is currently on disk

```
int a[1000];
main ()
{
    a[500] = 13;
}
```

```
80483b7: c7 05 10 9d 04 08 0d     movl    $0xd,0x8049d10
```

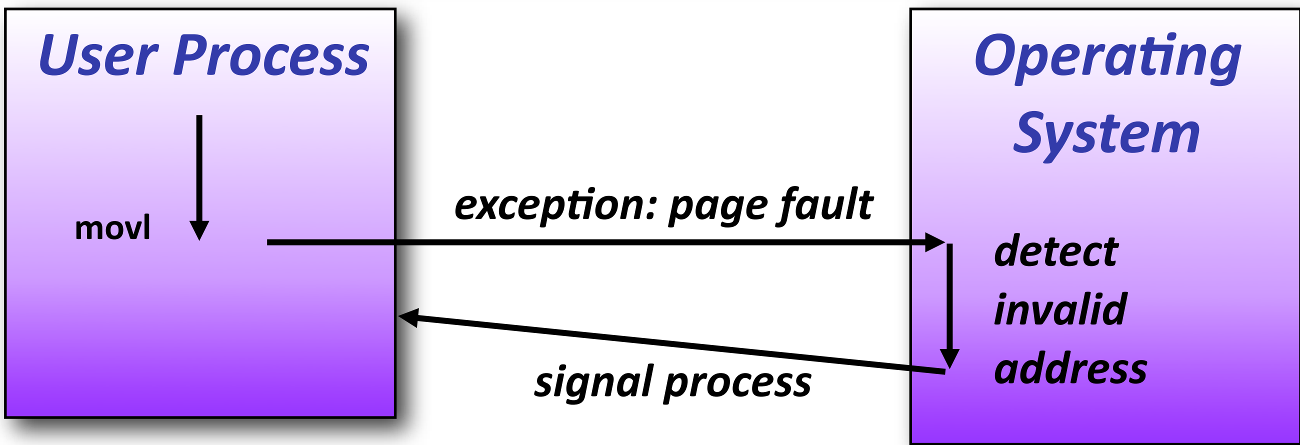


- Page handler must load page into physical memory
- Returns to faulting instruction
- Successful on second try

Fault Example: Invalid Memory Reference

```
int a[1000];
main ()
{
    a[5000] = 13;
}
```

```
80483b7: c7 05 60 e3 04 08 0d  movl   $0xd,0x804e360
```



- Page handler detects invalid address
- Sends `SIGSEGV` signal to user process
- User process exits with "segmentation fault"

Exception Table IA32 (Excerpt)

Exception Number	*Description*	*Exception Class*
0	Divide error	Fault
13	General protection fault	Fault
14	Page fault	Fault
18	Machine check	Abort
32-127	OS-defined	Interrupt or trap
128 (0x80)	System call	Trap
129-255	OS-defined	Interrupt or trap

Check pp. 183: http://download.intel.com/design/processor/manuals/253665.pdf

Today

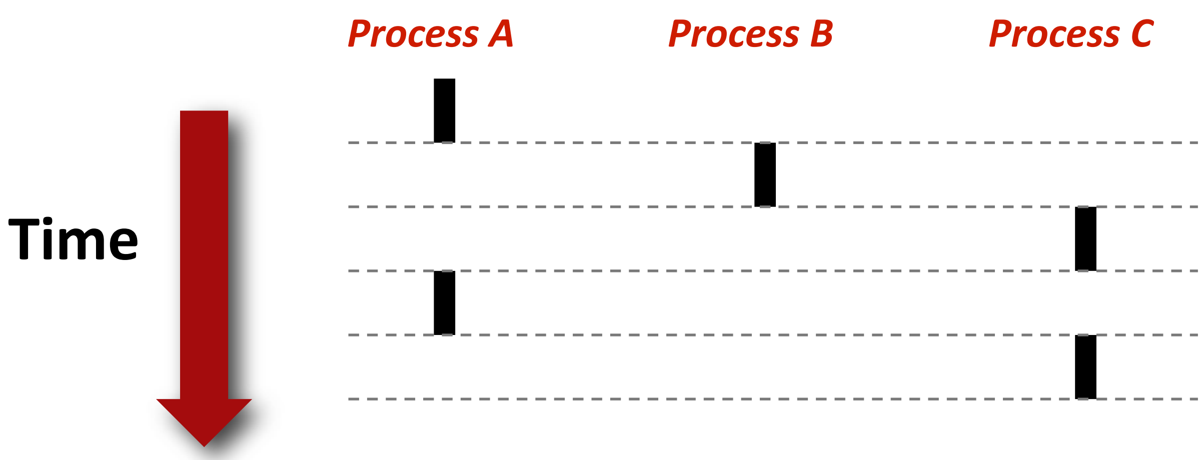
- Exceptional Control Flow
- **Processes**

