14-513

18-613

Exceptional Control Flow: Exceptions and Processes

15-213/18-213/14-5 n to Computer Systems

19th Lecture, Novem

Printers Used to Catch on Fire

Highly Exceptional Control Flow

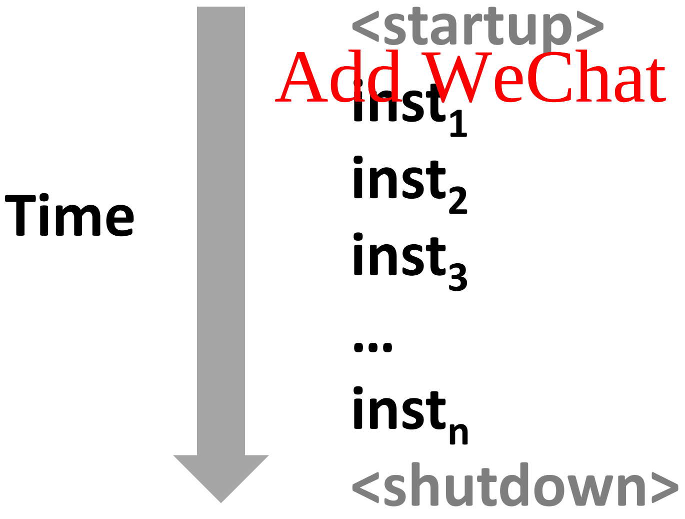
https://git.kernel.org/pub/scm/linux/kernel/git/torvalds/linux.git/tree/drivers/char/lp.c?h=v5.0-rc3

Today

■ **Exceptional Control Flow**	CSAPP 8
■ Exceptions	CSAPP 8.1
■ Processes	CSAPP 8.2
■ Process Control	CSAPP 8.3-8.4

Control Flow

- **Processors do only one thing:**
  - From startup to shutdown, each CPU core 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*)



* Externally, from an architectural viewpoint (internally, the CPU may use parallel out-of-order execution)

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**

  Difficult to react to changes in *s*

  - Data arrives from a disk or a netwo
  - 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
    - Implemente re and OS software

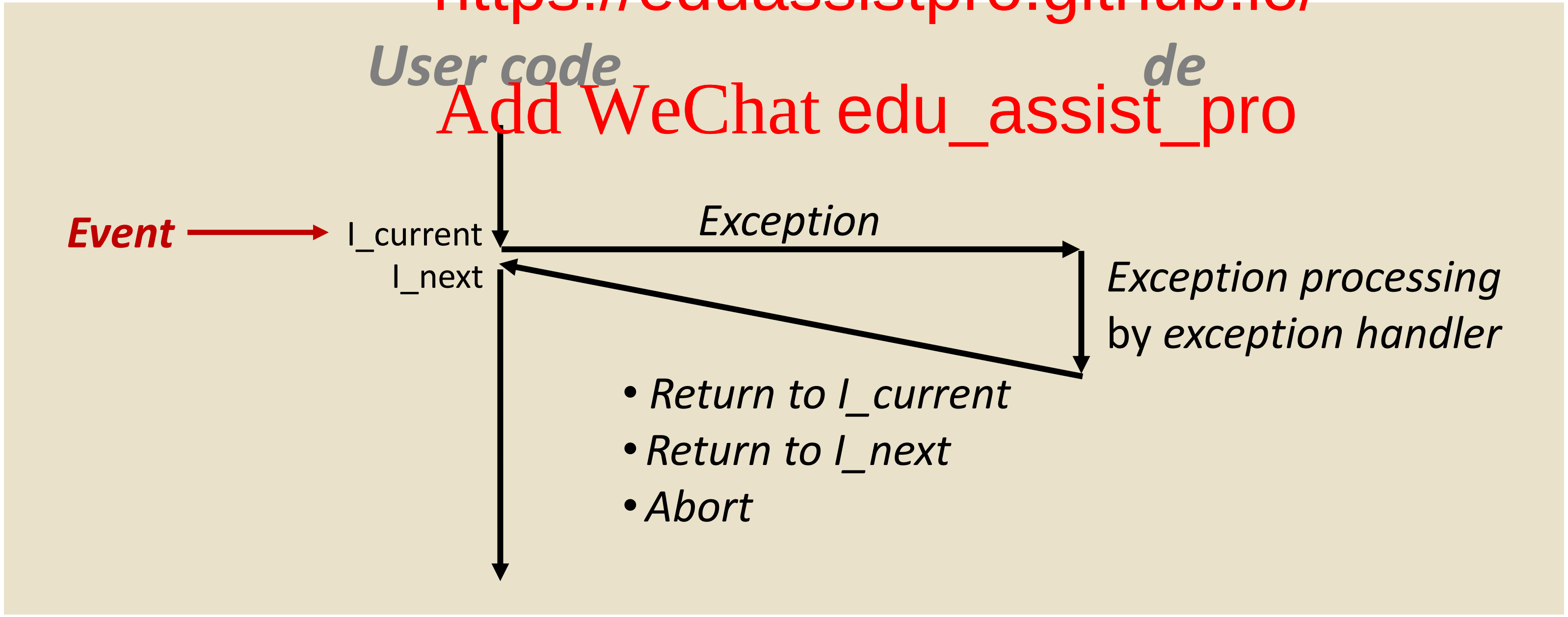
- Higher level mechanisms
  - 2. **Process context switch**
    - Implemented by OS software and hardware timer
  - 3. **Signals**
    - Implemented by OS software
  - 4. **Nonlocal jumps**: `setjmp()` and `longjmp()`
    - Implemented by C runtime library

Today

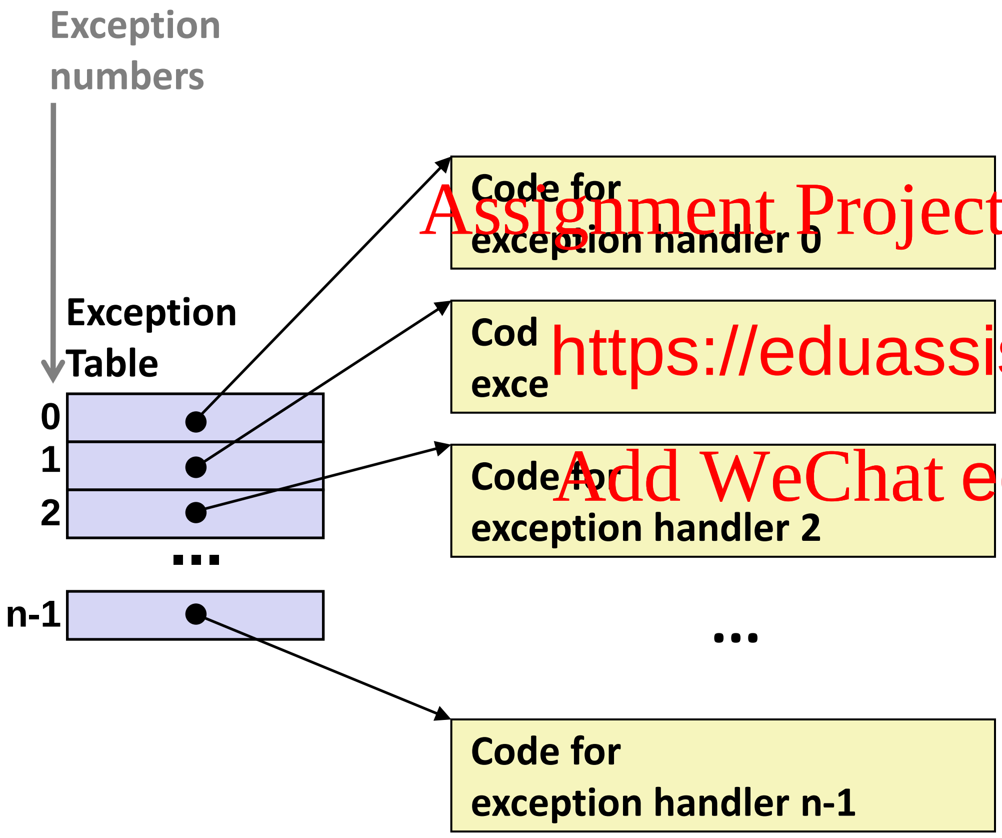
- Exceptional Control Flow
- **Exceptions**
- Processes
- Process Control

