CSCI2467: Systems Programming Concepts

Slideset 7: Exceptional Control Flow

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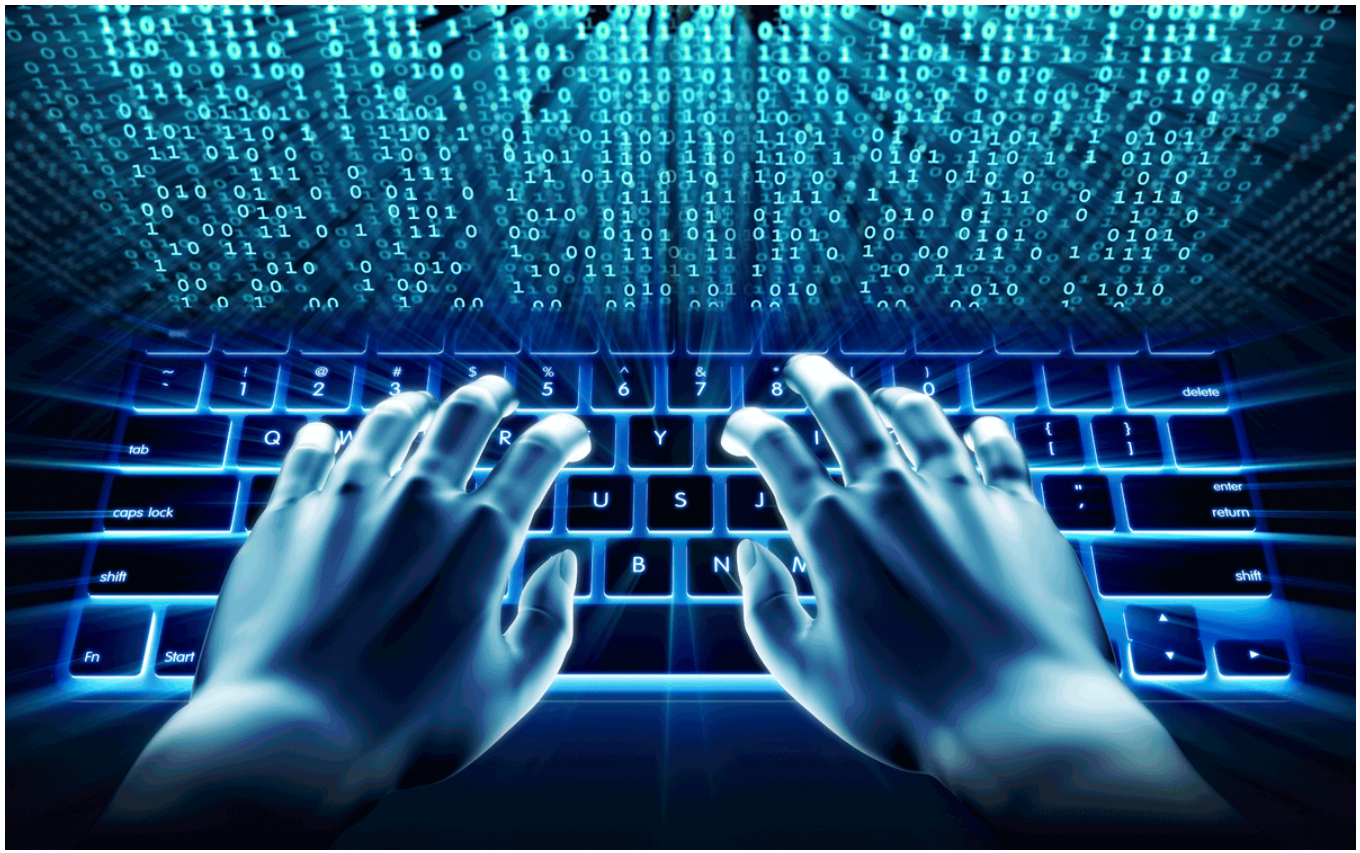
THE UNIVERSITY of NEW ORLEANS

DEPARTMENT OF COMPUTER SCIENCE

Bash script extra credit

Your (first) shell script (using bash)



Bash script extra credit

Your (first) shell script (using bash)

- Due in Autolab by 11:59pm
- Should only be a few (6-10) lines
- Don't use absolute path to `grep.tar`
  - Autolab won't have your own home directory
  - just assume grep.tar is in the current directory where the script *starts*
  - either copy it into new directory, or use `../grep.tar`
- Don't forget comments!
  - for each step
  - no points if comments omitted

Today

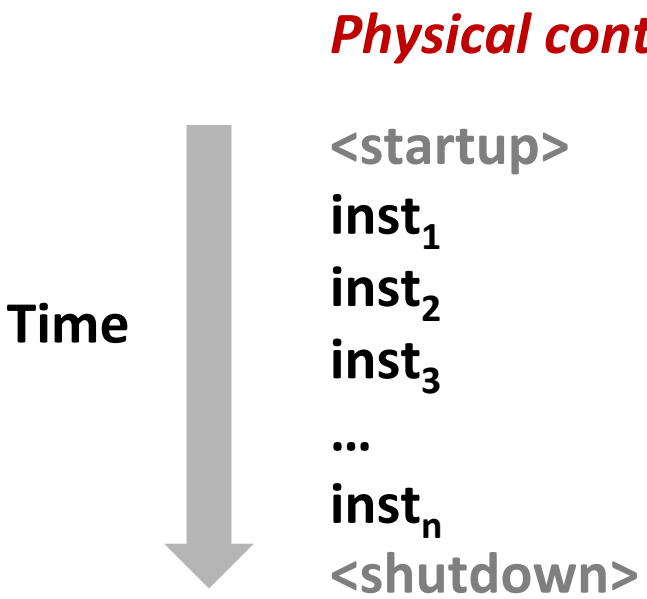
- Shell lab

1. Intro to processses
   - Control flow
   - Processes

2. Exceptional Control Flow
   - Process Control
   - Exceptions
   - Summary

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*)



Altering the Control Flow

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

  React to changes in ***program state***

Altering the Control Flow

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

  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"**

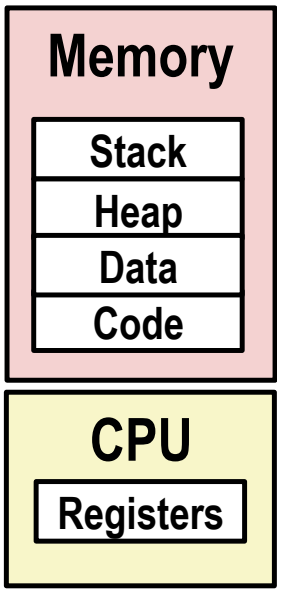
Exceptional Control Flow

- **Exists at all levels of a computer system**
- **Low level mechanisms**
  - 1. **Exceptions**
    - Change in control flow in response to a system event (i.e., change in system state)
    - Implemented using combination of hardware and OS software
- **Higher level mechanisms**
  - 2. **Process context switch**
    - Implemented by OS software and hardware timer
  - 3. **Signals**
    - Implemented by OS software
  - 4. **Nonlocal jumps**: `setjmp()` and `longjmp()`
    - Implemented by C runtime library

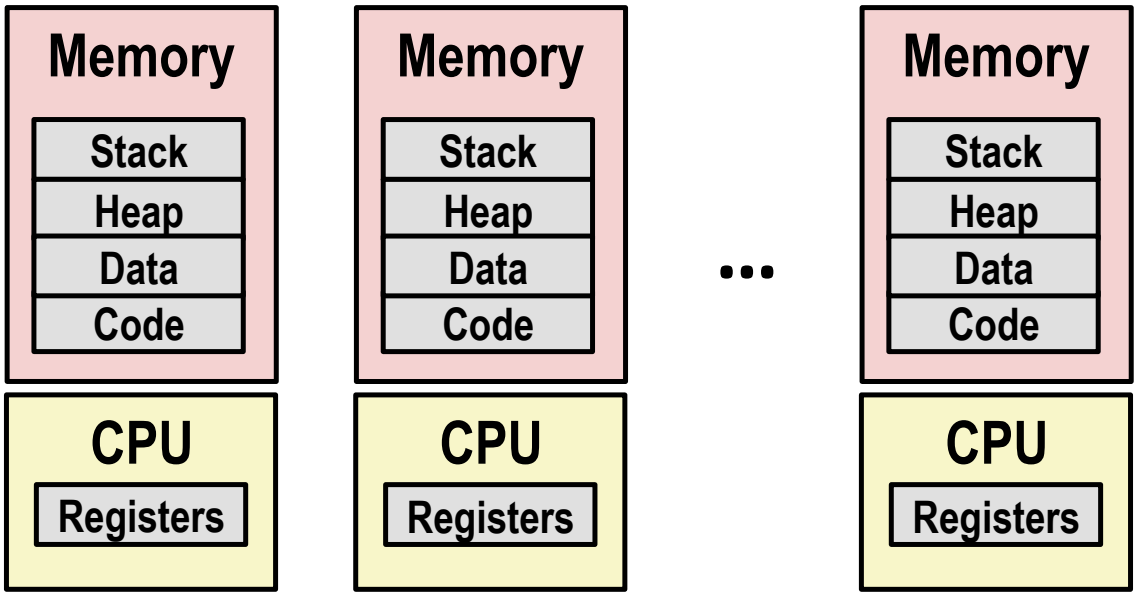
Processes

- **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
    - Provided by kernel mechanism called *context switching*
  - ***Private address space***
    - Each program seems to have exclusive use of main memory.
    - Provided by kernel mechanism called *virtual memory*



Multiprocessing: The illusion



- **Computer runs many processes simultaneously**
  - Applications for one or more users
    - Web browsers, email clients, editors, …
  - Background tasks
    - Monitoring network & I/O devices

