Exceptional Control Flow: Exceptions and Processes

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

What about try/catch/throw?

ECF Exists at All Levels of a System

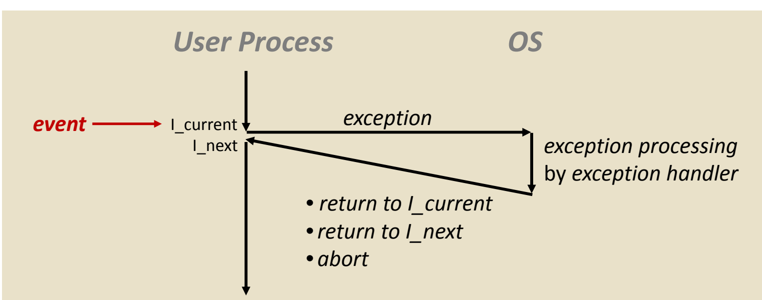
- **Exceptions**
  - Hardware and operating system kernel software
- **Process Context Switch**
  - Hardware timer and kernel software
- **Signals**
  - Kernel software and application software
- **Nonlocal jumps**
  - Application code

This Lecture (Exceptions, Process Context Switch)

Next Lecture (Signals, Nonlocal jumps)

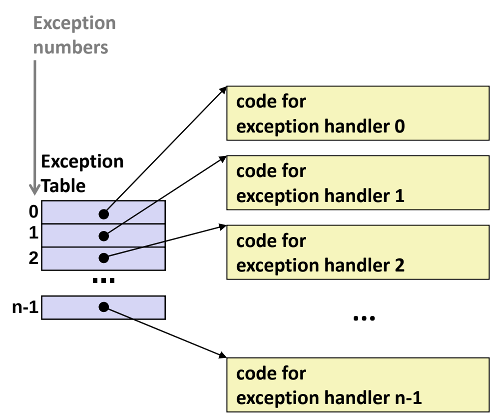
Exceptions

- **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

Exception Tables



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

almost

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

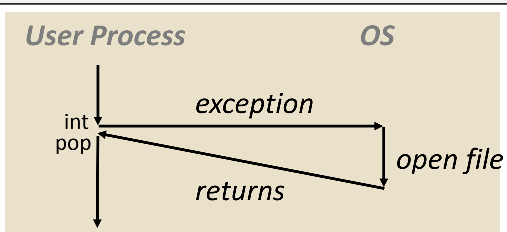
Synchronous Exceptions

- **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
 . . .
```



Different privilege levels!

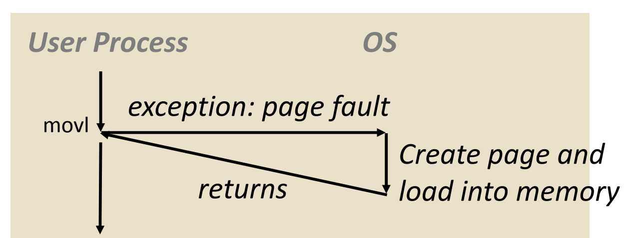
- OS must find or create file, get it ready for reading or writing
- Returns integer file descriptor

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
```



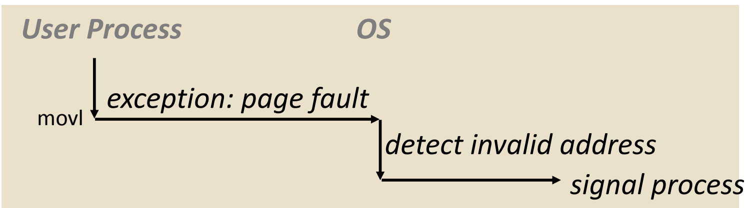
- Page handler must load page into physical memory
- Returns to faulting instruction
- Successful on second try

Different privilege levels!

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”

Different privilege levels!