Exceptions

- **An *exception* is a transfer of control to the OS *kernel* in response to some *event* (i.e., change in processor state)**
  - Kernel is the memory-resident part of the OS
  - Examples of events: Divide by 0, arithmetic overflow, page fault, I/O request complet

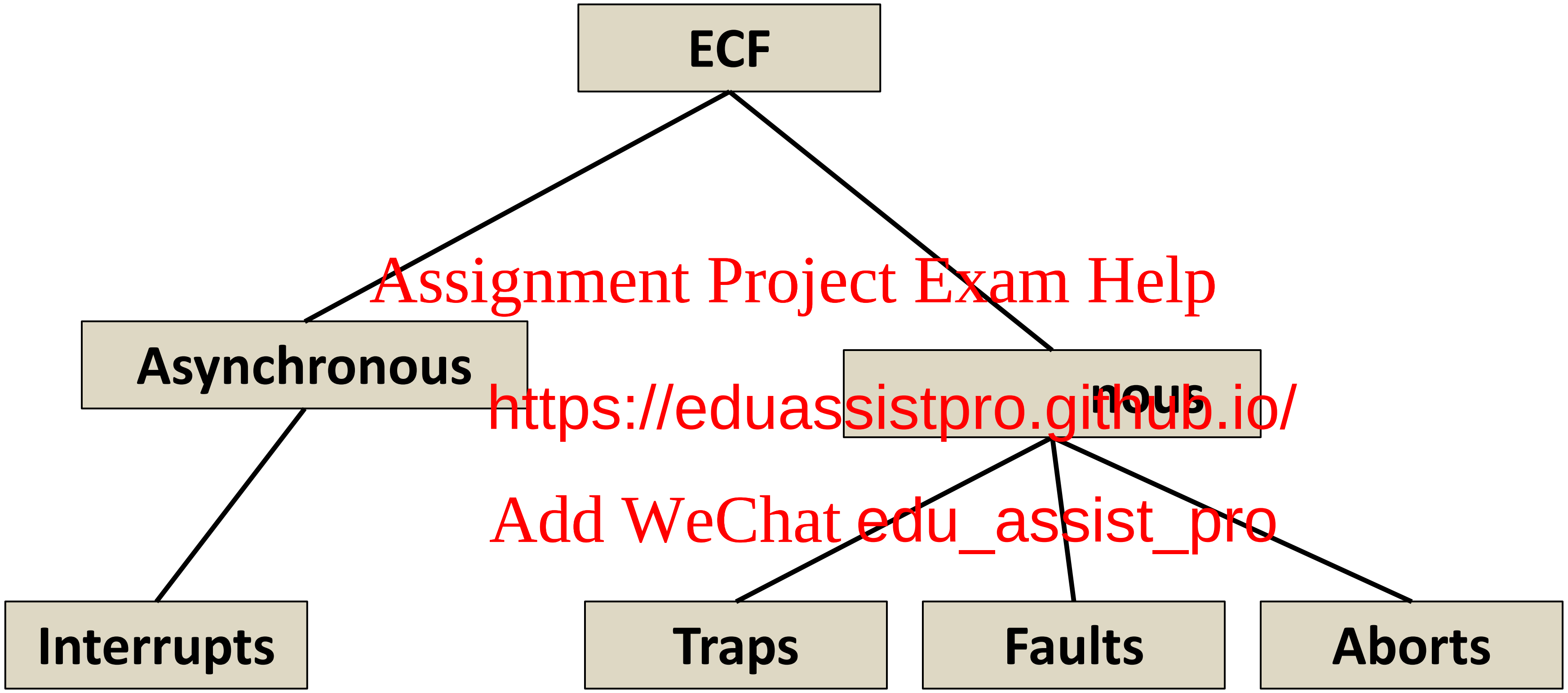


Exception Tables


Exception numbers
Exception Table
0
1
2
...
n-1
Code for exception handler 0
Cod exce
Code for exception handler 2
...
Code for exception handler n-1

- Each type of event has a unique exception number k
- xception table interrupt vector)
- Handler k is called each time exception k occurs

(partial) Taxonomy



Asynchronous Exceptions (Interrupts)

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

- **Examples:**
  - Timer interrupt
    - Every few ms, an external time [illegible] an interrupt
    - Used by the kernel to take back control from user programs
  - I/O interrupt from external device
    - Hitting Ctrl-C at the keyboard
    - Arrival of a packet from a network
    - Arrival of data from a disk

Synchronous Exceptions

- **Caused by events that occur as a result of executing an instruction:**
  - ***Traps***
    - Intentional, set program up to “trip the trap” and do something
    - Examples: ***system calls***, gdb breakpoints
    - Returns con
  - ***Faults***
    - Unintentional but possibly reco
    - Examples: page faults (recoverable), protection faults (unrecoverable), floating point exceptions
    - Either re-executes faulting (“current”) instruction or aborts
  - ***Aborts***
    - Unintentional and unrecoverable
    - Examples: illegal instruction, parity error, machine check
    - Aborts current program

System Calls

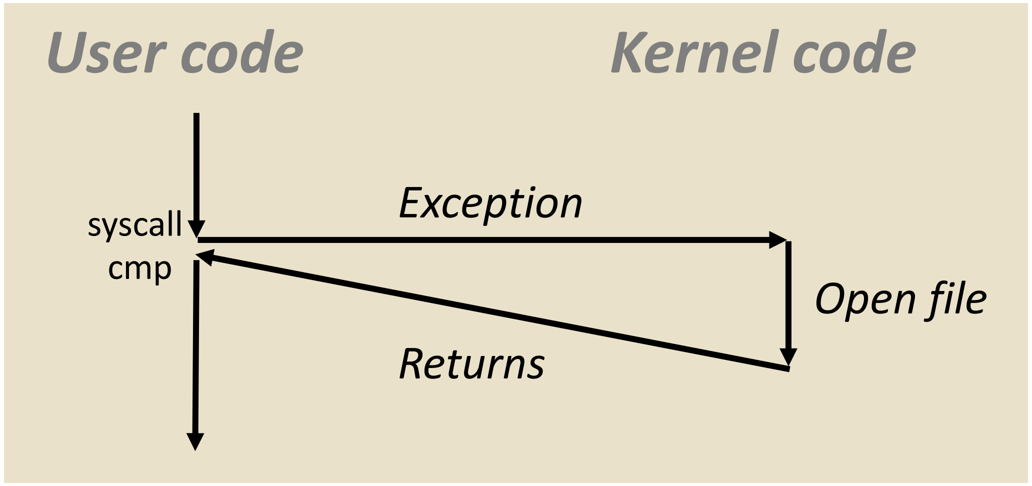
- Each x86-64 system call has a unique ID number
- Examples:

Number	*Name*	*Description*
0	`read`	Read file
1	`write`	
2	`open`	Op
3	`close`	Clo
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`**

```
00000000000e5d70 <__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   c
...
e5dfa:   c3                  retq
```

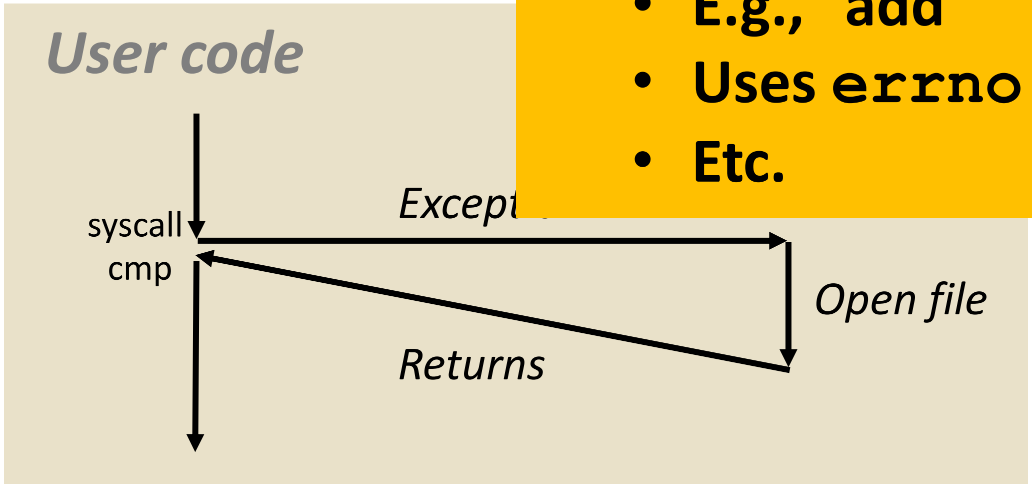


- `%rax` contains syscall number
- Other arguments in `%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9`
- Return value in `%rax`
- Negative value is an error corresponding to negative `errno`

System Call

- User calls: **open(f**
- Calls **__open** functi

```
00000000000e5d70 <__op
...
e5d79:   b8 02 00 00 00
e5d7e:   0f 05           sysca
e5d80:   48 3d 01 f0 ff ff   c
...
e5dfa:   c3              retq
```



- Return value in %rax
- Negative value is an error corresponding to negative errno

Almost like a function call
- **Transfer of control**
- **On return, executes next instruction**
- **Passes arguments using calling convention**
- **Gets result in `%rax`**

One important exception!

es

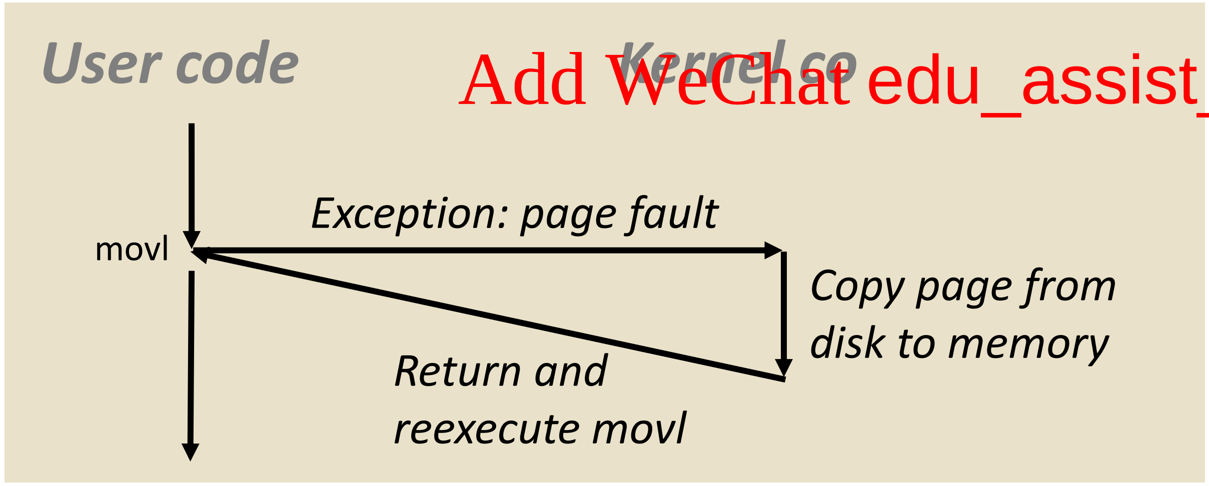
- **And other dif**
  - **E.g., "add   nction" is in `%rax`**
  - **Uses `errno`**
  - **Etc.**