Processes

- **Definition: A *process* is an instance of a running program**
  - One of the most profound ideas in computer science
  - Not the same as "program" or "processor"
- **Process provides each program with two key abstractions:**
  - Logical control flow
    - Each program seems to have exclusive use of the CPU
  - Private virtual address space
    - Each program seems to have exclusive use of main memory
- **How are these Illusions maintained?**
  - Process executions interleaved (multitasking)
  - Address spaces managed by virtual memory system
    - we'll talk about this in a couple of weeks

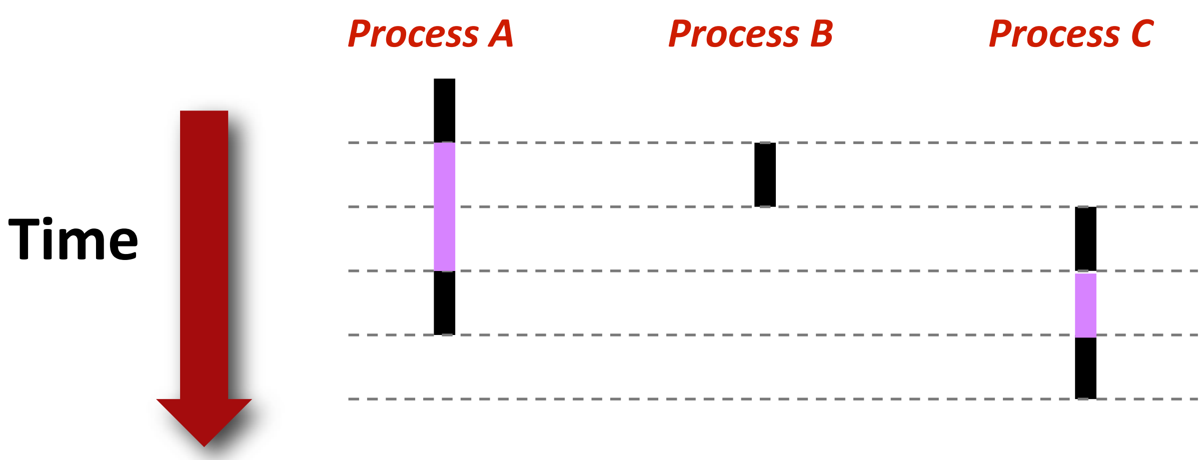
Concurrent Processes

- **Two processes *run concurrently* if their flows overlap in time**
- **Otherwise, they are *sequential***
- **Examples:**
  - Concurrent: A & B, A & C
  - Sequential: B & C



