Exceptional Control Flow Part I

Today

- Exceptions
- Process context switches
- Creating and destroying processes

Next time

- Signals, non-local jumps, …

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Control flow

- Computers 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 system's physical *control flow* (or *flow of control*).

Physical control flow

Time ↓

<startup>
inst_1
inst_2
inst_3
…
inst_n
<shutdown>

Altering the control flow

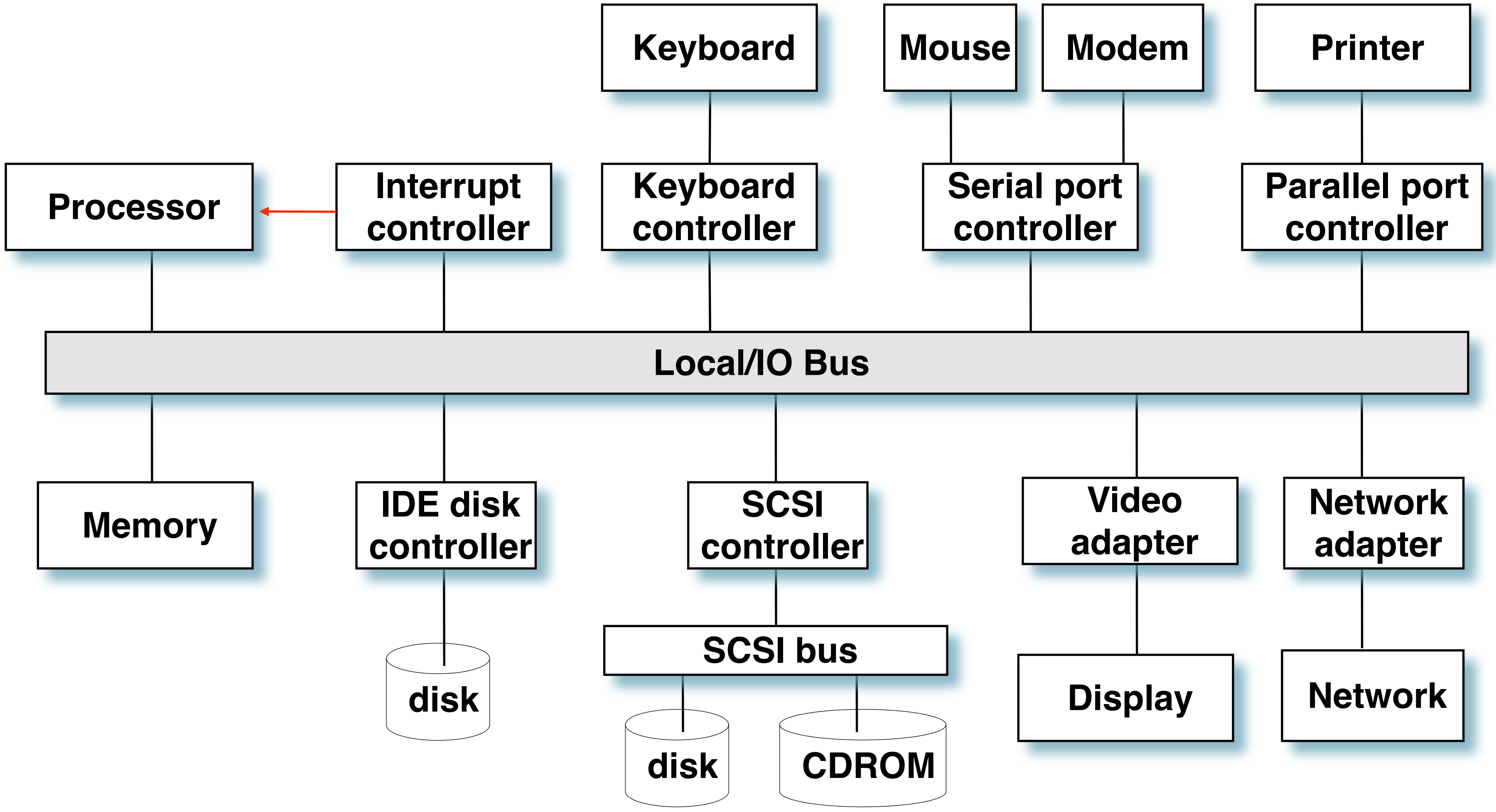
- Up to now: two mechanisms for changing control flow
  - Jumps and branches
  - Call and return using the stack discipline.
  - Both react to changes in program state.
- Insufficient for a useful system
  - Difficult for the CPU to react to changes in system state.
    - Data arrives from a disk or a network adapter.
    - Instruction divides by zero
    - User hits ctl-c at the keyboard
    - System timer expires
- System needs mechanisms for “exceptional control flow”