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;
}
```

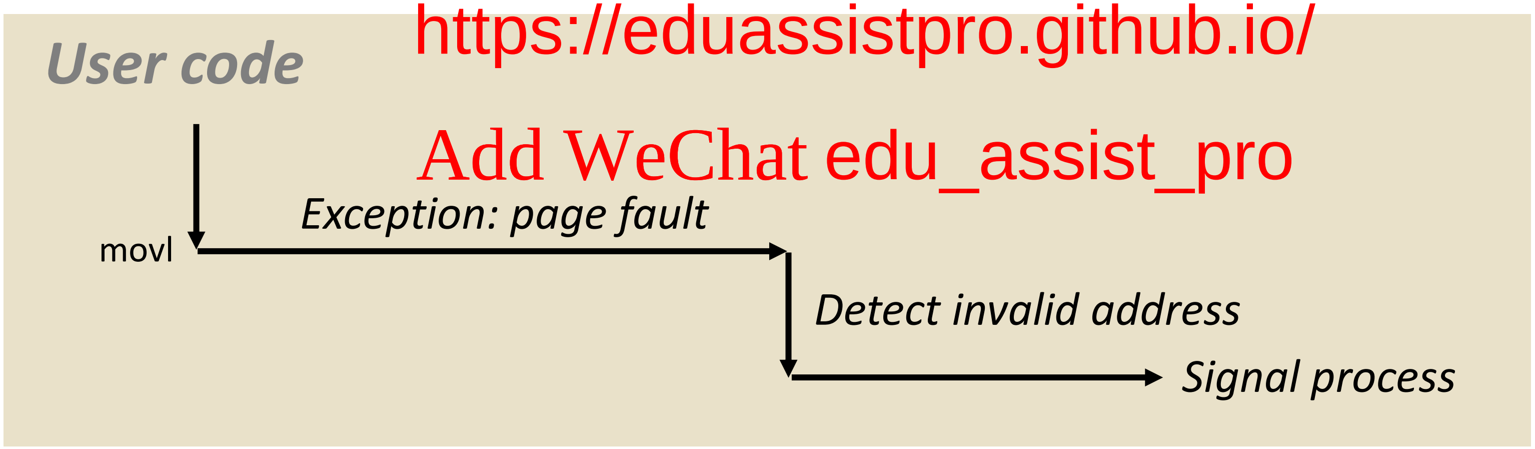
```
80483b7:   c7 05 10 9d 04 08 0d    movl    $0xd,0x8049d10
```



Fault Example: 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"

Today

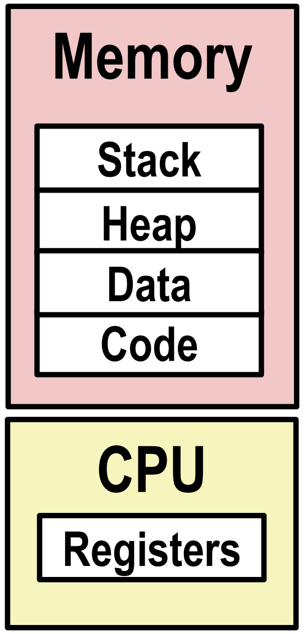
- Exceptional Control Flow
- Exceptions
- **Processes**
- Process Control

Processes

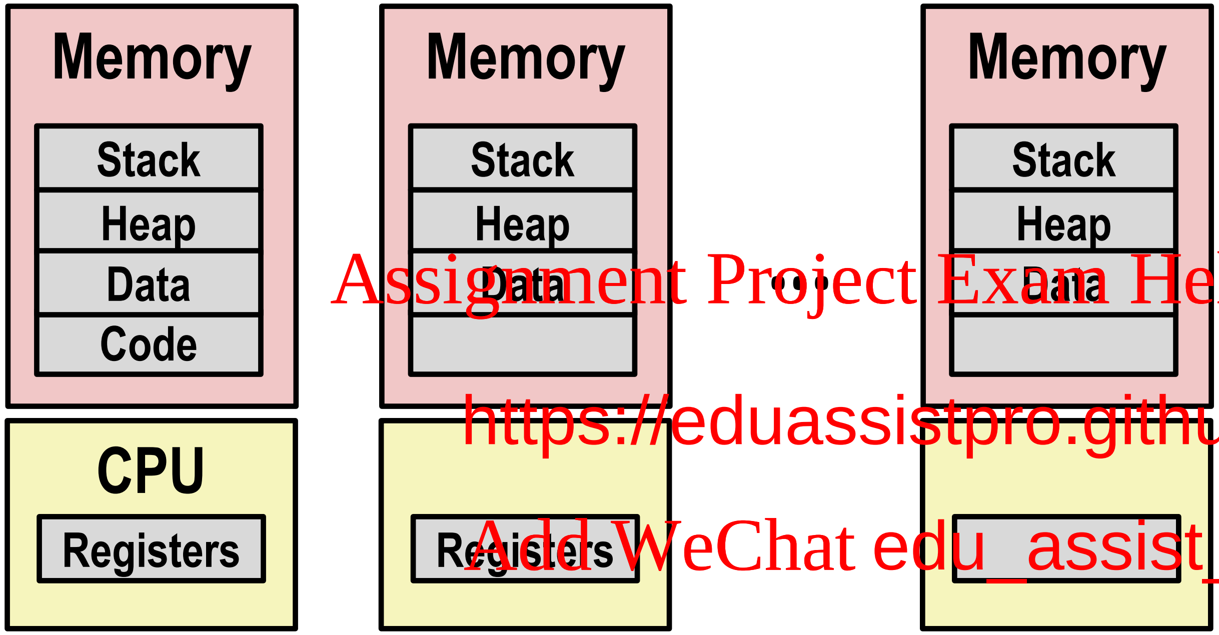
- **Definition: A *process* is an instance of a running program.**
  - One of the most profound ideas in computer science
  - Not the same as "program" or "processor"

- **Process provides** **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

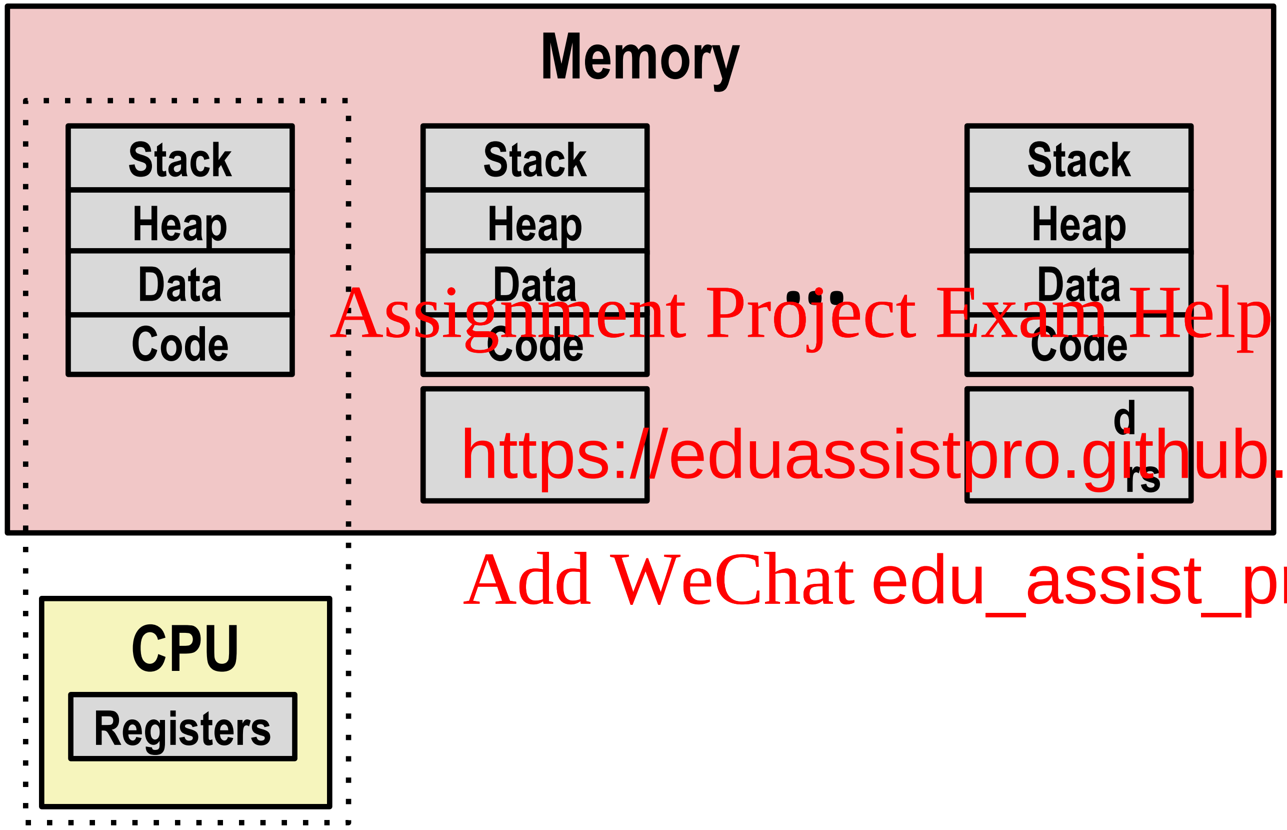


- **Computer runs many processes simultaneously**
  - Applications for one or more users
    - Web browsers, email clients, editors, …
  - Background tasks