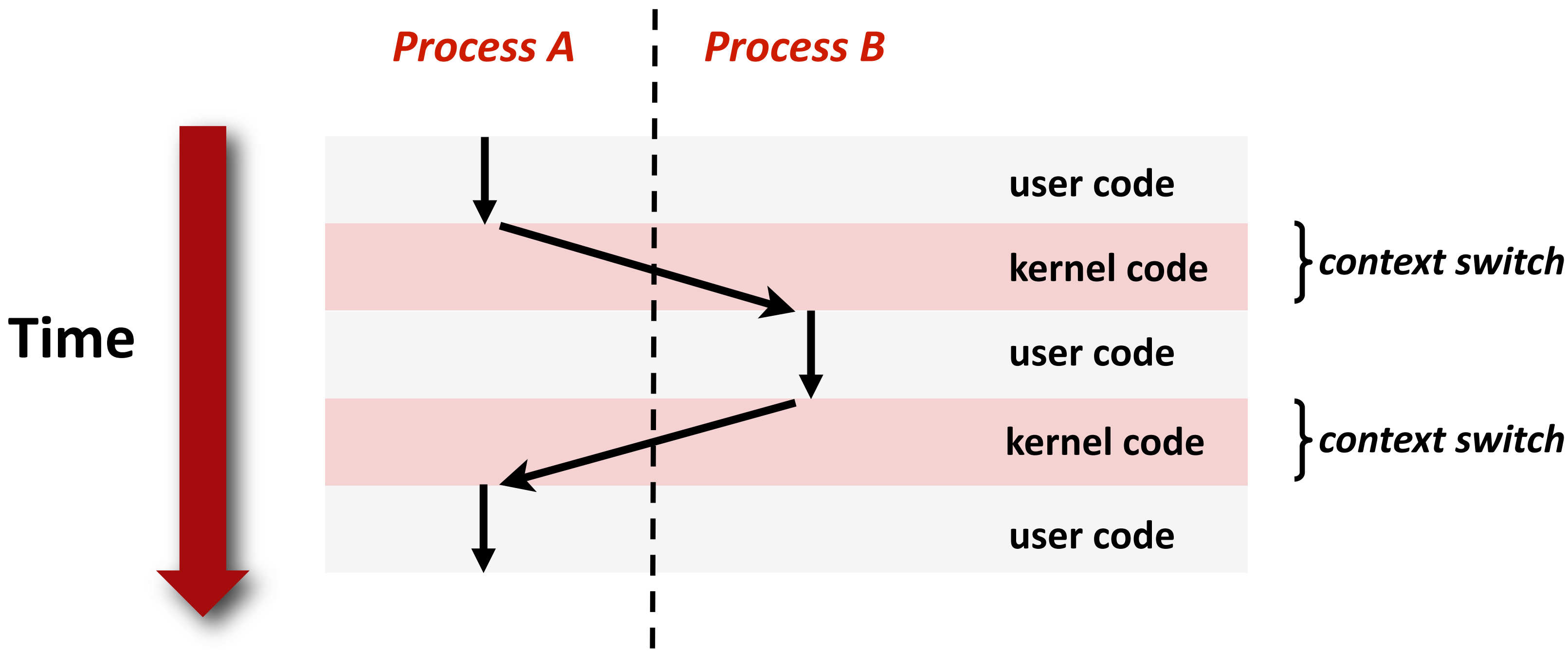
User View of Concurrent Processes

- **Control flows for concurrent processes are physically disjoint in time**
- **However, we can think of concurrent processes are running in parallel with each other**



Context Switching

- **Processes are managed by a shared chunk of OS code called the *kernel***
  - Important: the kernel is not a separate process, but rather runs as part of some user process
- **Control flow passes from one process to another via a *context switch***



`fork`: Creating New Processes

- **`int fork(void)`**
  - creates a new process (child process) that is identical to the calling process (parent process)
  - returns 0 to the child process
  - returns child's **`pid`** to the parent process

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

- **Fork is interesting (and often confusing) because it is called *once* but returns *twice***

Understanding fork

Process n

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

Child Process m

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

pid = m

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

pid = 0

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

`hello from parent` *Which one is first?* `hello from child`

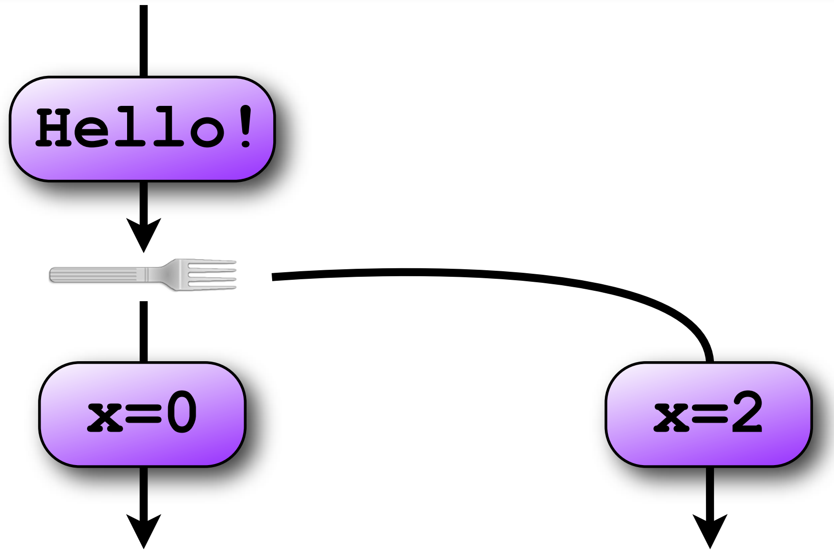
Fork Example #1

- **Parent and child both run same code**
  - Distinguish parent from child by return value from fork
- **Start with same state, but each has private copy**
  - Including shared output file descriptor
  - Relative ordering of their print statements undefined

```
void fork1()
{
  int x = 1;
  printf("Hello!");
  pid_t pid = fork();
  if (pid == 0) {
    printf("Child has x = %d\n", ++x);
  } else {
    printf("Parent has x = %d\n", --x);
  }
  printf("Bye from process %d with x = %d\n", getpid(), x);
}
```