Exceptional control flow

Mechanisms for exceptional control flow exists at all levels of a computer system

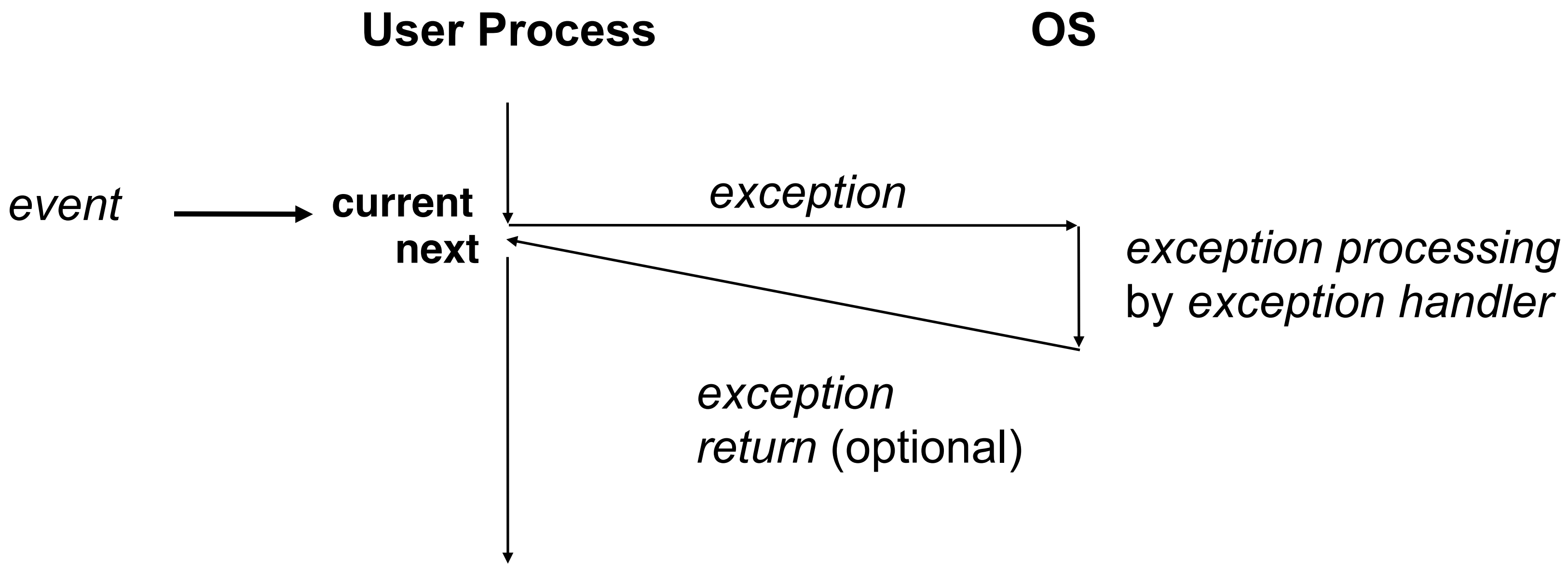
- Low level mechanism
  - Exceptions
    - change in control flow in response to a system event (i.e., change in system state)
  - Combination of hardware and OS software
- Higher level mechanisms
  - Process context switch
  - Signals
  - Nonlocal jumps (setjmp/longjmp)
  - Implemented by either:
 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