    - Monitoring network & I/O devices

Multiprocessing Example

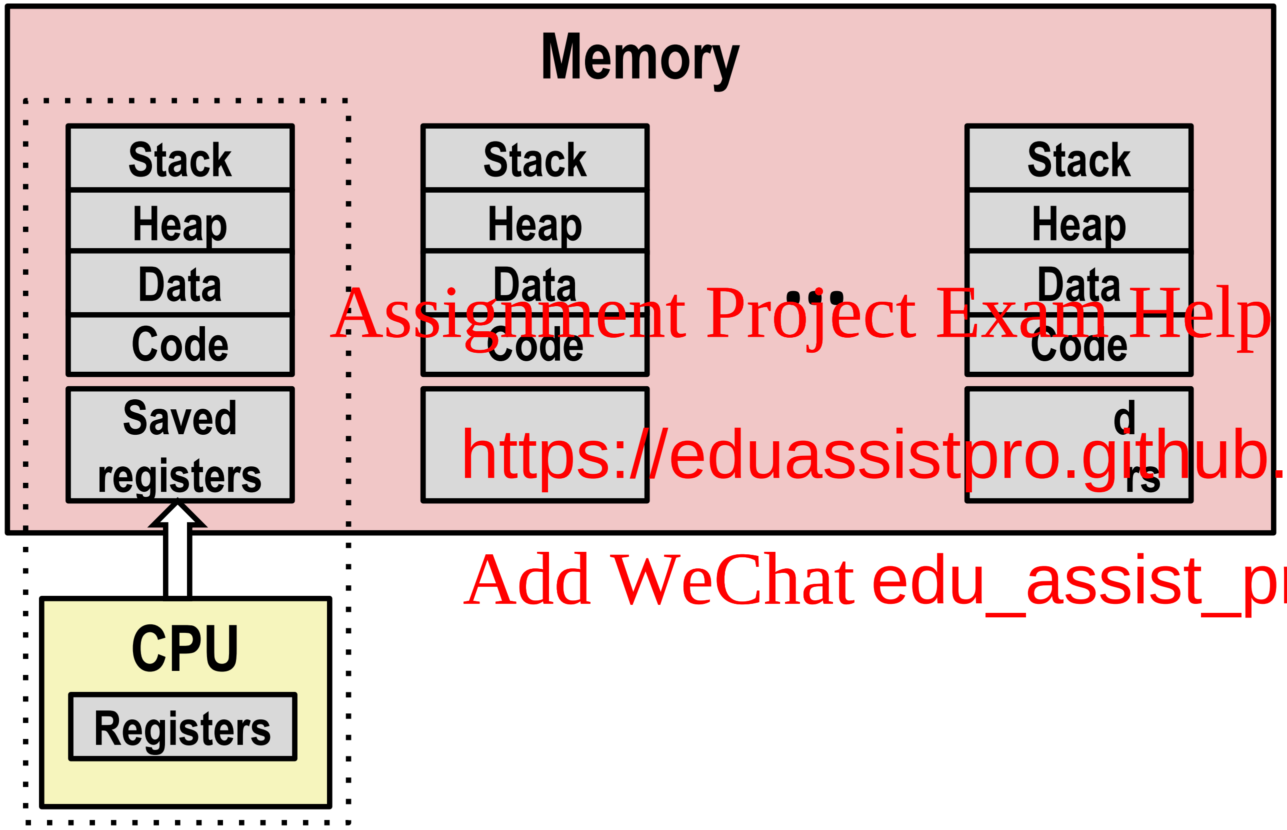
- **Running program "top" on Mac**
  - System has 123 processes, 5 of which are active
  - Identified by Process ID (PID)

Multiprocessing: The (Traditional) Reality



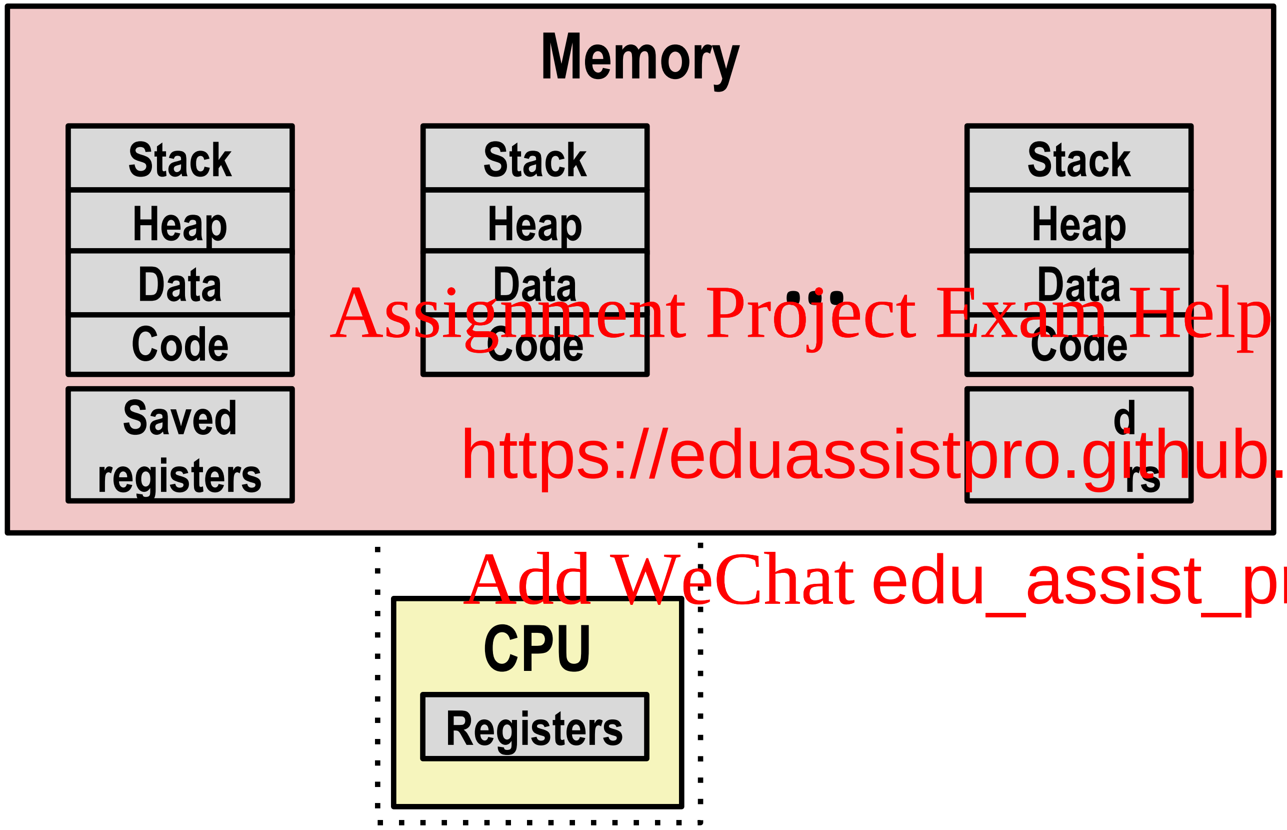
- **Single processor executes multiple processes concurrently**
  - Process executions interleaved (multitasking)
  - Address spaces managed by virtual memory system (like last week)
  - Register values for nonexecuting processes saved in memory

Multiprocessing: The (Traditional) Reality



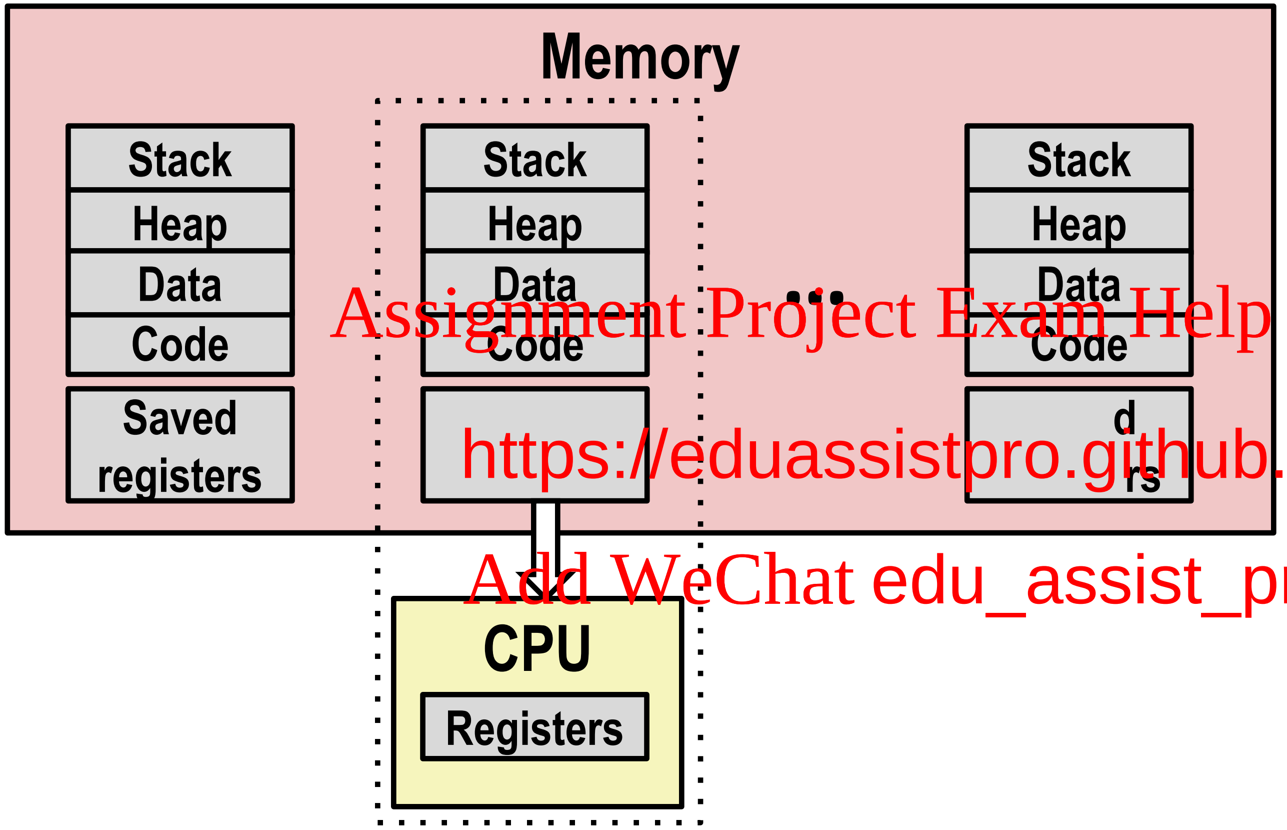
- Save current registers in memory

Multiprocessing: The (Traditional) Reality



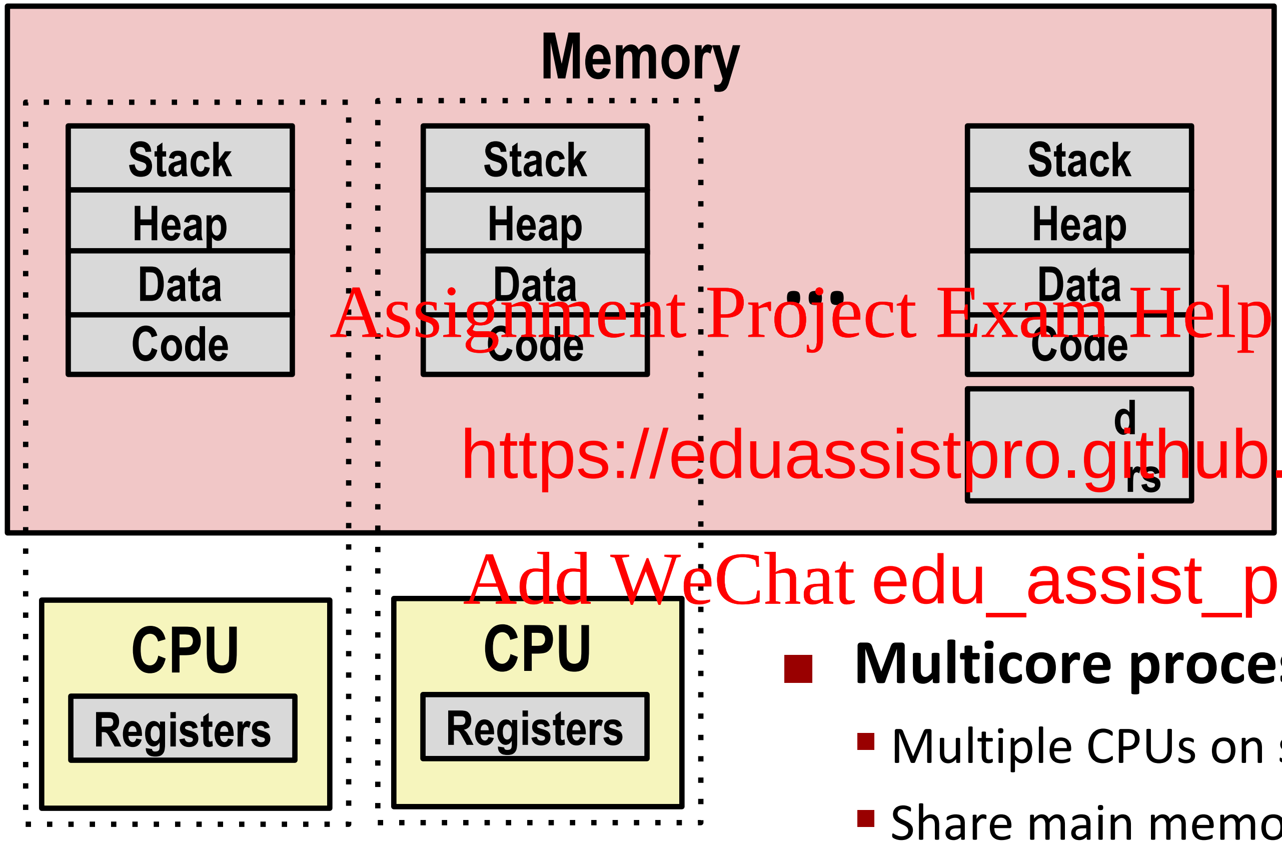
- Schedule next process for execution

Multiprocessing: The (Traditional) Reality



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