Fork Example #1

```
void fork1()
{
  int x = 1;
  printf("Hello!");
  pid_t pid = fork();
  if (pid == 0) {
    printf("Child has x = %d\n", ++x);
  } else {
    printf("Parent has x = %d\n", --x);
  }
  printf("Bye from process %d with x = %d\n", getpid(), x);
}
```



Fork Example #2

- **Both parent and child can continue forking**

```
void fork2()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("Bye\n");
}
```

Fork Example #3

```
void fork3()
{
  printf("L0\n");
  if (fork() != 0){
    printf("L1\n");
    if (fork() != 0){
      printf("L2\n");
      fork();
    }
  }
  printf("Bye\n");
}
```

Fork Example #4

```
void fork4()
{
  printf("L0\n");
  if (fork() == 0) {
    printf("L1\n");
    if (fork() == 0) {
      printf("L2\n");
      fork();
    }
  }
  printf("Bye\n");
}
```

`exit`: Ending a process

- **`void exit(int status)`**
  - exits a process
    - Normally return with status 0
  - **`atexit()`** registers functions to be executed upon exit

```
void cleanup(void) {
   printf("cleaning up\n");
}

void fork5() {
   atexit(cleanup);
   fork();
   exit(0);
}
```

Zombies

- **Idea**
  - When process terminates, still consumes system resources
    - Various tables maintained by OS
  - Called a "zombie"
    - Living corpse, half alive and half dead
- **Reaping**
  - Performed by parent on terminated child
  - Parent is given exit status information
  - Kernel discards process
- **What if parent doesn't reap?**
  - If any parent terminates without reaping a child, then child will be reaped by init process
  - So, only need explicit reaping in long-running processes
    - e.g., shells and servers

Zombie Example

```
void fork7()
{
  if (fork() == 0) {
    /* Child */
    printf("Child, PID = %d\n",
           getpid());
    exit(0);
  } else {
    printf("Parent, PID = %d\n",
            getpid());
    while (1)
      ; /* Infinite loop */
  }
}
```

```
linux> ./forks 7 &
[1] 6639
Parent, PID = 6639
Child, PID = 6640
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6639 ttyp9    00:00:03 forks
 6640 ttyp9    00:00:00 forks <defunct>
 6641 ttyp9    00:00:00 ps
linux> kill 6639
[1]    Terminated
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6642 ttyp9    00:00:00 ps
```

- ps shows child process as “defunct”
- Killing parent allows child to be reaped by `init`

Nonterminating Child Example

```
void fork8()
{
  if (fork() == 0) {
    /* Child */
    printf("Child, PID = %d\n",
           getpid());
    while (1)
      ; /* Infinite loop */
  } else {
    printf("Parent, PID = %d\n",
           getpid());
    exit(0);
  }
}
```

```
linux> ./forks 8
Parent, PID = 6675
Child, PID = 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6676 ttyp9    00:00:06 forks
 6677 ttyp9    00:00:00 ps
linux> kill 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6678 ttyp9    00:00:00 ps
```

- Child process still active even though parent has terminated
- Must kill explicitly, or else will keep running indefinitely

`wait`: Synchronizing with Children

- **`int wait(int *child_status)`**
  - suspends current process until one of its children terminates
  - return value is the **`pid`** of the child process that terminated
  - if **`child_status != NULL`**, then the object it points to will be set to a status indicating why the child process terminated
    - Terminated normally
    - Terminated by signal
    - Terminated and dumped core
    - etc.

wait: Synchronizing with Children

```
void fork9() {
   int child_status;

   if (fork() == 0) {
      printf("HC: hello from child\n");
   }
   else {
      printf("HP: hello from parent\n");
      wait(&child_status);
      printf("CT: child has terminated\n");
   }
   printf("Bye\n");
   exit();
}
```

wait() Example

- If multiple children completed, will take in arbitrary order
- Can use macros **WIFEXITED** and **WEXITSTATUS** to get information about exit status

```
void fork10()
{
  pid_t pid[N];
  int i;
  int child_status;
  for (i = 0; i < N; i++)
    if ((pid[i] = fork()) == 0)
      exit(100+i); /* Child */
  for (i = 0; i < N; i++) {
    pid_t wpid = wait(&child_status);
    if (WIFEXITED(child_status))
      printf("Child %d terminated with exit status %d\n",
             wpid, WEXITSTATUS(child_status));
    else
      printf("Child %d terminate abnormally\n", wpid);
  }
}
```