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 Table 6-1:
http://download.intel.com/design/processor/manuals/253665.pdf

Altering the Control Flow (revisited)

- **Up to now: two mechanisms for changing control flow:**
  - Jum
  - Call

  Both r

Is there an alternative?
- For general purpose processors?
- For embedded processors?

- **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”**

Today

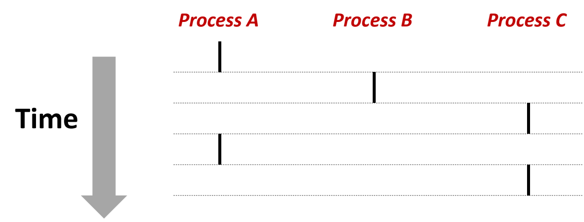
- Exceptional Control Flow
- **Processes**

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) or run on separate cores
  - Address spaces managed by virtual memory system
    - we’ll talk about this in a couple of weeks

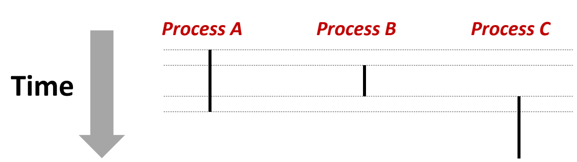
Concurrent Processes

- **Two processes *run concurrently* (*are concurrent)* if their flows overlap in time**
- **Otherwise, they are *sequential***
- **Examples (running on single core):**
  - Concurrent: A & B, A & C
  - Sequential: B & C



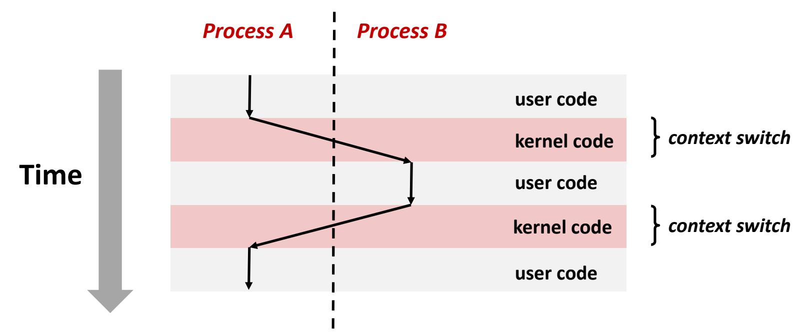
User View of Concurrent Processes

- **Control flows for concurrent processes are physically disjoint in time**
- **However, we can think of concurrent processes as 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** (process id) 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");
}
```

pid = m

```
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");
}
```

Child Process 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");
}
```

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

Fork Example #1

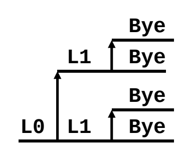
- **Parent and child both run same code**
  - Distinguish parent from child by return value from **fork**
- **Start with same state, but each has private copy**
  - Including shared output file descriptor
  - Relative ordering of their print statements undefined

```
void fork1()
{
    int x = 1;
    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

- **Two consecutive forks**

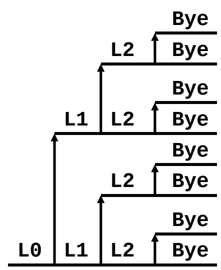
```
void fork2()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("Bye\n");
}
```



Fork Example #3

- Three consecutive forks

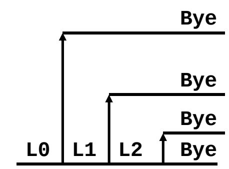
```
void fork3()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("L2\n");
    fork();
    printf("Bye\n");
}
```



Fork Example #4

- Nested forks in parent

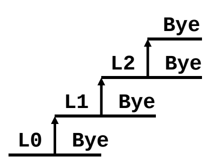
```
void fork4()
{
    printf("L0\n");
    if (fork() != 0) {
       printf("L1\n");
       if (fork() != 0) {
          printf("L2\n");
          fork();
       }
    }
    printf("Bye\n");
}
```



Fork Example #5

- Nested forks in children