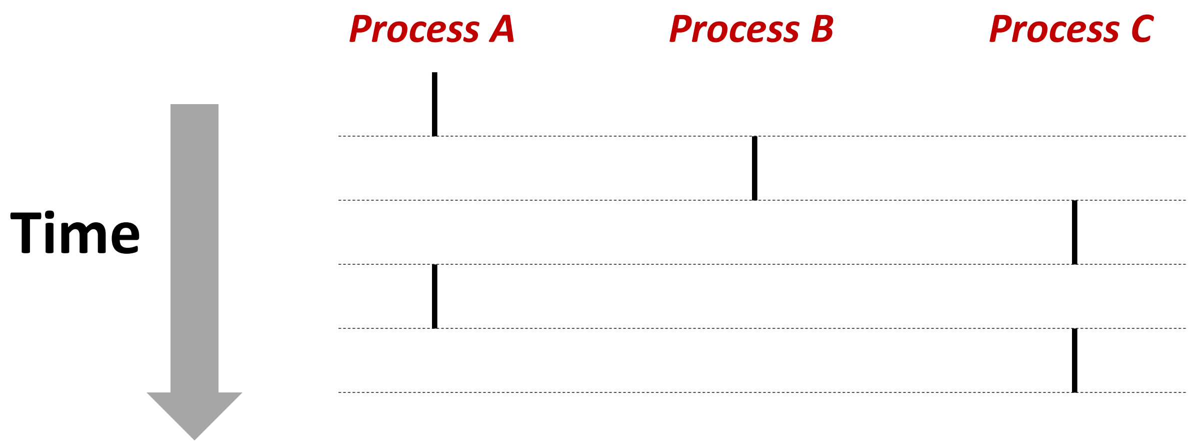
Multiprocessing: The (Modern) Reality



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

Concurrent Processes

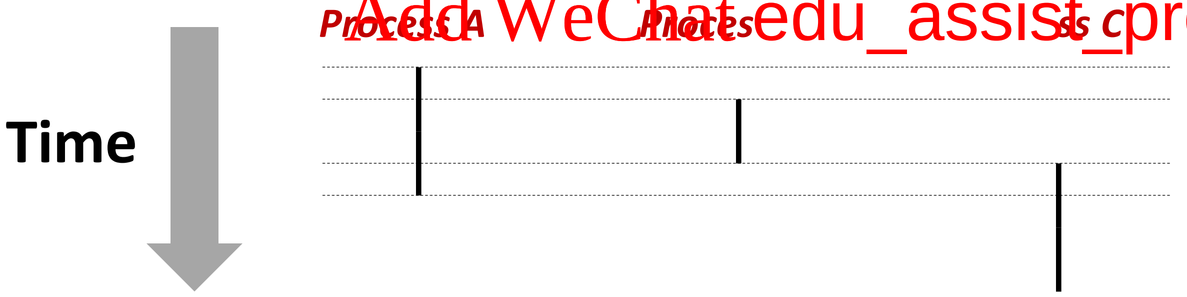
- Each process is a logical control flow.
- Two processes *run **concurrently*** (*are concurrent)* if their flows overlap in time
- Otherwise, they are *sequential*
- Examples (runni
  - Concurrent: A &
  - Sequential: B & C



User View of Concurrent Processes

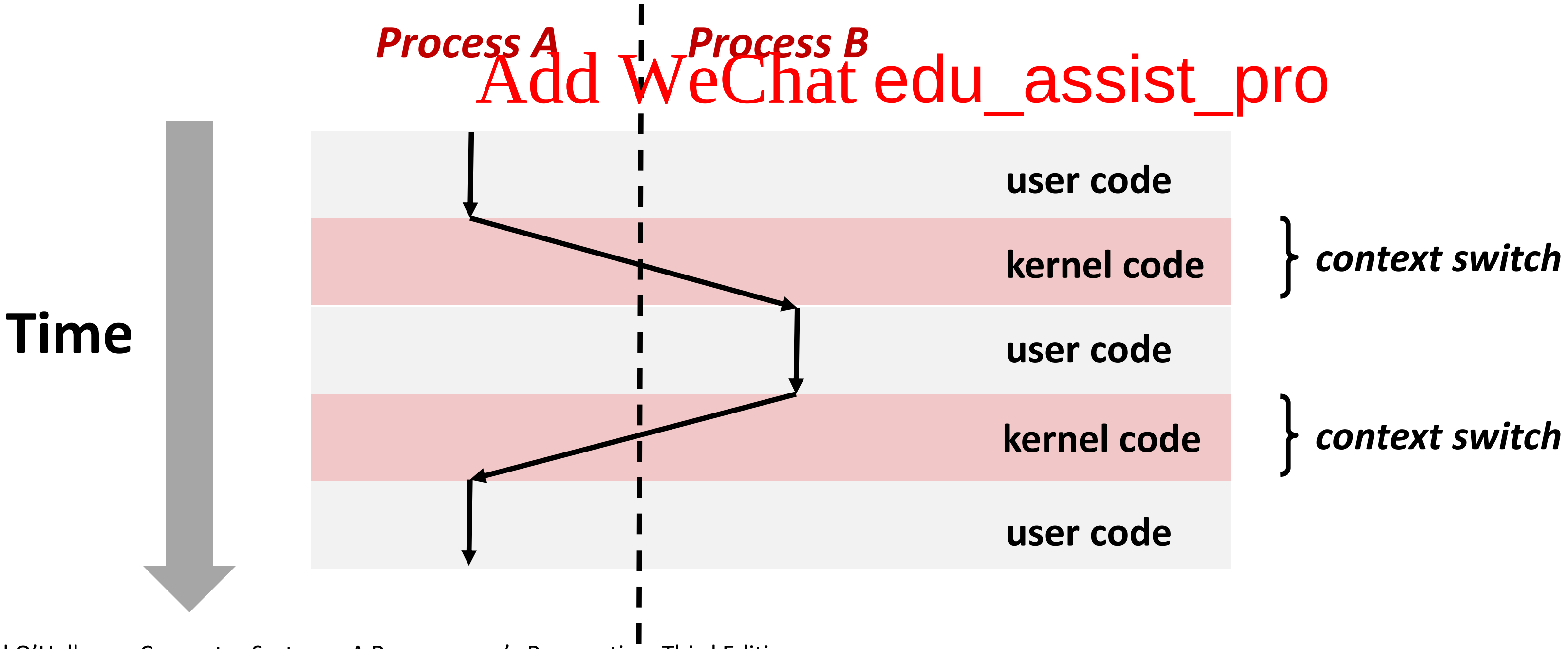
- Control flows for concurrent processes are physically disjoint in time

- However, we can think of concurrent processes as running in paral



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

- Exceptional Control Flow
- Exceptions
- Processes
- **Process Control**

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(-1);
    }
```