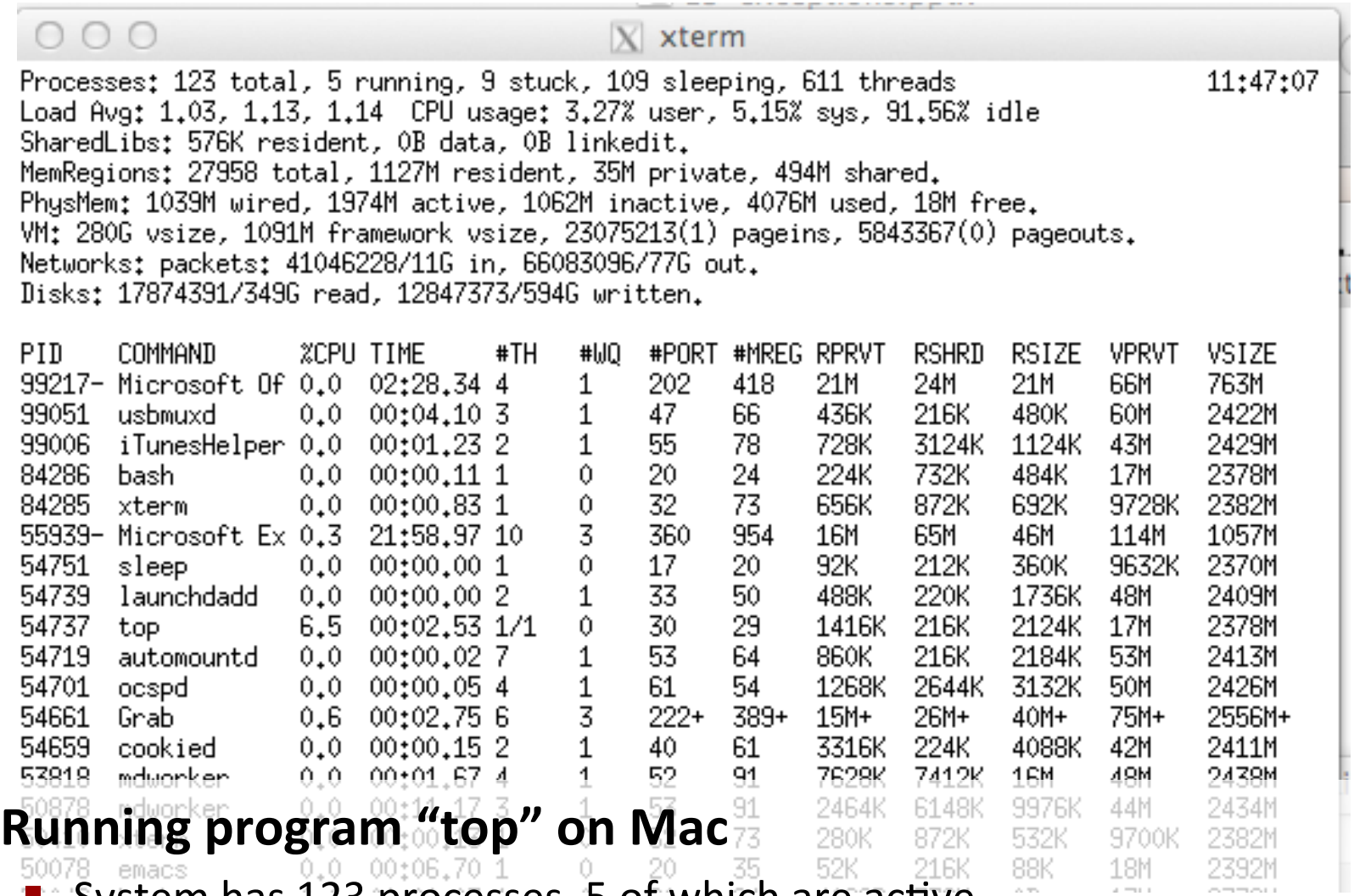
Multiprocessing example (Linux)

ps command

```
csadmin@math209:~$ ps
  PID TTY          TIME CMD
 1775 pts/0    00:00:00 bash
 5124 pts/0    00:00:00 ps
csadmin@math209:~$
```

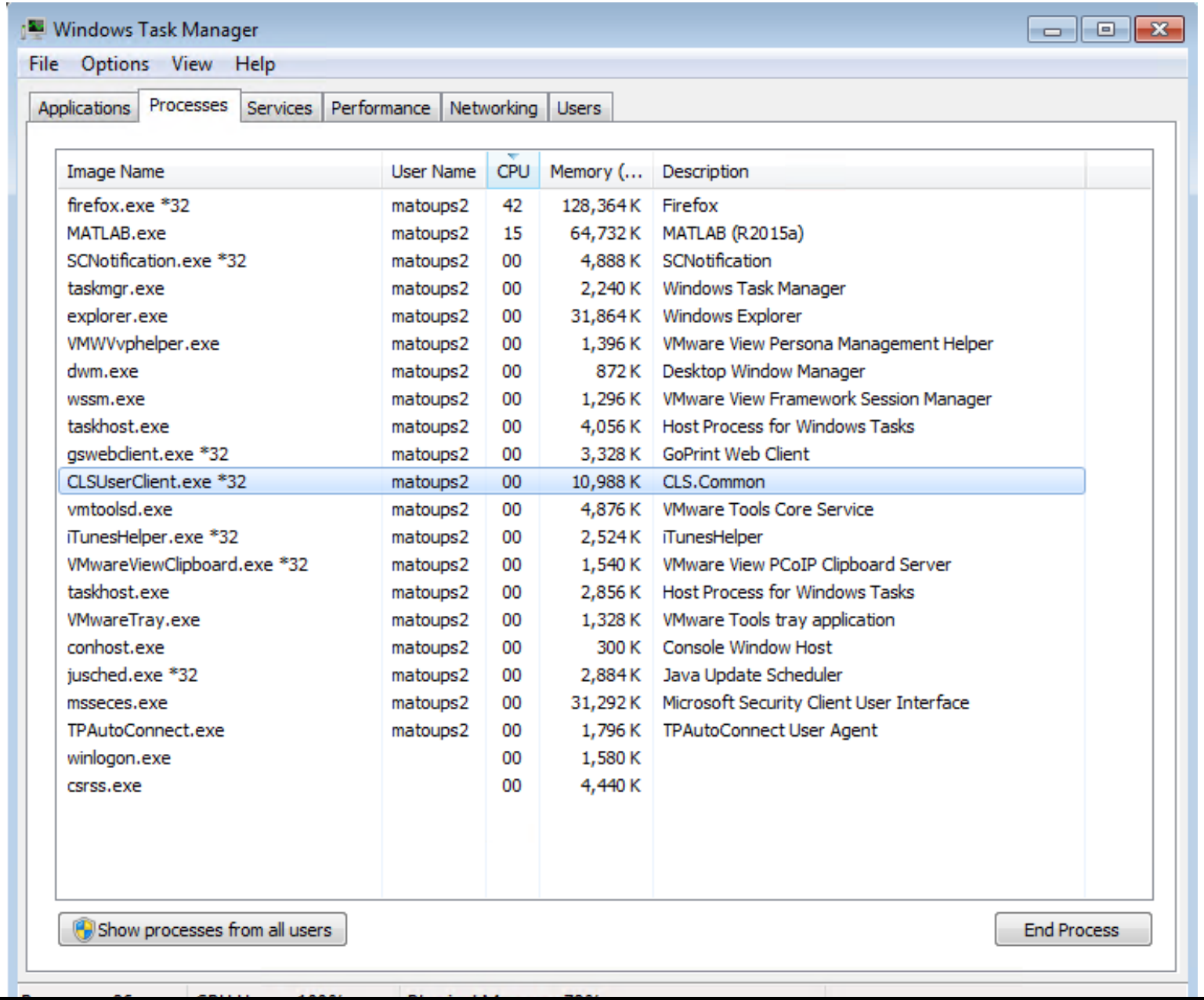
```
csadmin@math209:~/2467/shlab-handout$ ./myspin 10 &
[1] 5304
csadmin@math209:~/2467/shlab-handout$ ./myspin 20 &
[2] 5306
csadmin@math209:~/2467/shlab-handout$ ps
  PID TTY          TIME CMD
 1775 pts/0    00:00:00 bash
 5304 pts/0    00:00:00 myspin
 5306 pts/0    00:00:00 myspin
 5307 pts/0    00:00:00 ps
csadmin@math209:~/2467/shlab-handout$
```

Multiprocessing example (Mac OS)

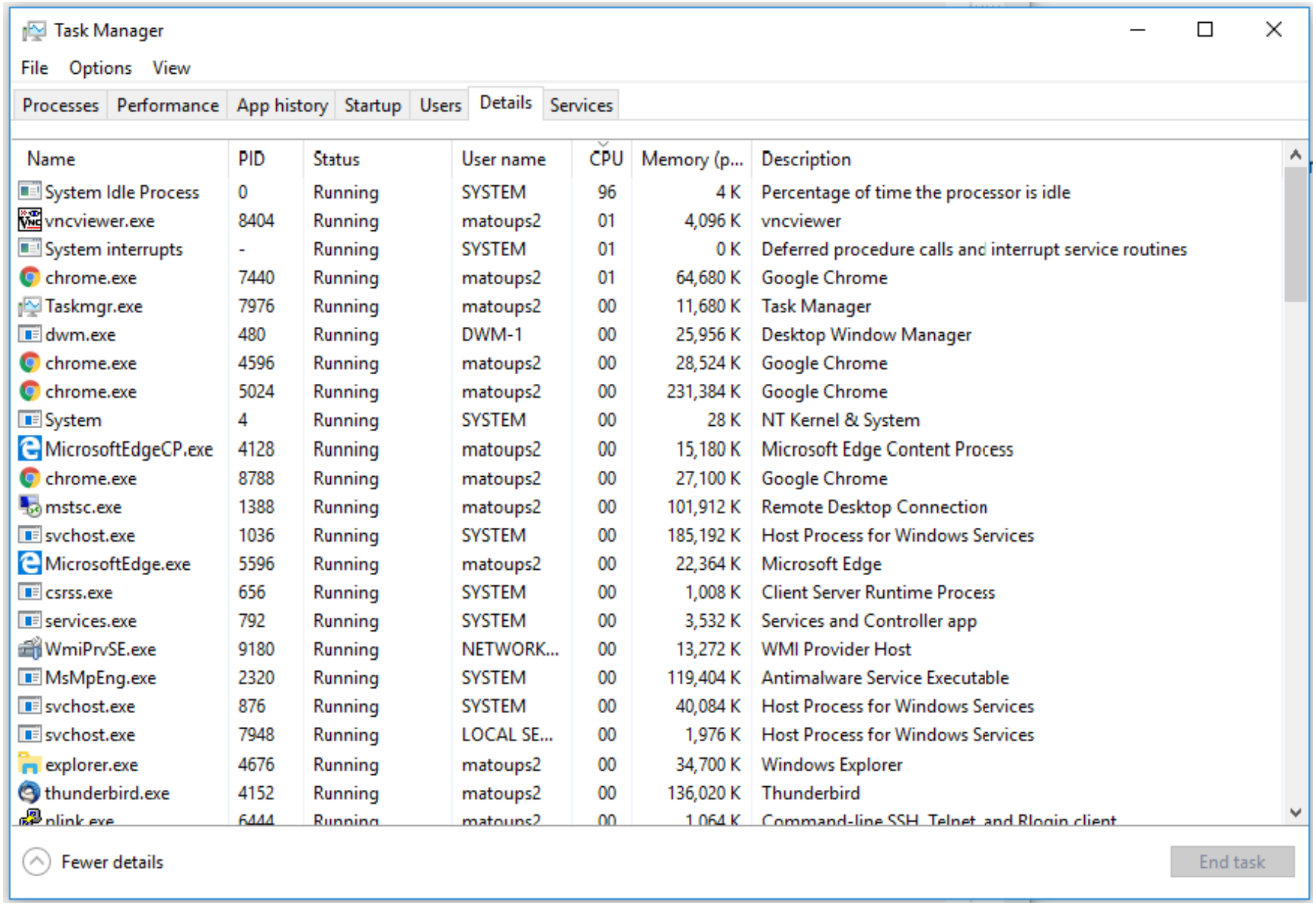


- **Running program "top" on Mac**
  - System has 123 processes, 5 of which are active
  - Identified by Process ID (PID)