```
void fork5()
{
    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 fork6() {
   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 (using `wait` or `waitpid`)
  - 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 (pid == 1)
  - So, only need explicit reaping in long-running processes
    - e.g., shells and servers

Zombie Example

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

```
linux> ./forks 7 &
[1] 6639
Running Parent, PID = 6639
Terminating 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>
```

- **`ps`** shows child process as "defunct"

Zombie Example

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

```
linux> ./forks 7 &
[1] 6639
Running Parent, PID = 6639
Terminating 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("Running Child, PID = %d\n",
               getpid());
        while (1)
            ; /* Infinite loop */
    } else {
        printf("Terminating Parent, PID = %d\n",
               getpid());
        exit(0);
    }
}
```

```
linux> ./forks 8
Terminating Parent, PID = 6675
Running 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>
```

- Child process still active even though parent has terminated

Nonterminating Child Example

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

```
linux> ./forks 8
Terminating Parent, PID = 6675
Running 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

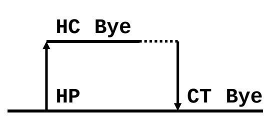
`wait`: Synchronizing with Children

- **Parent reaps child by calling the `wait` function**
- **`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

`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);
    }
}
```

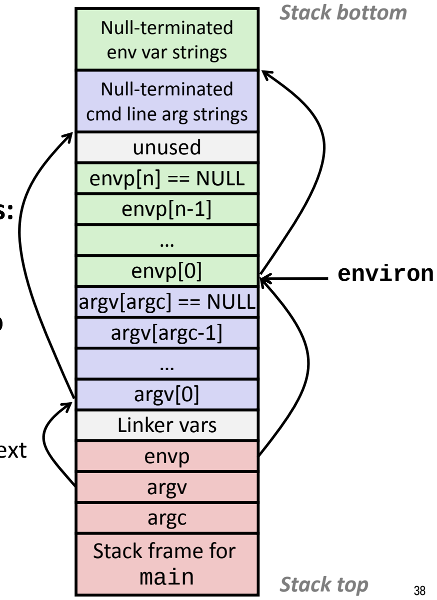
waitpid(): Waiting for a Specific Process

- **waitpid(pid, &status, options)**
  - suspends current process until specific process terminates
  - various options (see textbook)

```
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 = N-1; i >= 0; 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);
    }
}
```

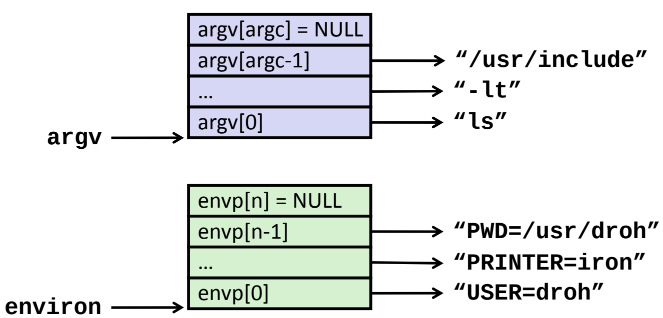

execve: Loading and Running Programs

- `int execve(`
  `char *filename,`
  `char *argv[],`
  `char *envp[]`
  `)`
- **Loads and runs in current process:**
  - Executable **filename**
  - With argument list **argv**
  - And environment variable list **envp**
- **Does not return (unless error)**
- **Overwrites code, data, and stack**
  - keeps pid, open files and signal context
- **Environment variables:**
  - "name=value" strings
  - getenv and putenv



execve Example

```
if ((pid = Fork()) == 0) { /* Child runs user job */
    if (execve(argv[0], argv, environ) < 0) {
        printf("%s: Command not found.\n", argv[0]);
        exit(0);
    }
}
```



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 on a single core, though
  - Each process appears to have total control of processor + private memory space

Summary (cont.)

- **Spawning processes**
  - Call `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 `execve` (or variant)
  - One call, (normally) no return