System context for exceptions

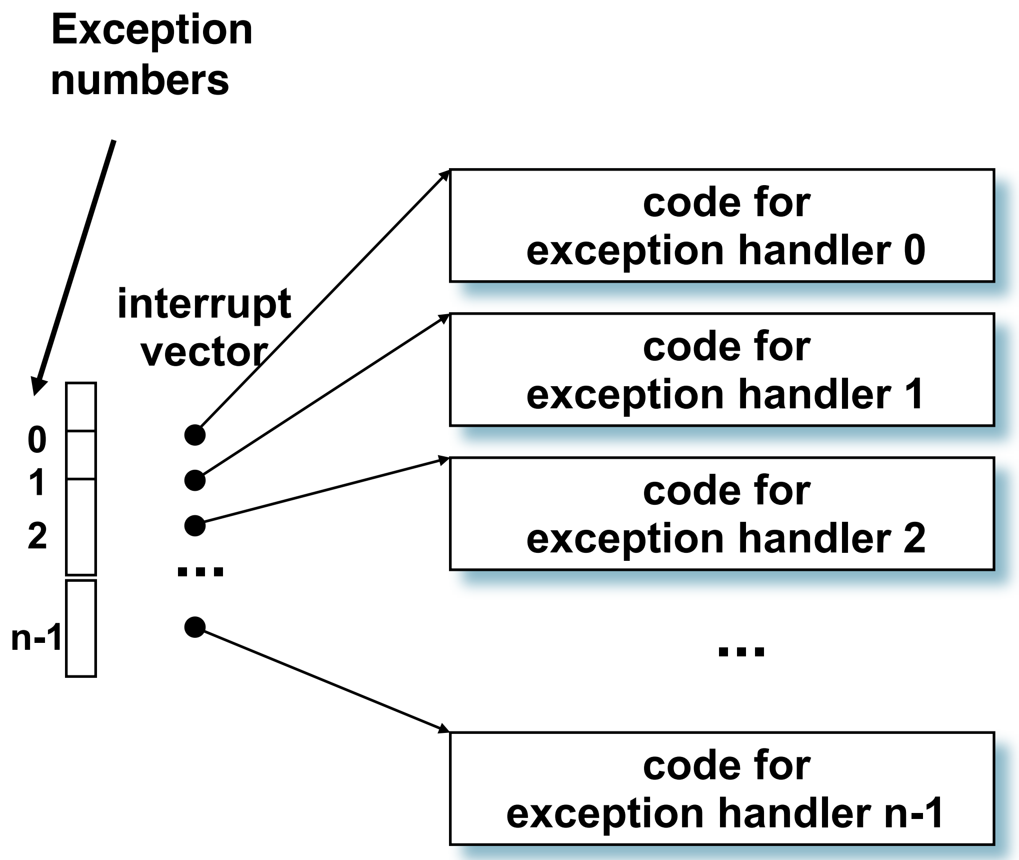


Exceptions

- Exception – a transfer of control to the OS in response to some event (i.e., change in processor state)



Interrupt vectors


Exception numbers
interrupt vector
0
1
2
...
n-1
code for exception handler 0
code for exception handler 1
code for exception handler 2
...
code for exception handler n-1

- Each type of event has a unique exception number k
- Index into jump table (a.k.a., interrupt vector)
- Jump table entry k points to a function (exception handler).
- Handler k is called each time exception k occurs.

Exceptions

- Exception numbers created by
  - processor designers
  - OS kernel designers
- Exception handling
  - like procedure call
  - return address pushed on stack
  - might be current instruction or next, depending on type of exception
  - additional processor state pushed, e.g., condition flags
  - data be pushed on either user stack or kernel stack
  - handler run in *kernel mode*

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 ctl-c at the keyboard
    - arrival of a packet from a network
    - arrival of a data sector from a disk
  - Hard reset interrupt
    - hitting the reset button
  - Soft reset interrupt
    - hitting ctl-alt-delete on a PC

Synchronous exceptions

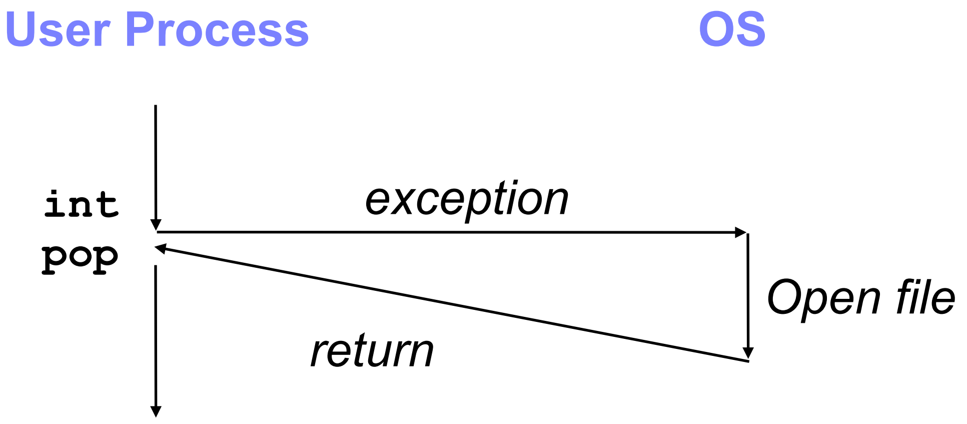
- Caused by events that occur as a result of executing an instruction:
  - Traps
    - Intentional
    - Examples: system calls, breakpoint traps, special instructions
    - Like procedure call but in kernel mode
    - Returns control to “next” instruction
  - Faults
    - Unintentional but possibly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