Multiprocessing example (Windows 7)



Multiprocessing example (Windows 10)



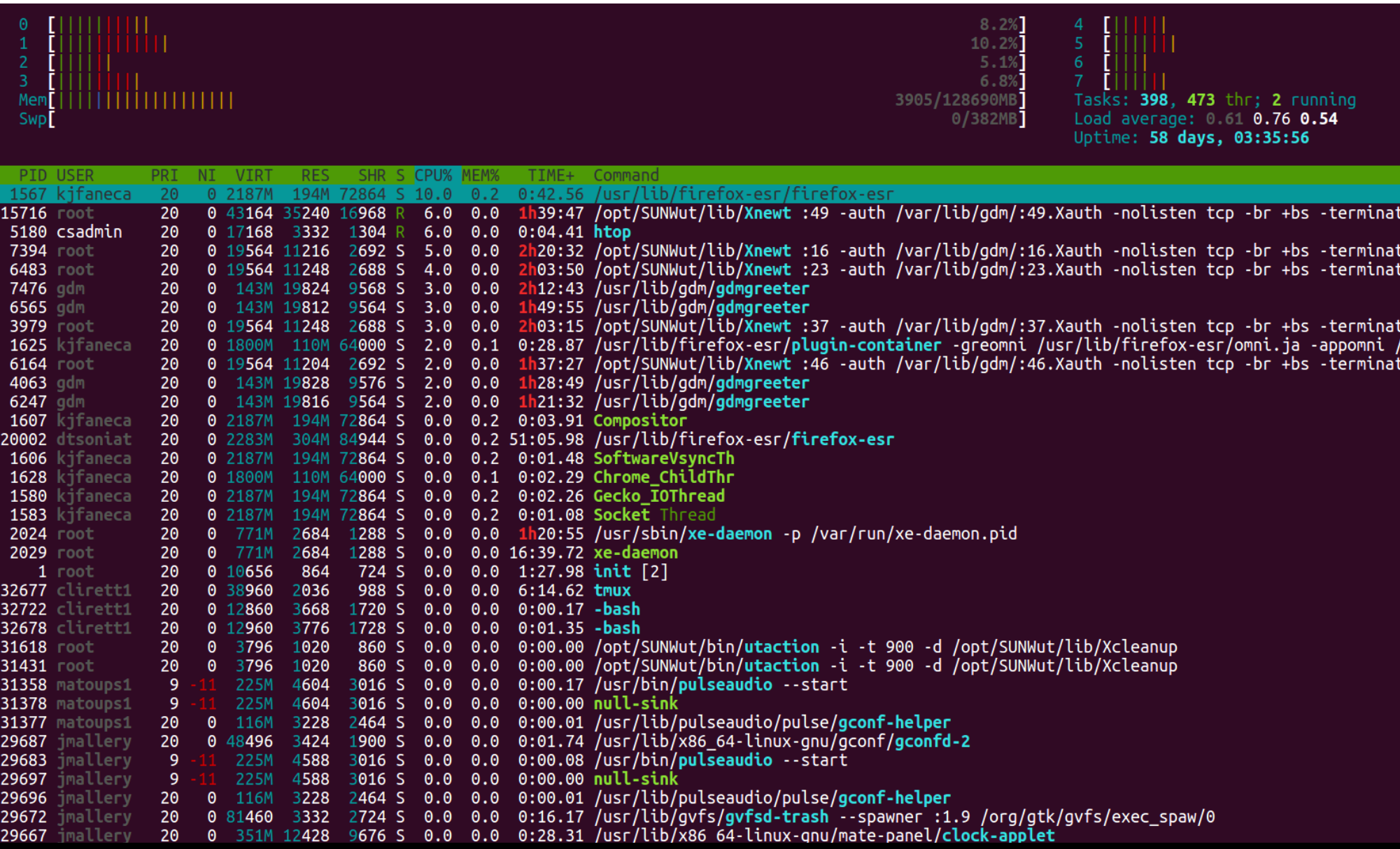
Multiprocessing example (Linux)

`ps af` command

```
  PID TTY      STAT   TIME COMMAND
32722 pts/10   Ss+    0:00 -bash
32678 pts/8    Ss+    0:01 -bash
28133 pts/4    Ss     0:00 sh -c /bin/bash
28136 pts/4    S+     0:00  \_ /bin/bash
25137 pts/5    Ss     0:00 -bash
30336 pts/5    S+     0:00  \_ /usr/bin/perl /usr/bin/dpkg-buildpackage -rfakeroot
30454 pts/5    S+     0:00      \_ /usr/bin/make -f debian/rules build
30455 pts/5    S+     0:00          \_ /usr/bin/perl -w /usr/bin/dh build --with python3 --buildsys
30459 pts/5    S+     0:00              \_ /usr/bin/perl -w /usr/bin/dh_auto_configure -O--buildsys
22407 pts/3    Ss     0:00 -bash
30468 pts/3    R+     0:00  \_ ps fa
20840 pts/1    Ss     0:00 -bash
20926 pts/1    S      0:00  \_ su - csadmin
20934 pts/1    S+     0:00      \_ -su
17962 pts/2    Ss+    0:00 -bash
 9922 pts/9    Ss     0:00 sh -c /bin/bash
 9926 pts/9    S+     0:00  \_ /bin/bash
 1129 pts/48   Ss     0:00 sh -c /bin/bash
 1132 pts/48   S+     0:00  \_ /bin/bash
25684 pts/5    S      0:00 sh -c ./sdriver.pl -t trace01.txt -s ./tsh -a '-p'
25685 pts/5    S      0:00  \_ /usr/bin/perl ./sdriver.pl -t trace01.txt -s ./tsh -a -p
25686 pts/5    S      0:00      \_ ./tsh -p
 3481 tty6     Ss+    0:00 /sbin/getty 38400 tty6
 3480 tty5     Ss+    0:00 /sbin/getty 38400 tty5
 3479 tty4     Ss+    0:00 /sbin/getty 38400 tty4
 3478 tty3     Ss+    0:00 /sbin/getty 38400 tty3
 3477 tty2     Ss+    0:00 /sbin/getty 38400 tty2
```

Multiprocessing example (Linux)

`htop` command

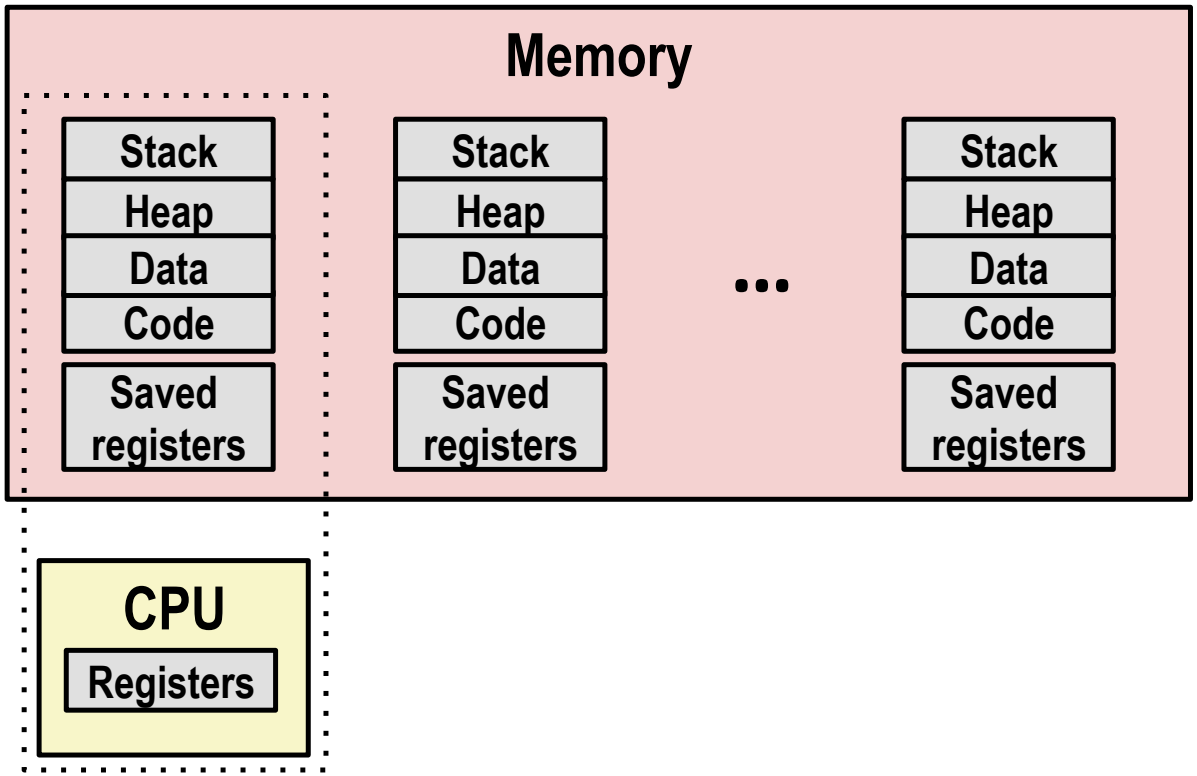


Multiprocessing example (Linux)