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(-1);
}
```

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

Note: csapp.c exits with 0.

- But, must think about application. Not alway appropriate to exit when something goes wrong.

Error-handling Wrappers

- We simplify the code we present to you even further by using Stevens[1]-style error-handling wrappers:

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

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

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

- NOT what you generally want to do in a real application

[1]e.g., in “UNIX Network Programming: The sockets networking API“ W. Richard Stevens

Obtaining Process IDs

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

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 ecuted and will eventually be *sc* e) 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(i`**

  - Terminates with an *exit status* of `s`

  - 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.**

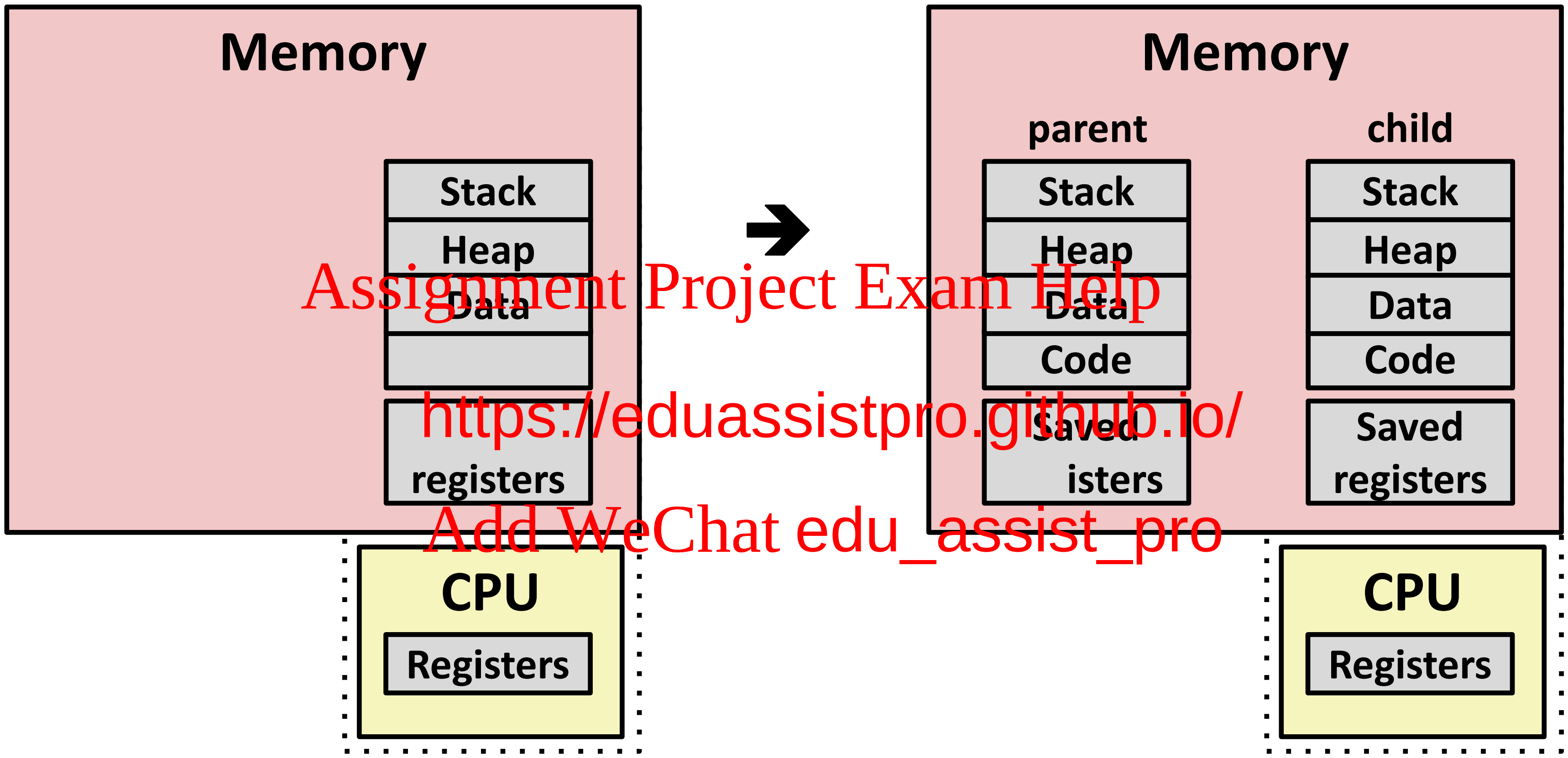
Creating Processes

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

- `int fork(void)`
  - Returns 0 to the rent process
  - Child is *almost* i
    - Child get an identical (but sepa he 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*

Conceptual View of `fork`



- **Make complete copy of execution state**
  - Designate one as parent and one as child
  - Resume execution of parent or child

The `fork` Function Revisited

- **VM and memory mapping explain how `fork` provides private address space for each process.**

- **To create virtual address for new process:**
  - Create exact co **`m_area_struct`**, and page tables.
  - Flag each page in both processes a
  - Flag each **`vm_area_struct`** in both processes as private COW

- **On return, each process has exact copy of virtual memory.**

- **Subsequent writes create new pages using COW mechanism.**

fork Example