Trap example

- Opening a File
  - User calls `open(filename, options)`

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

    - Function open executes system call instruction `int`
  - OS must find or create file, get it ready for reading or writing
  - Returns integer file descriptor



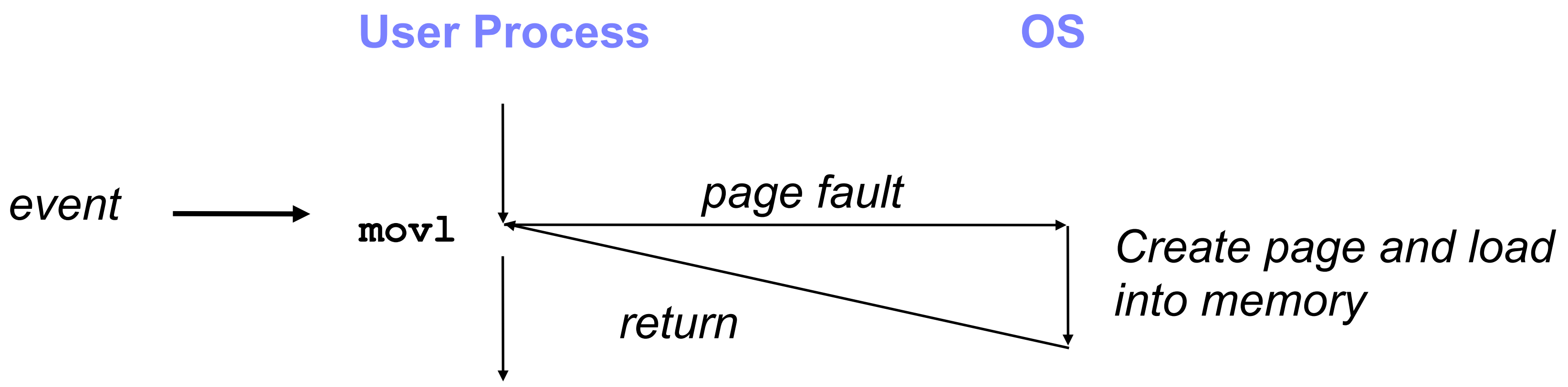
Fault example #1

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

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

```
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



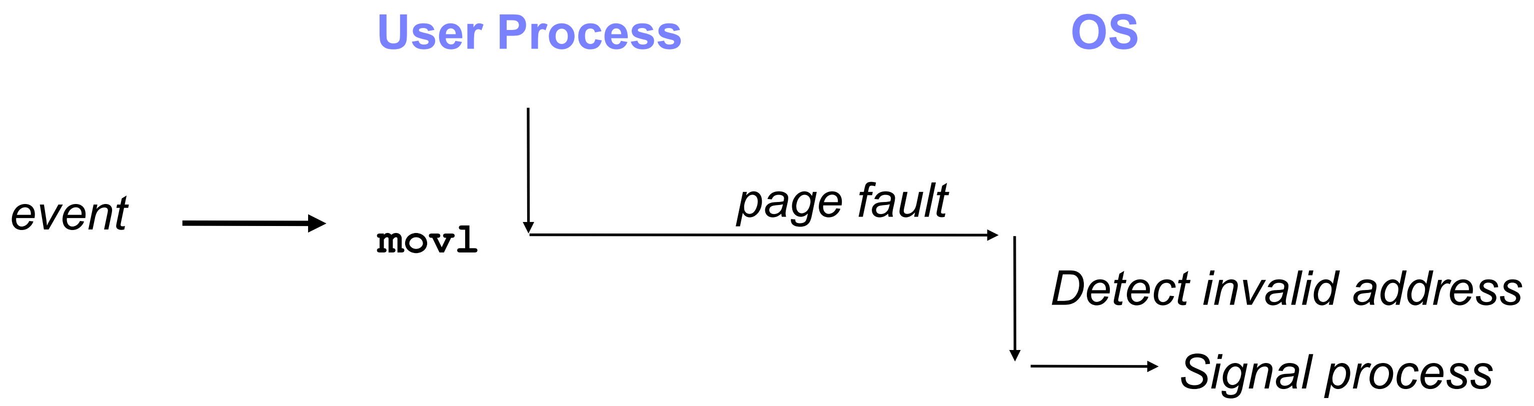
Fault example #2

- Memory reference