`glances` command

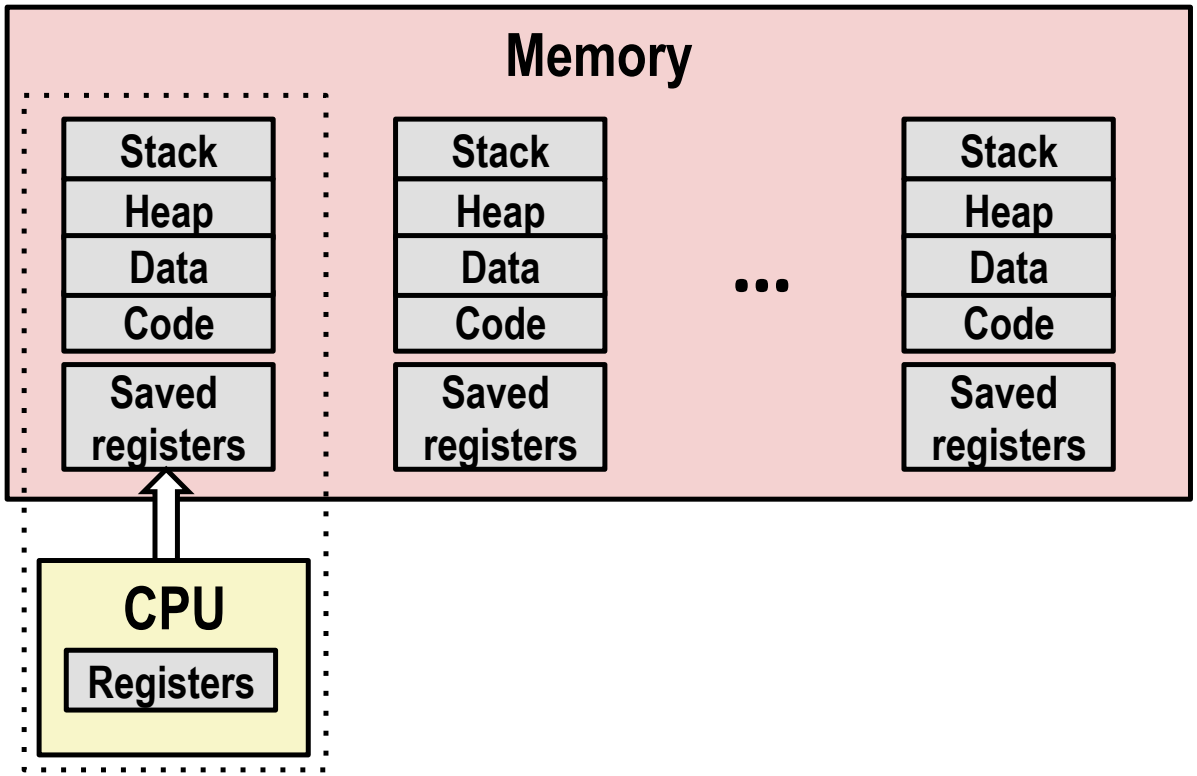
```
TASKS 259 (936 thr), 1 run, 258 slp, 0 oth sorted automatically by cpu_percent, tree view

  CPU%  MEM%  VIRT   RES   PID USER        NI S    TIME+ IOR/s IOW/s Command
   0.0   0.0  181M 5.06M     1 root         0 S  3:34.32     0     0 /sbin/init splash
   0.0   0.0  342M 3.90M  1222 root         0 S  0:02.93     0     0 ├─ /usr/sbin/lightdm
   0.0   0.0  225M 5.69M  1636 root         0 S  0:00.59     0     0 │  ├─ lightdm --session-child 12 19
   0.0   0.0 45.4M 3.14M  1992 mtoups       0 S  0:10.69     0     0 │  │  └─ /sbin/upstart --user
   0.0   5.1 3.62G  811M 18749 mtoups       0 S 58:49.58     0     0 │  │     ├─ /usr/lib/firefox/firefox -private
  10.9   4.7 3.07G  743M 11153 mtoups       0 S 11:58.84     0     0 │  │     │  ├─ /usr/lib/firefox/firefox -cont
   5.3  11.8 16.0G 1.84G 10769 mtoups       0 S 15:37.80     0     0 │  │     │  ├─ /usr/lib/firefox/firefox -cont
   0.3   3.0 2.86G  471M 18813 mtoups       0 S 21:40.65     0     0 │  │     │  ├─ /usr/lib/firefox/firefox -cont
   0.0   3.7 2.79G  595M 11186 mtoups       0 S 32:42.62     0     0 │  │     │  ├─ /usr/lib/firefox/firefox -cont
   0.0   0.6 1.84G 88.1M  5698 mtoups       0 S  1:47.94     0     0 │  │     │  └─ /usr/lib/firefox/firefox -cont
  12.5   4.9 3.65G  783M  3056 mtoups       0 S 18:46.47     0     0 │  │     ├─ compiz
   2.8   0.5  732M 81.3M  7687 mtoups       0 S  1:39.29     0     0 │  │     ├─ /usr/lib/gnome-terminal/gnome-ter
   0.0   0.0 23.1M 6.00M  2303 mtoups       0 S  0:00.40     0     0 │  │     │  ├─ bash
   6.2   0.2 93.2M 29.9M  4096 mtoups       0 R  1:04.82     0     0 │  │     │  │  └─ /usr/bin/python3 /usr/bin/g
   0.0   0.0 23.0M 6.12M   947 mtoups       0 S  0:00.21     0     0 │  │     │  ├─ bash
   0.3   0.0 47.9M 5.09M  2158 mtoups       0 S  0:00.12     0     0 │  │     │  │  └─ ssh csadmin@math209.cs.uno.
   0.0   0.0 22.9M 5.97M 27951 mtoups       0 S  0:00.60     0     0 │  │     │  ├─ bash
   0.0   0.2  192M 26.3M 27974 mtoups       0 S  0:00.75     0     0 │  │     │  │  └─ vim FAIL
   0.0   0.0 24.0M 7.07M 28066 mtoups       0 S  0:01.98     0     0 │  │     │  ├─ bash
   0.0   0.0 22.9M 5.98M 30713 mtoups       0 S  0:01.84     0     0 │  │     │  ├─ bash
   0.0   0.0 48.0M 5.80M 18229 mtoups       0 S  0:00.17     0     0 │  │     │  │  └─ ssh csadmin@autolab.cs.uno.
   0.0   0.0 22.6M 2.07M  9877 mtoups       0 S  0:00.36     0     0 │  │     │  ├─ bash
   0.0   0.0 23.4M 5.57M 21113 mtoups       0 S  0:01.22     0     0 │  │     │  ├─ bash
   0.0   0.0 23.4M 5.33M 20982 mtoups       0 S  0:00.85     0     0 │  │     │  ├─ bash
   0.0   0.0 22.5M 3.56M 26694 mtoups       0 S  0:00.30     0     0 │  │     │  ├─ bash
   0.0   0.0 22.9M 6.02M 24970 mtoups       0 S  0:00.80     0     0 │  │     │  ├─ bash
   0.0   0.2  192M 27.4M 28683 mtoups       0 S  0:00.78     0     0 │  │     │  │  └─ vim README.md
   0.0   0.0 22.9M 6.00M 16403 mtoups       0 S  0:00.25     0     0 │  │     │  ├─ bash
   0.0   0.0 23.0M 5.86M 15823 mtoups       0 S  0:00.40     0     0 │  │     │  ├─ bash
   0.0   0.0 22.9M 6.02M 28625 mtoups       0 S  0:00.90     0     0 │  │     │  ├─ bash
   0.0   0.0 23.0M 6.00M 12036 mtoups       0 S  0:00.15     0     0 │  │     │  ├─ bash
   0.0   0.7 1.26G  115M  2080 mtoups       0 S  0:12.25     0     0 │  │     │  │  └─ evince 07ecf.pdf
```

Multiprocessing: The (traditional) reality



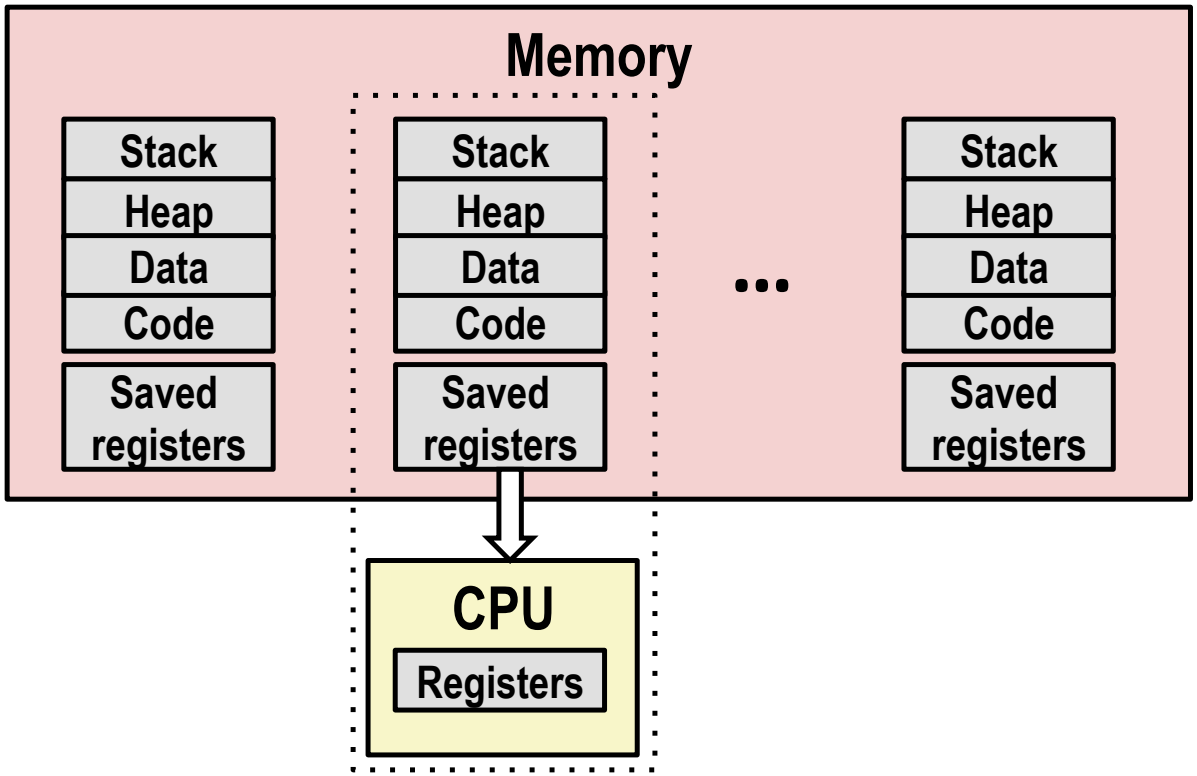
- **Single processor executes multiple processes concurrently**
  - Process executions interleaved (multitasking)
  - Address spaces managed by virtual memory system (later in course)
  - Register values for nonexecuting processes saved in memory