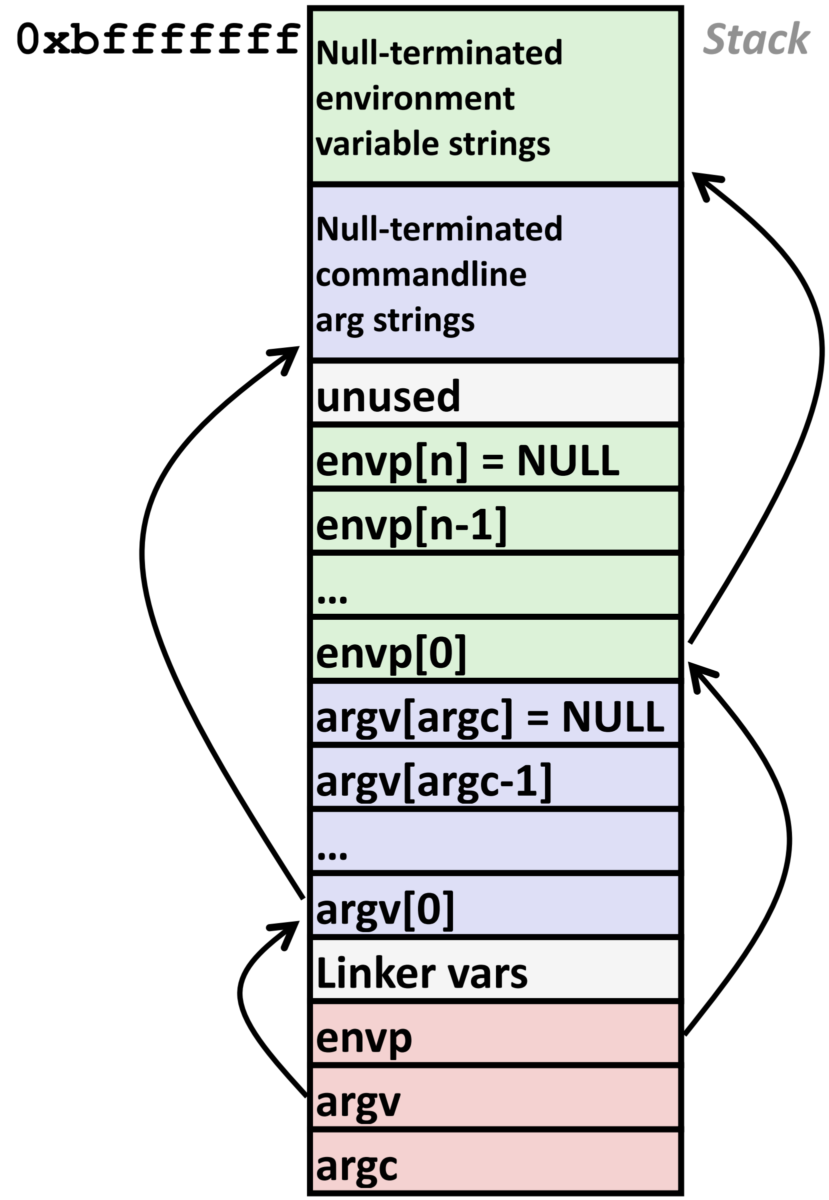
`waitpid()`: Waiting for a Specific Process

- **`waitpid(pid, &status, options)`**
  - suspends current process until specific process terminates
  - various options (that we won't talk about)