  - User writes to memory location
  - Address is not valid

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

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

  - Page handler detects invalid address
  - Sends SIGSEG signal to user process
  - User process exits with “segmentation fault”

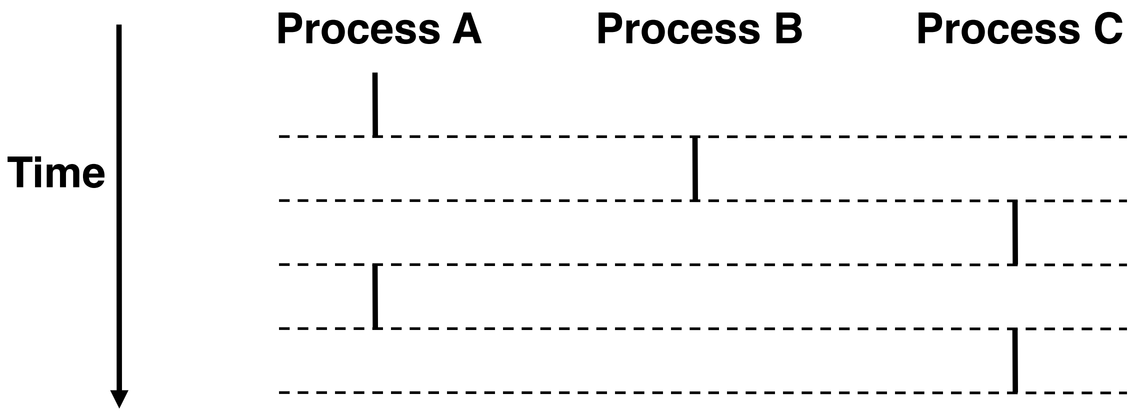


Processes

- Def: 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 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

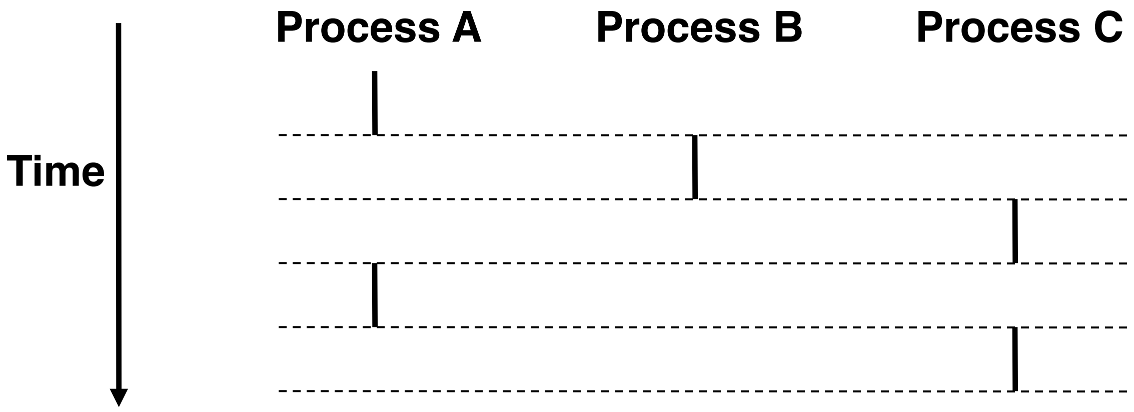
Logical control flows

Each process has its own logical control flow



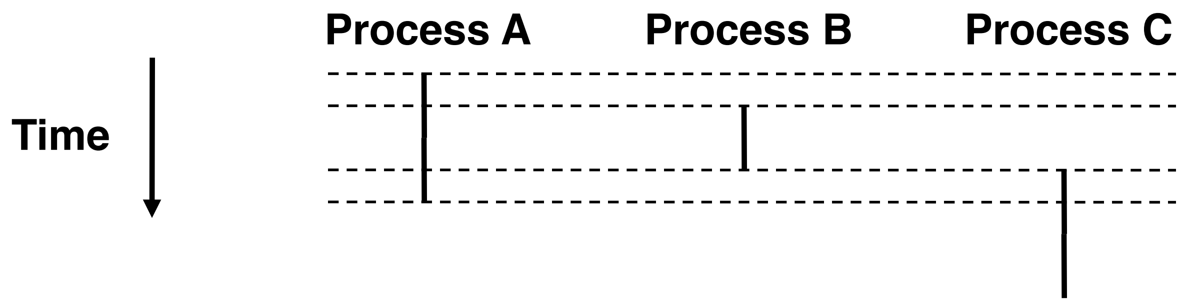