Multiprocessing: The (traditional) reality



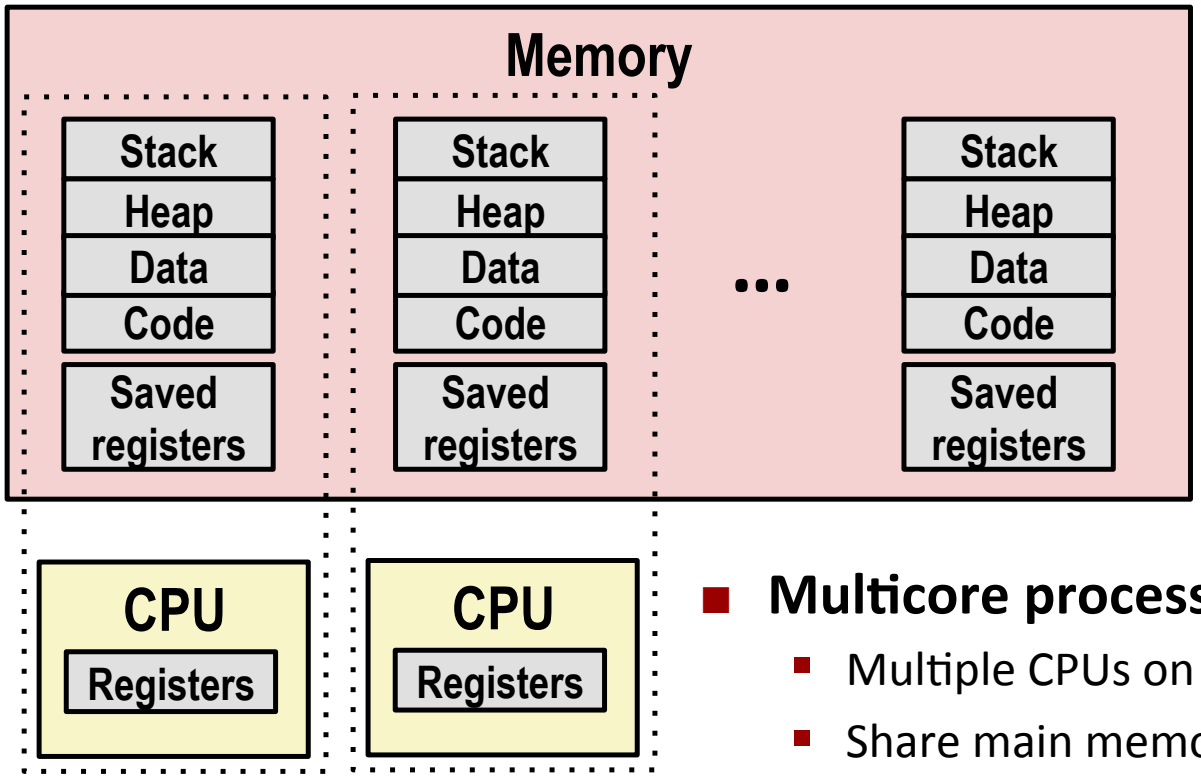
- **Save current registers in memory**

Multiprocessing: The (traditional) reality



- **Load saved registers and switch address space (context switch)**

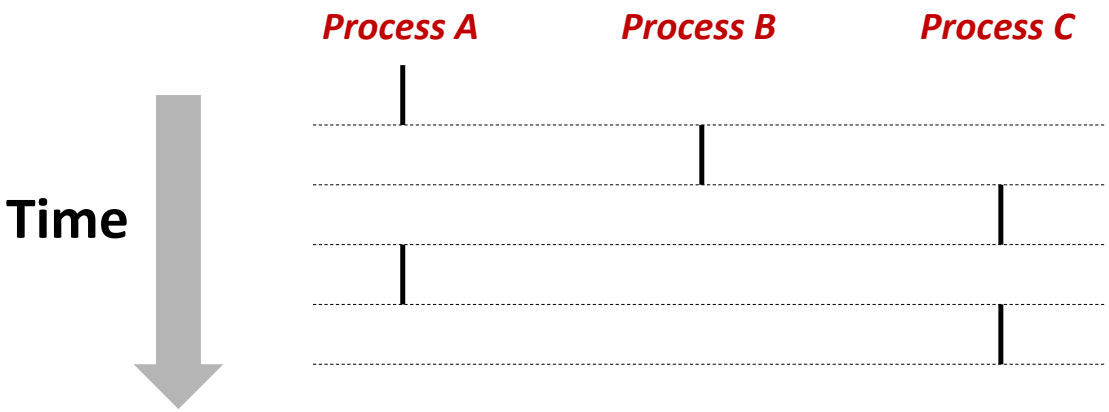
Multiprocessing: The (modern) reality



- **Multicore processors**
  - Multiple CPUs on single chip
  - Share main memory (and some of the caches)
  - Each can execute a separate process
    - Scheduling of processors onto cores done by kernel

Concurrent processes

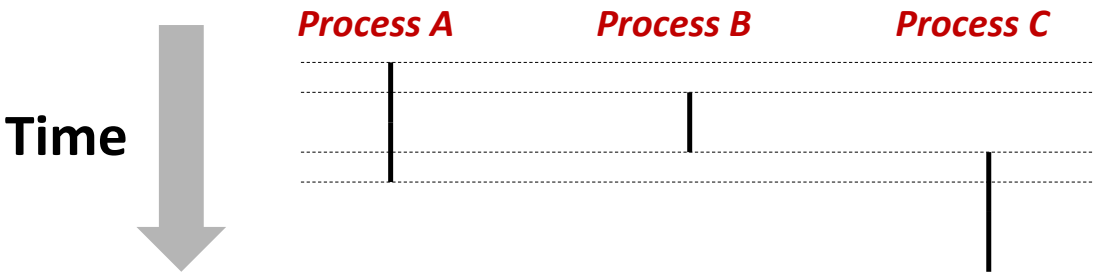
- **Each process is a logical control flow.**
- **Two processes *run concurrently* (*are concurrent)* if their flows overlap in time**
- **Otherwise, they are *sequential***
- **Examples (running on single core):**
  - Concurrent: A & B, A & C
  - Sequential: B & C



Concurrent processes

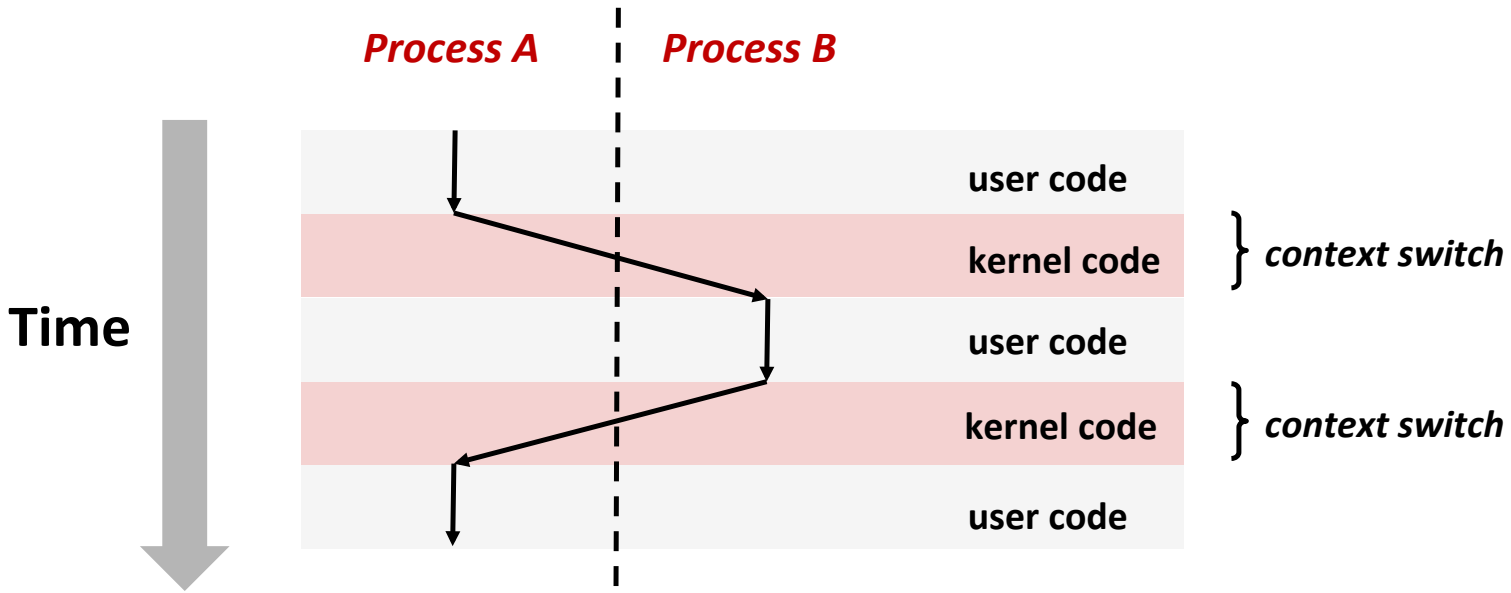
- **Control flows for concurrent processes are physically disjoint in time**

- **However, we can think of concurrent processes as running in parallel with each other**



Context switching

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



Today

- Shell lab

1. Intro to processses
   - Control flow
   - Processes

2. Exceptional Control Flow
   - Process Control
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Obtaining process IDs

- **`pid_t getpid(void)`**
  - Returns PID of current process
- **`pid_t getppid(void)`**
  - Returns PID of parent process

Example from lab activity
(starting point)

```c
#include <sys/types.h>
#include <unistd.h>
#include <stdio.h>

void main()
{
        pid_t mypid;
        /* pid_t is defined as int (32-bit signed) */

        mypid = getpid();

        printf(" my PID is: %d\n", mypid);

}
```

Creating and terminating processes

From a programmer's perspective, we can think of a process as being in one of three states

- **Running**
  - Process is either executing, or waiting to be executed and will eventually be *scheduled* (i.e., chosen to execute) by the kernel
- **Stopped**
  - Process execution is *suspended* and will not be scheduled until further notice (next lecture when we study signals)
- **Terminated**
  - Process is stopped permanently

Terminating processes

- **Process becomes terminated for one of three reasons:**
  - Receiving a signal whose default action is to terminate (next lecture)
  - Returning from the `main` routine
  - Calling the `exit` function

- **`void exit(int status)`**
  - Terminates with an *exit status* of `status`
  - Convention: normal return status is 0, nonzero on error
  - Another way to explicitly set the exit status is to return an integer value from the main routine

- **`exit` is called once but never returns.**

Example of exit()

You can run this program on systems-lab:

```
$ /home/CSCI2467/labs/misc/ch08/exit
$ /home/CSCI2467/labs/misc/ch08/exit 4
```

```c
int main(int argc, char** argv)
{
    int value;

    if (argc<2) { exit(7); }
    /* atoi converts char to int */
    value = atoi(argv[1]);

    printf(" value is %d\n", value);
    return value+1;
}
```

Notes:

- argc is **c**ount of arguments
- argv is **v**ector of arguments (array of strings)
- atoi() converts characters to int

Creating processes
The indispensable `fork()`

- ***Parent process*** **creates a new running** ***child process*** **by calling `fork`**

Creating processes
The indispensable `fork()`

- ***Parent process* creates a new running *child process* by calling `fork`**

- **`int fork(void)`**
  - Returns 0 to the child process, child's PID to parent process
  - Child is *almost* identical to parent:
    - Child get an identical (but separate) copy of the parent's virtual address space.
    - Child gets identical copies of the parent's open file descriptors
    - Child has a different PID than the parent

Creating processes
The indispensable `fork()`

- ***Parent process* creates a new running *child process* by calling `fork`**

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  - Child is *almost* identical to parent:
    - Child get an identical (but separate) copy of the parent's virtual address space.
    - Child gets identical copies of the parent's open file descriptors
    - Child has a different PID than the parent

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

Example from lab activity
(one line added)

```
void main()
{
        pid_t mypid;

        fork(); /* this line: crucial difference */
        mypid = getpid();

        printf(" my PID is: %d\n", mypid);
}
```

A more practical `fork()` use

- What's the point of doing this?