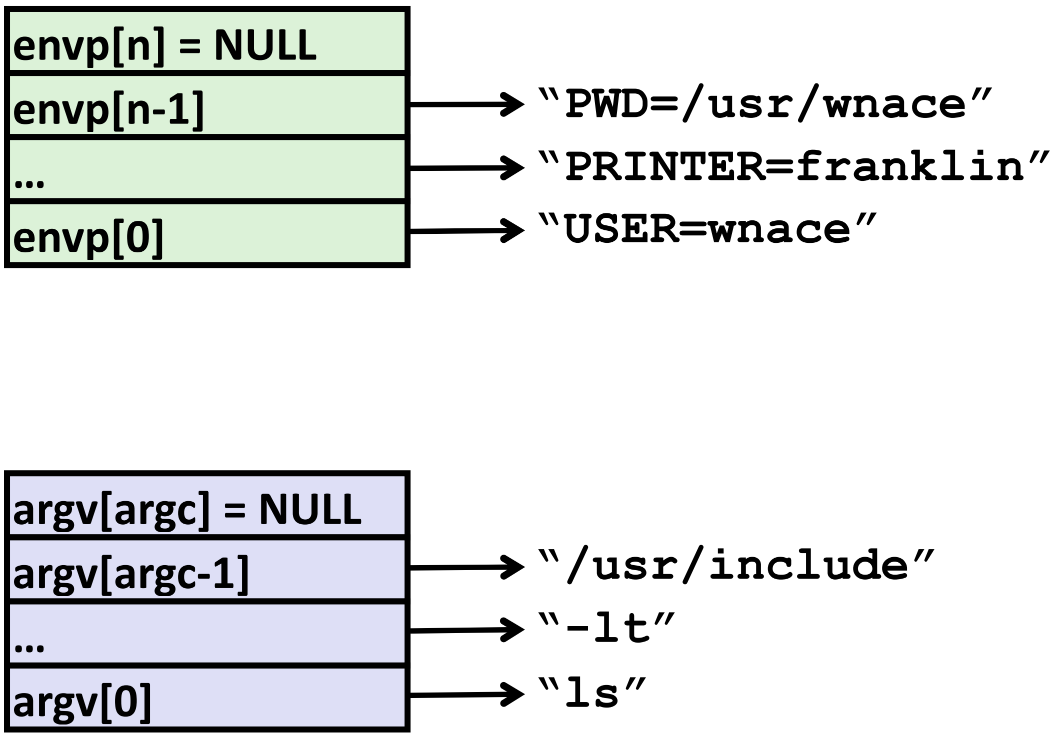
```
void fork11()
{
  pid_t pid[N];
  int i;
  int child_status;
  for (i = 0; i < N; i++)
    if ((pid[i] = fork()) == 0)
      exit(100+i); /* Child */
  for (i = 0; i < N; i++) {
    pid_t wpid = waitpid(pid[i], &child_status, 0);
    if (WIFEXITED(child_status))
      printf("Child %d terminated with exit status %d\n",
             wpid, WEXITSTATUS(child_status));
    else
      printf("Child %d terminated abnormally\n", wpid);
  }
}
```

`execve`: Loading and Running Programs

- `int execve(`
  `char *filename,`
  `char *argv[],`
  `char *envp[]`
  `)`
- **Loads and runs**
  - Executable **`filename`**
  - With argument list **`argv`**
  - And environment variable list **`envp`**
- **Does not return (unless error)**
- **Overwrites process, keeps pid**
- **Environment variables:**
  - "name=value" strings



execve: Example



`execl` and `exec` Family

- `int execl(char *path, char *arg0, char *arg1, …, 0)`
- **Loads and runs executable at `path` with args `arg0`, `arg1`, …**
  - `path` is the complete path of an executable object file
  - By convention, `arg0` is the name of the executable object file
  - "Real" arguments to the program start with `arg1`, etc.
  - List of args is terminated by a `(char *)0` argument
  - Environment taken from `char **environ`, which points to an array of "name=value" strings:
    - USER=wnace
    - LOGNAME=wnace
    - HOME=/afs/cs.cmu.edu/user/wnace
- **Returns −1 if error, *otherwise doesn't return*!**
- **Family of functions includes `execv`, `execve` (base function), `execvp`, `execl`, `execle`, and `execlp`**

exec: Loading and Running Programs

```
main() {
  if (fork() == 0) {
    execl("/usr/bin/cp", "cp", "foo", "bar", 0);
  }
  wait(NULL);
  printf("copy completed\n");
  exit();
}
```

Summary

- **Exceptions**
  - Events that require nonstandard control flow
  - Generated externally (interrupts) or internally (traps and faults)

- **Processes**
  - At any given time, system has multiple active processes
  - Only one can execute at a time, though
  - Each process appears to have total control of processor + private memory space

Summary (cont.)

- **Spawning processes**
  - Call to **`fork`**
  - One call, two returns
- **Process completion**
  - Call **`exit`**
  - One call, no return
- **Reaping and waiting for Processes**
  - Call **`wait`** or **`waitpid`**
- **Loading and running Programs**
  - Call **`execl`** (or variant)
  - One call, (normally) no return