Concurrent processes

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



User view of concurrent processes

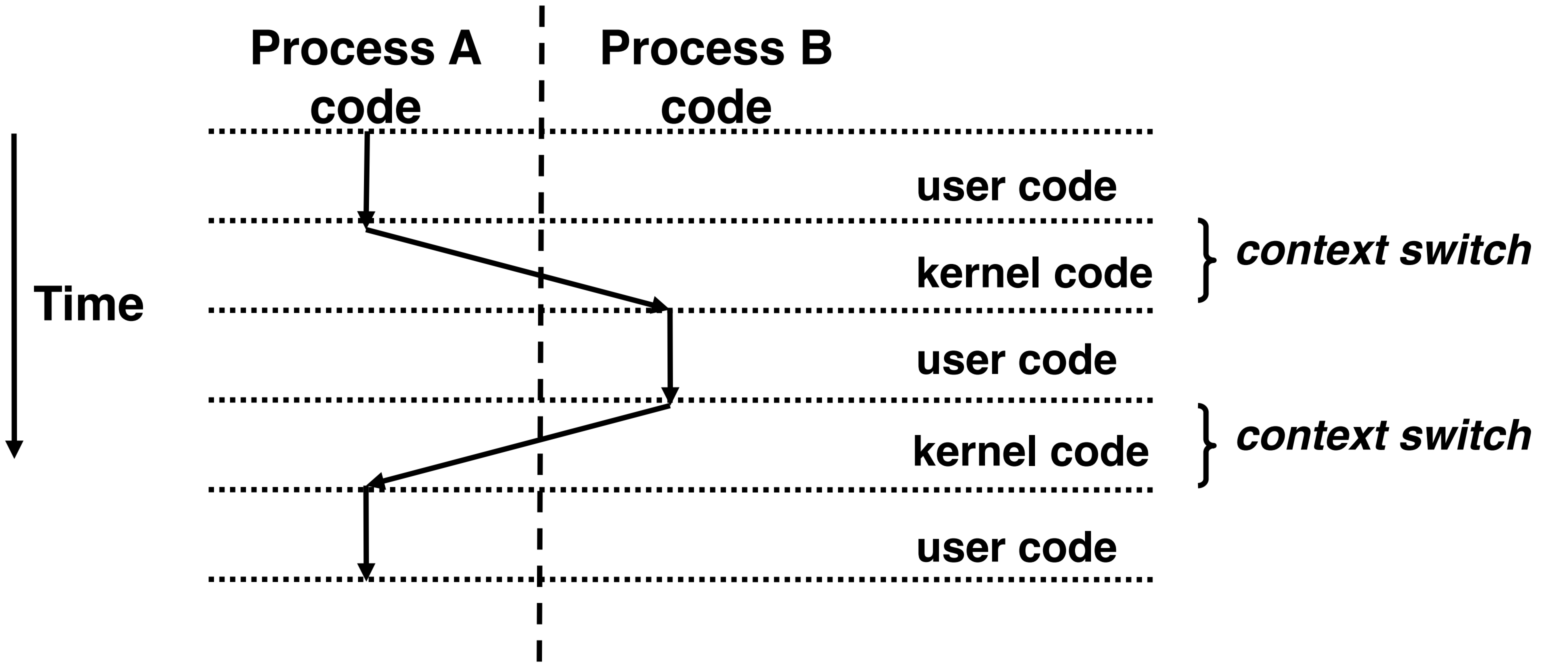
- Control flows for concurrent processes are physically disjoint in time.
- However, we can think of concurrent processes are running in parallel with each other.



Checkpoint

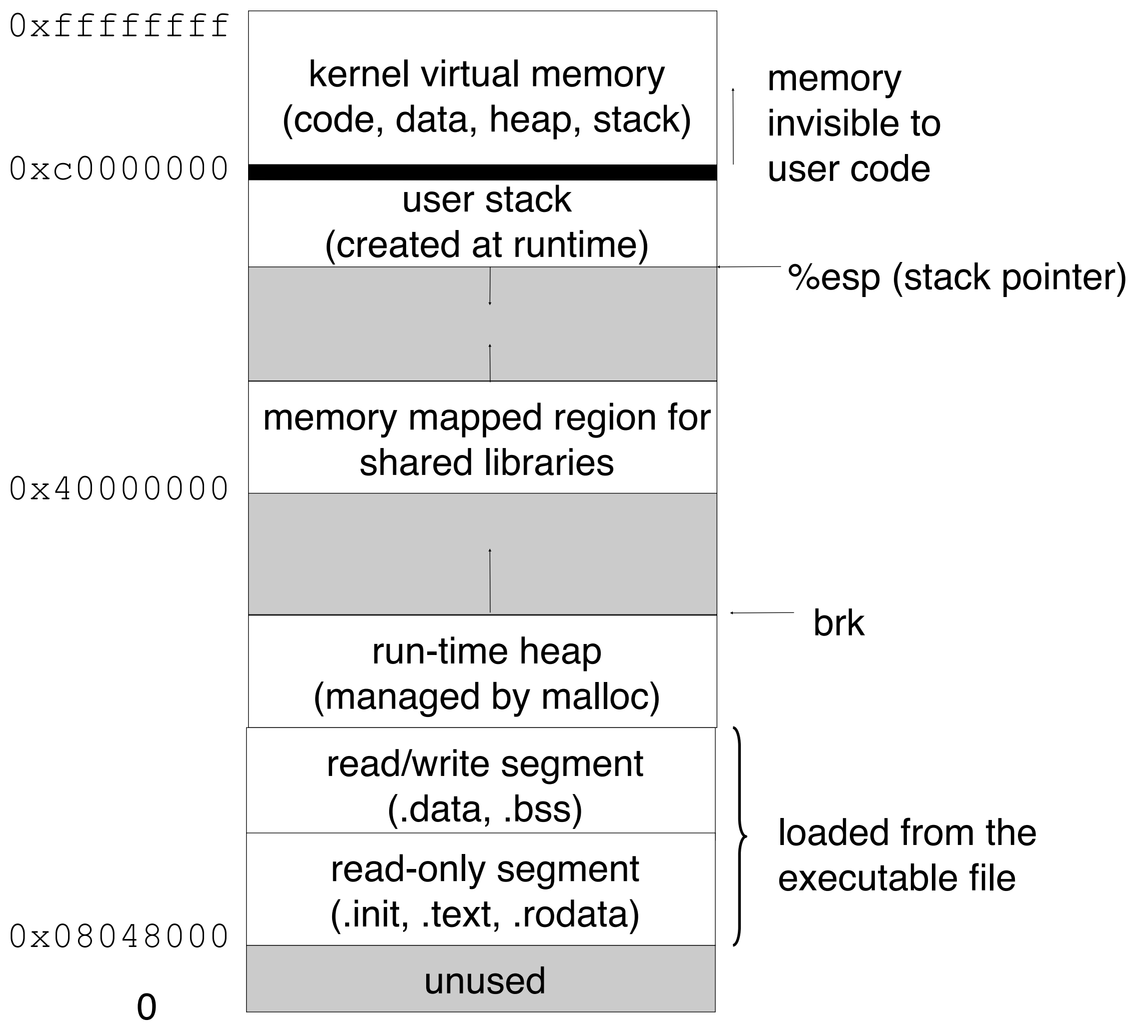
Context switching

- Processes are managed by a shared chunk of OS code called the *kernel*
  - Not a separate process, but runs as part of user process
- Control flow passes from one process to another via a *context switch.*
- A context is all the data needed to restart a process, e.g., register values, stack values, page table, …



Private address spaces

- Each process has its own private address space.


0xffffffff
kernel virtual memory (code, data, heap, stack)
memory invisible to user code
0xc0000000
user stack (created at runtime)
%esp (stack pointer)
memory mapped region for shared libraries
0x40000000
brk
run-time heap (managed by malloc)
read/write segment (.data, .bss)
read-only segment (.init, .text, .rodata)
loaded from the executable file
0x08048000
unused
0

`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