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- Crucial observation: `fork()` has two *distinct* return values

A more practical `fork()` use

- What's the point of doing this?
- Program does twice as much stuff
- But we want to be able to create a child process that can do more than just duplicate the parent
- Crucial observation: `fork()` has two *distinct* return values
- Solution: we can use an `if( )` statement in order to have the parent and child do different things

Example from lab activity

```
void main()
{
  int mypid,forkresult;

  printf("program starts, pid is: %d\n", getpid());

  forkresult = fork();

  mypid = getpid();

  if (forkresult == 0) {
    printf("ZERO fork returned %d, my PID is: %d\n",
        forkresult, mypid);
  } else {
    printf("NONZERO fork returned %d, my PID is: %d\n"
        , forkresult, mypid);
  }
}
```

Running the fork example

When you ran this in class, your got a unique PID (each time)

```
program starts, pid is: 8805
NONZERO fork returned 8806, my PID is: 8805
ZERO fork returned 0, my PID is: 8806
```

`fork()` is essential!

- This is not an obscure detail
- This is what makes a multi-process system possible!
- All processes begin with `fork()`

  (called by `init`, `bash`, `sshd`, `firefox`, etc)

  ... also crucial to Shell Lab

fork example

See similar code on systems-lab: `/home/CSCI2467/labs/misc/forks.c`

```c
int main()
{
    pid_t pid;
    int x = 1;

    pid = Fork();
    if (pid == 0) {  /* Child */
        printf("child : x=%d\n", ++x);
        exit(0);
    }

    /* Parent */
    printf("parent: x=%d\n", --x);
    exit(0);
}
```

fork.c

```
linux> ./fork
parent: x=0
child : x=2
```

- **Call once, return twice**
- **Concurrent execution**
  - **Can't predict execution order of parent and child**
- **Duplicate but separate address space**
  - **`x` has a value of 1 when fork returns in parent and child**
  - **Subsequent changes to `x` are independent**
- **Shared open files**
  - **`stdout` is the same in both parent and child**

Modeling `fork` with process graphs

- **A *process graph* is a useful tool for capturing the partial ordering of statements in a concurrent program:**
  - Each vertex is the execution of a statement
  - a -> b means `a` happens before b
  - Edges can be labeled with current value of variables
  - `printf` vertices can be labeled with output
  - Each graph begins with a vertex with no inedges
- **Any *topological sort* of the graph corresponds to a feasible total ordering.**
  - Total ordering of vertices where all edges point from left to right

Process graph example

```c
int main()
{
    pid_t pid;
    int x = 1;

    pid = Fork();
    if (pid == 0) {  /* Child */
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    /* Parent */
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    exit(0);
}
```
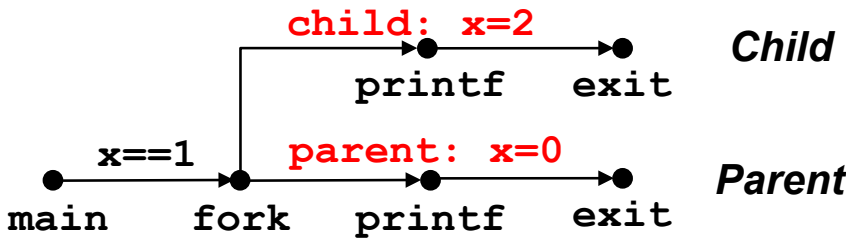
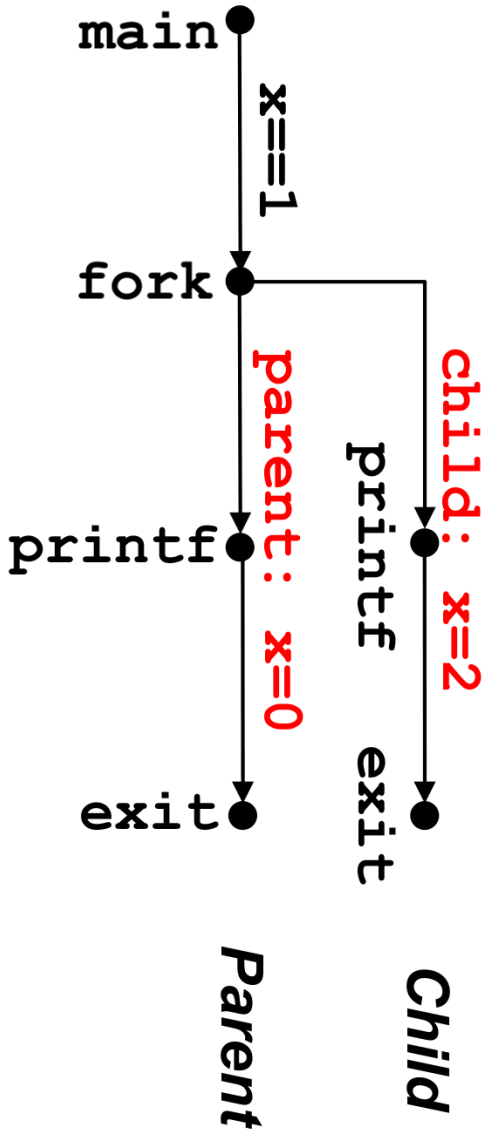

fork.c



Process graph example (rotated)

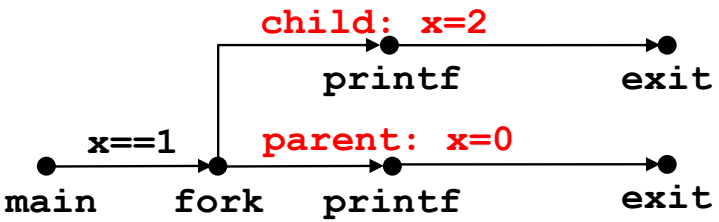
```c
int main()
{
    pid_t pid;
    int x = 1;

    pid = Fork();
    if (pid == 0) {  /* Child */
        printf("child : x=%d\n", ++x);
        exit(0);
    }

    /* Parent */
    printf("parent: x=%d\n", --x);
    exit(0);
}
```

fork.c

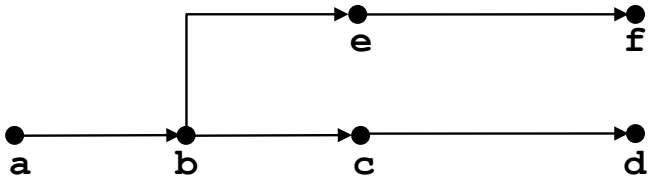


Interpreting process graphs

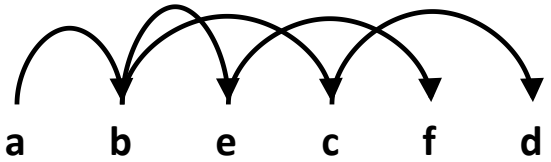
- **Original graph:**



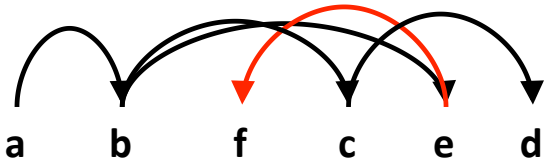
- **Relabled graph:**



Feasible total ordering:

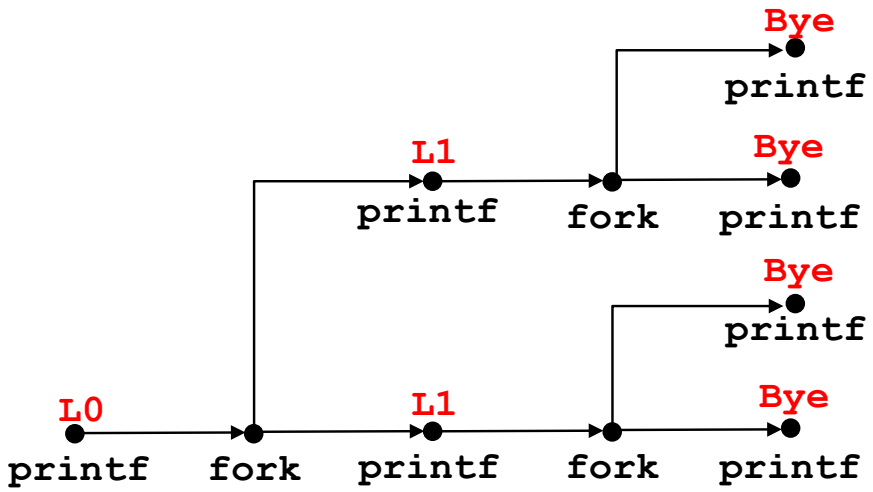


Infeasible total ordering:



fork() example: two consecutive fork()s

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



Feasible output:

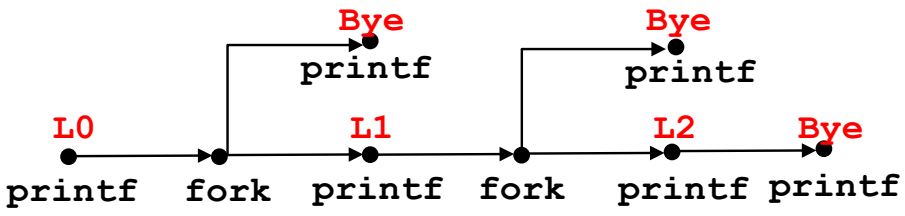
L0
L1
Bye
Bye
L1
Bye
Bye

Infeasible output:

L0
Bye
L1
Bye
L1
Bye
Bye

fork() example: nested fork()s in parent

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



Feasible output:

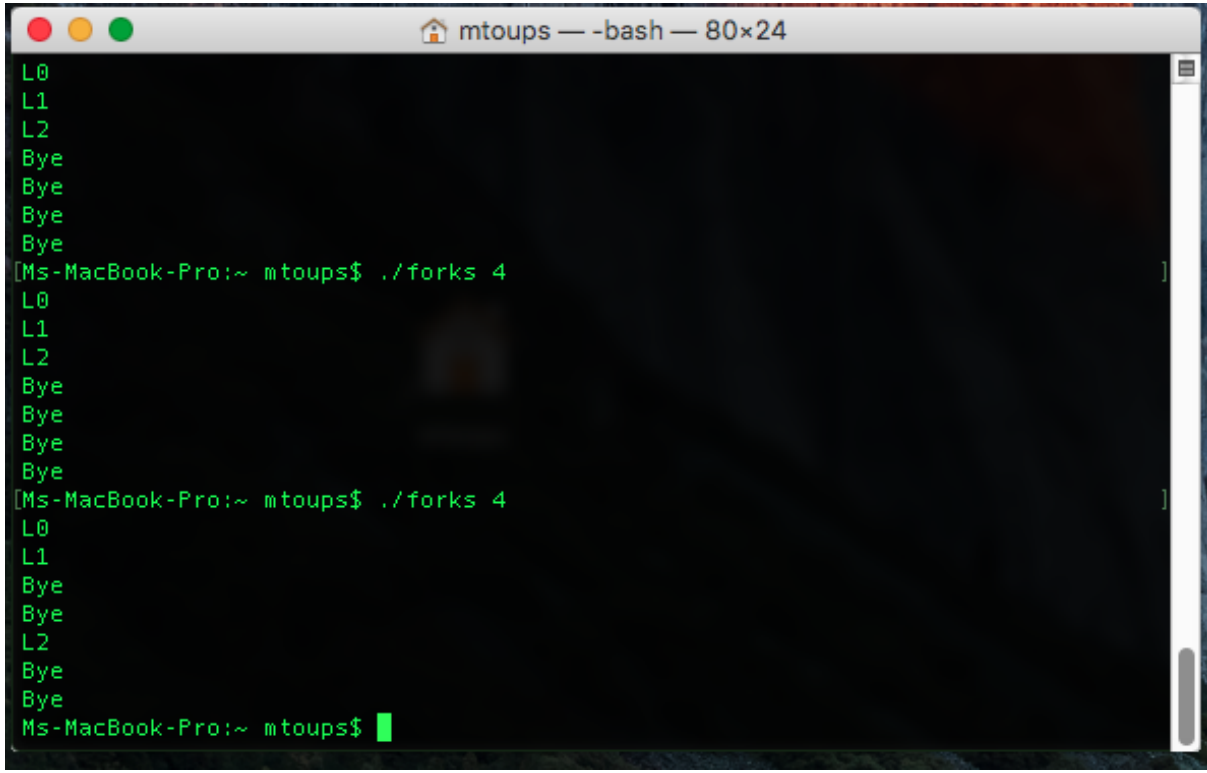
L0
L1
Bye
Bye
L2
Bye

Infeasible output:

L0
Bye
L1
Bye
Bye
L2

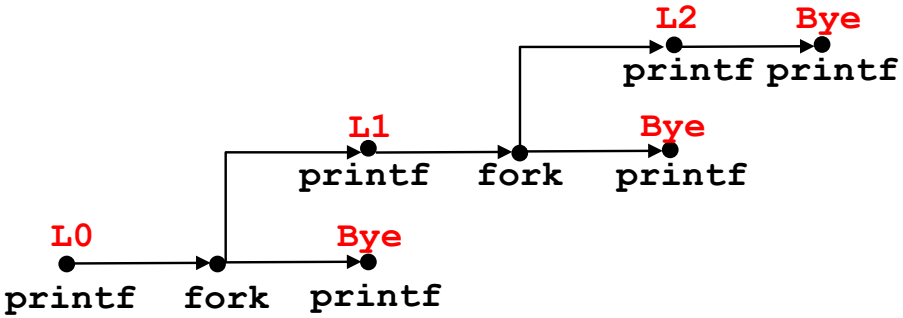
`fork()` example: `./forks 4` has multiple feasible orderings

```
mtoups@x1ubuntu:/tmp$ ./forks 4
L0
L1
L2
Bye
Bye
Bye
Bye
mtoups@x1ubuntu:/tmp$ ./forks 4
L0
L1
Bye
L2
Bye
Bye
Bye
mtoups@x1ubuntu:/tmp$
```



fork() example: nested fork()s in children

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



Feasible output:

L0
Bye
L1
L2
Bye
Bye

Infeasible output:

L0
Bye
L1
Bye
Bye
L2

Reaping child processes

- **Idea**
  - When process terminates, it still consumes system resources
    - Examples: Exit status, various OS tables
  - 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 then deletes zombie child process
- **What if parent doesn’t reap?**
  - If any parent terminates without reaping a child, then the orphaned 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 */
    }
}
```

forks.c

```
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" (i.e., a zombie)
- Killing parent allows child to be reaped by **init**

Non-terminating Child Example

```c
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);
    }
}
```

forks.c

```
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 child explicitly, or else will keep running indefinitely

`wait()`: synchronizing with children

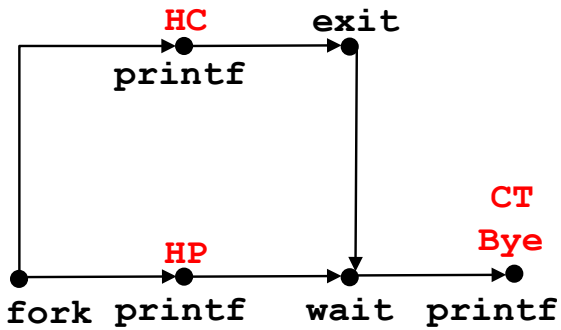
- **Parent reaps a child by calling the `wait` function**

- **`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 integer it points to will be set to a value that indicates reason the child terminated and the exit status:
    - Checked using macros defined in `wait.h`
      - `WIFEXITED, WEXITSTATUS, WIFSIGNALED, WTERMSIG, WIFSTOPPED, WSTOPSIG, WIFCONTINUED`
      - See textbook for details

wait(): synchronizing with children

```c
void fork9() {
    int child_status;

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

forks.c



Feasible output:

HC
HP
CT
Bye

Infeasible output:

HP
CT
Bye
HC

Another `wait()` example

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

```c
void fork10() {
    pid_t pid[N];
    int i, child_status;

    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0) {
            exit(100+i); /* Child */
        }
    for (i = 0; i < N; i++) { /* Parent */
        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);
    }
}
```

forks.c

waitpid(): waiting for a specific process

- **pid_t waitpid(pid_t pid, int &status, int options)**
  - Suspends current process until specific process terminates
  - Various options (see textbook)

```c
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 terminate abnormally\n", wpid);
    }
}
```

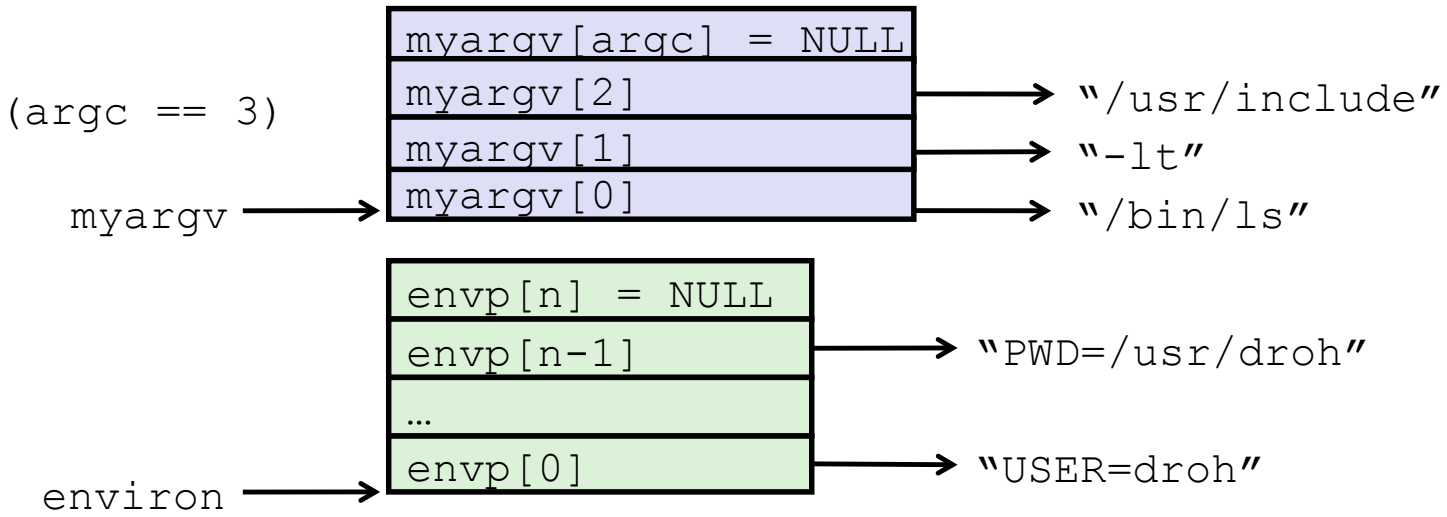
forks.c

execve(): loading and running programs

- **`int execve(char *filename, char *argv[], char *envp[])`**
- **Loads and runs in the current process:**
  - Executable file **`filename`**
    - Can be object file or script file beginning with `#!interpreter` (e.g., `#!/bin/bash`)
  - …with argument list **`argv`**
    - By convention **`argv[0]==filename`**
  - …and environment variable list **`envp`**
    - "name=value" strings (e.g., `USER=droh`)
    - `getenv, putenv, printenv`
- **Overwrites code, data, and stack**
  - Retains PID, open files and signal context
- **Called once and never returns**
  - …except if there is an error