```
if (fork() == 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*

Fork example #1

- Key points
  - 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

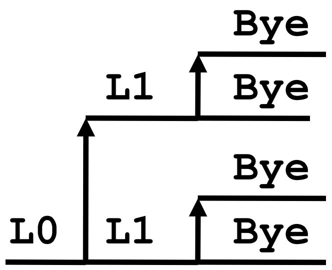
```
void fork1()
{
    int x = 1;
    pid_t pid = fork();
    if (pid == 0) {
        printf("Child has x = %d\n", ++x);
    } else {
        printf("Parent has x = %d\n", --x);
    }
    printf("Bye from process %d with x = %d\n", getpid(), x);
}
```

Book uses Fork() wrapper function. See 8.3 for why it's important.

Fork example #2

- Key points
  - Both parent and child can continue forking

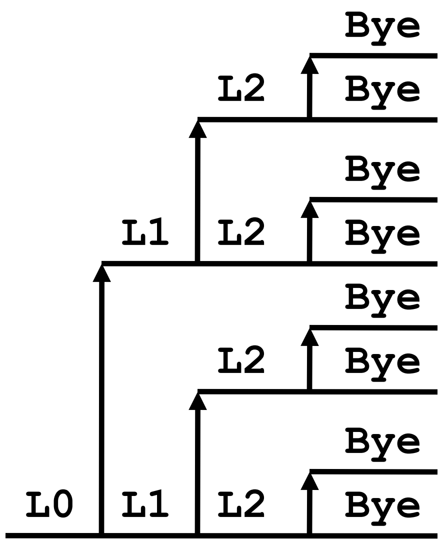
```
void fork2()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("Bye\n");
}
```



Fork example #3

- Key points
  - Both parent and child can continue forking

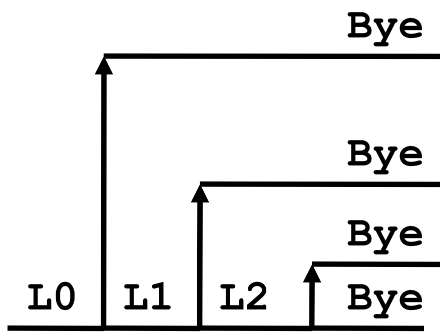
```
void fork3()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("L2\n");
    fork();
    printf("Bye\n");
}
```



Fork example #4

- Key points
  - Both parent and child can continue forking

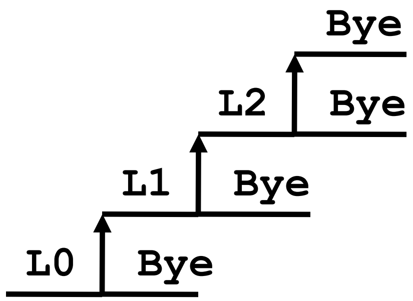
```
void fork4()
{
    printf("L0\n");
    if (fork() != 0) {
       printf("L1\n");
       if (fork() != 0) {
            printf("L2\n");
            fork();
       }
    }
    printf("Bye\n");
}
```



Fork example #5

- Key points
  - Both parent and child can continue forking

```
void fork5()
{
    printf("L0\n");
    if (fork() == 0) {
      printf("L1\n");
      if (fork() == 0) {
          printf("L2\n");
          fork();
      }
    }
    printf("Bye\n");
}
```



`exit`: Destroying 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);
}
```

Checkpoint

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`
  - 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 the kernel's `init` process (PID = 1)
  - Only need explicit reaping for long-running processes
    - E.g., shells and servers

Zombie - Example

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

```
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
```

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

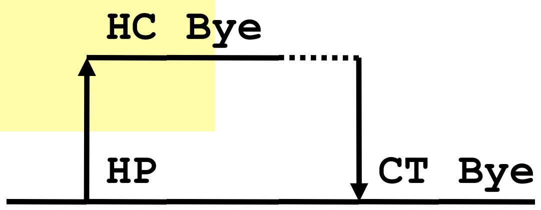
`wait`: Synchronizing with children

- `pid_t wait(int *child_status)`
  - suspends current process until one of its children terminates
  - return value is the `pid` of the child process that terminated
  - can happen in any order
  - if `child_status != NULL`, then the object it points to will be set to a status indicating why the child process terminated
- `pid_t waitpid(pid_t pid, &status, options)`
  - wait for specific process, various options
  - `wait(&status)` ≡ `waitpid(-1, &status, 0)`
- Use macros `WIFEXITED` and `WEXITSTATUS` from `<sys/wait.h>` to interpret exit status
- Both return -1 if error, e.g.,
  - `wait()` error if process has no child
  - `waitpid()` error if pid is not a child of this process

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

```
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++) { /* whichever ends first */
        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);
    }
}
```

```
Child 3565 terminated with exit status 103
Child 3564 terminated with exit status 102
Child 3563 terminated with exit status 101
Child 3562 terminated with exit status 100
Child 3566 terminated with exit status 104
```

waitpid

```
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);
    }
```

```
Child 3568 terminated with exit status 100
Child 3569 terminated with exit status 101
Child 3570 terminated with exit status 102
Child 3571 terminated with exit status 103
Child 3572 terminated with exit status 104
```

Checkpoint

`exec`: Running new programs

- `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
    - `arg0` becomes the name of the process
      - typically `arg0` is either identical to `path`, or else it contains only the executable filename from `path`
    - "real" arguments to the executable start with `arg1`, etc.
    - list of args is terminated by a `(char *)0` argument
  - returns `-1` if error, otherwise doesn't return!
- One of a family of `exec` function front-ends to `execve()`

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

Summarizing

- 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
- Spawning processes
  - Call to `fork:` one call, two returns
- Terminating processes
  - Call `exit:` one call, no return
- Reaping processes
  - Call `wait` or `waitpid`
- Replacing program executed by process
  - Call `execl` (or variant): one call, (normally) no return