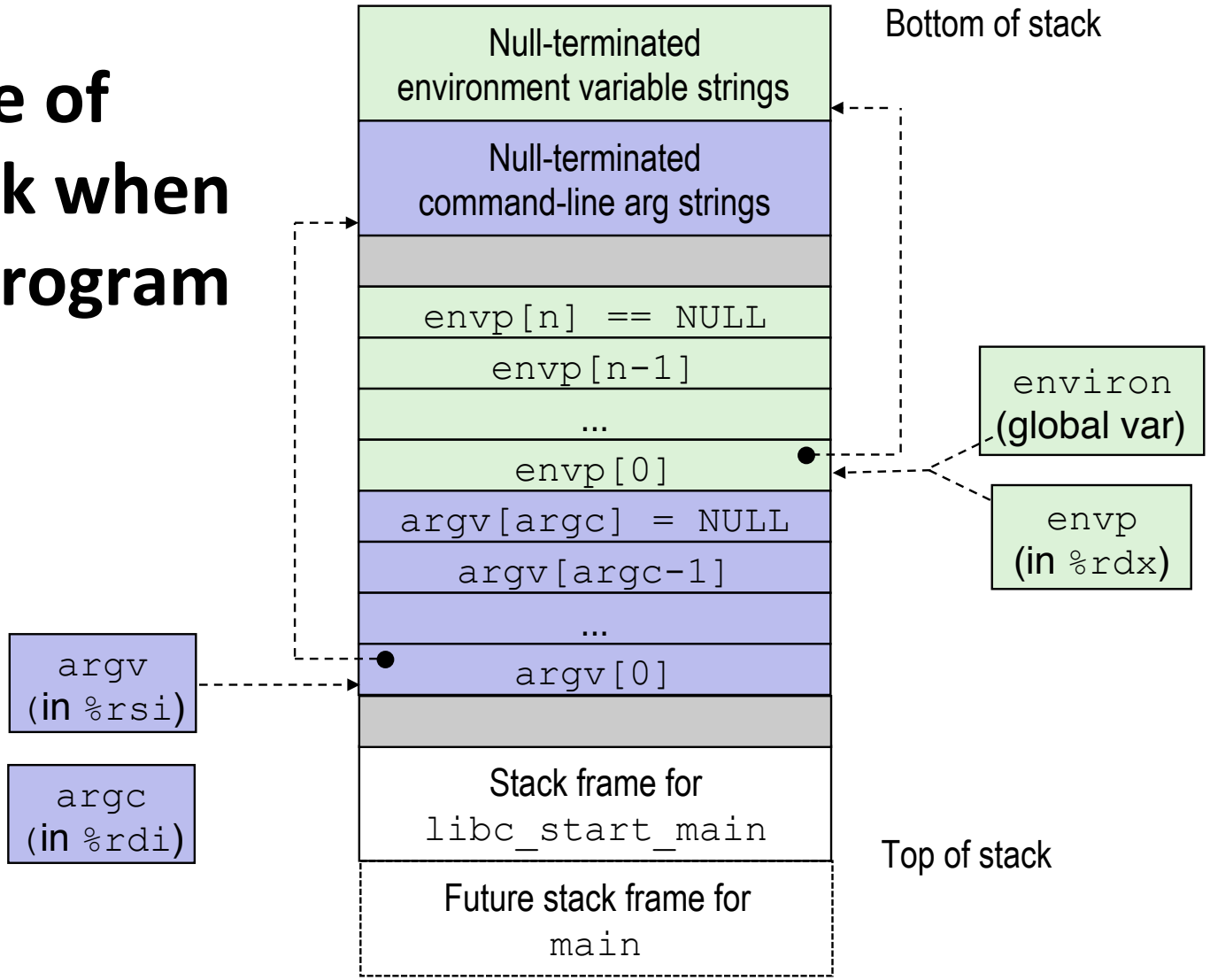
execve() example

- **Executes** "/bin/ls -lt /usr/include" **in child process using current environment:**




```
if ((pid = Fork()) == 0) {   /* Child runs program */
    if (execve(myargv[0], myargv, environ) < 0) {
        printf("%s: Command not found.\n", myargv[0]);
        exit(1);
    }
}
```

Structure of the stack when a new program starts



System call error handling

- **On error, Linux system-level functions typically return -1 and set global variable `errno` to indicate cause.**
- **Hard and fast rule:**
  - You must check the return status of every system-level function
  - Only exception is the handful of functions that return `void`
- **Example:**

```
if ((pid = fork()) < 0) {
    fprintf(stderr, "fork error: %s\n", strerror(errno));
    exit(0);
}
```

Error-reporting functions

- **Can simplify somewhat using an *error-reporting function*:**

```
void unix_error(char *msg) /* Unix-style error */
{
    fprintf(stderr, "%s: %s\n", msg, strerror(errno));
    exit(0);
}
```

```
 if ((pid = fork()) < 0)
    unix_error("fork error");
```

Error-handling wrapper functions

Info on the textbook's shorthand

- **We simplify the code we present to you even further by using Stevens-style error-handling wrappers:**

```
pid_t Fork(void)
{
    pid_t pid;

    if ((pid = fork()) < 0)
        unix_error("Fork error");
    return pid;
}
```

```
pid = Fork();
```

System Calls

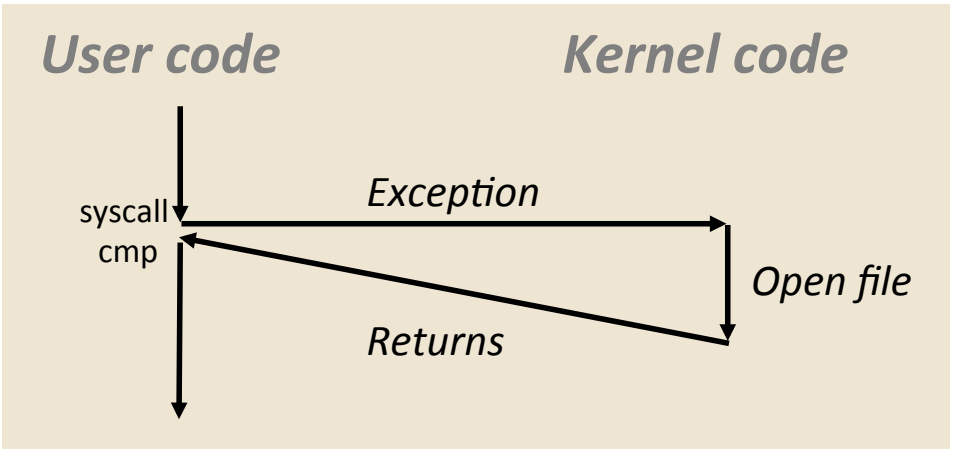
- **Each x86-64 system call has a unique ID number**
- **Examples:**

Number	*Name*	*Description*
0	`read`	Read file
1	`write`	Write file
2	`open`	Open file
3	`close`	Close file
4	`stat`	Get info about file
57	`fork`	Create process
59	`execve`	Execute a program
60	`_exit`	Terminate process
62	`kill`	Send signal to process

System Call example: opening file

- User calls: **`open(filename, options)`**
- Calls **`__open`** function, which invokes system call instruction **`syscall`**

```
0000000000e5d70 <__open>:
...
e5d79:   b8 02 00 00 00      mov  $0x2,%eax  # open is syscall #2
e5d7e:   0f 05               syscall         # Return value in %rax
e5d80:   48 3d 01 f0 ff ff   cmp  $0xfffffffffffff001,%rax
...
e5dfa:   c3                  retq
```



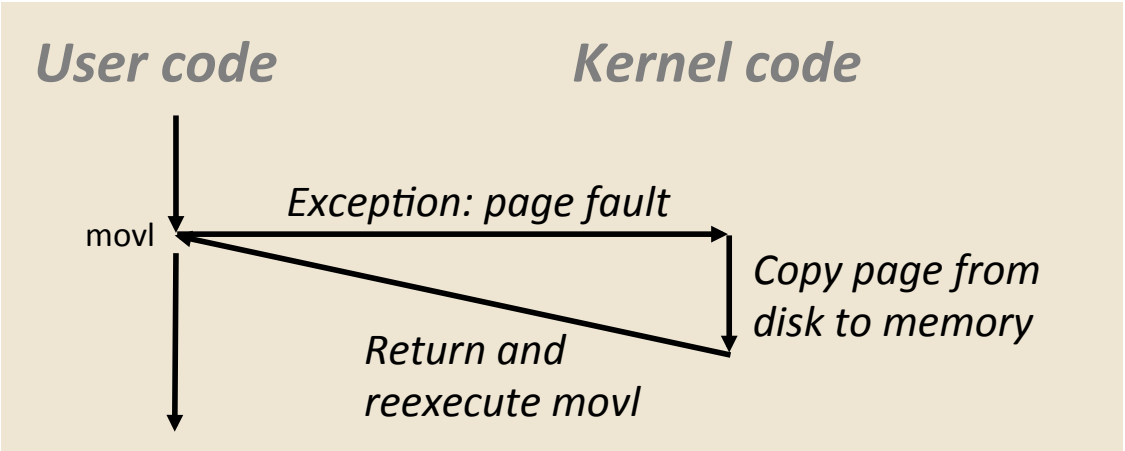
- `%rax` contains syscall number
- Other arguments in `%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9`
- Return value in `%rax`
- Negative value is an error corresponding to negative `errno`

Fault example (recoverable): 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;
}
```

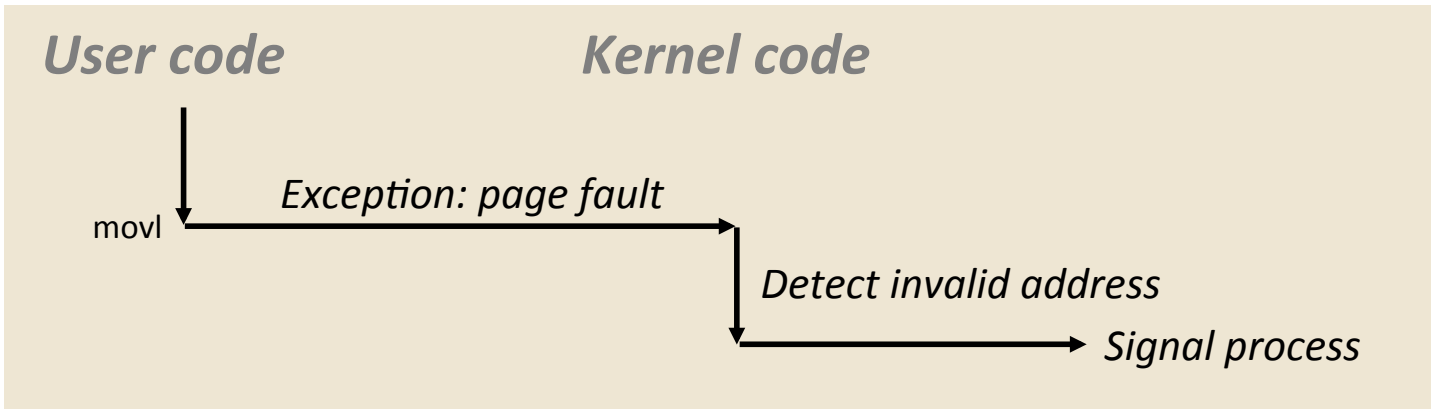
```
80483b7:      c7 05 10 9d 04 08 0d   movl   $0xd,0x8049d10
```



Fault example (unrecoverable): invalid memory reference

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

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



- Sends **`SIGSEGV`** signal to user process
- User process exits with “segmentation fault”

Summary of exceptions

Class	Cause		Return behavior
Interrupt	Signal from I/O device	Async	Always returns to *next* instruction
Trap	Intentional exception	Sync	Always returns to *next* instruction
Fault	Potentially recoverable error	Sync	Might return to *current* instruction
Abort	Nonrecoverable error	Sync	Never returns

Figure 8.4 in CS:APP3e (p.726)

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 (continued)

- **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