```c
int main(int argc, char** argv)
{
    pid_t pid;
    int x = 1;

    pid = Fork();
    if (pid == 0) {
        printf("child
        return 0;
    }

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

fork.c

- **Call once, return twice**
- **Concurrent execution**
  - **Can't predict execution order of parent and child**

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

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

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

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

fork Example

```
int main(int argc, char** argv)
{
    pid_t pid;
    int x = 1;

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

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

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

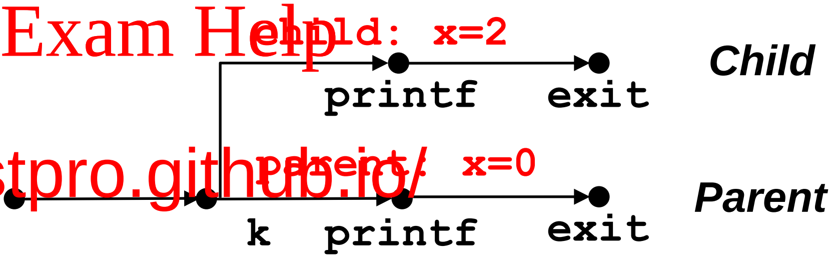
- Call once, return twice
- Concurrent execution
  - Can't predict execution order of parent and child
- Duplicate but separate address space
  - x has a value of 1 when fork returns in parent and child
  - Subsequent changes to x are independent
- Shared open files
  - stdout is the same in both parent 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 lab   ables
  - `printf` vertice
  - Each graph begins with a vertex wit
- **Any *topological sort* of the grap   ds to a feasible total ordering.**
  - Total ordering of vertices where all edges point from left to right

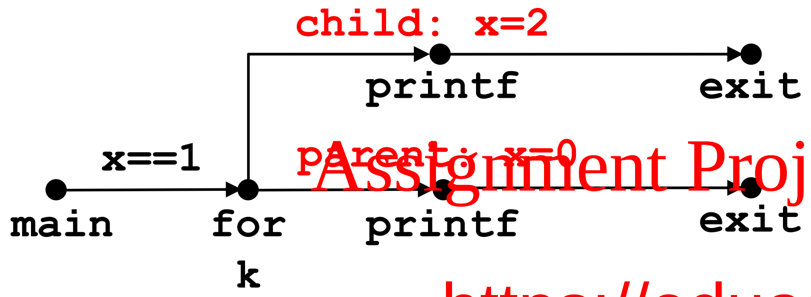
Process Graph Example

```
int main(int argc, char** argv)
{
    pid_t pid;
    int x = 1;

    pid = Fork();
    if (pid == 0) {  /
        printf("child
       return 0;
    }

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

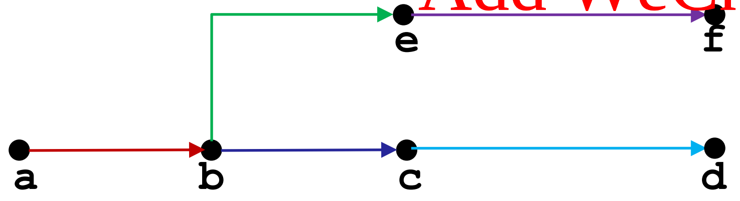


Interpreting Process Graphs

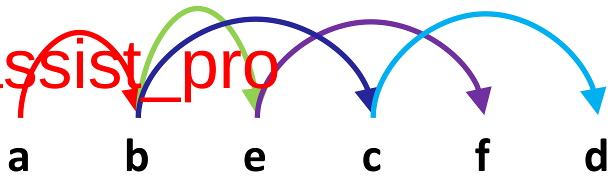
- Original graph:



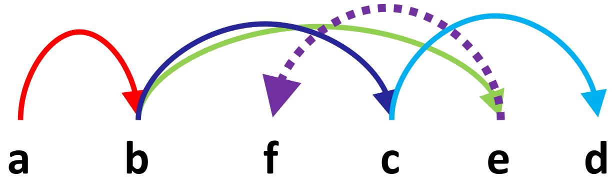
- Relabeled graph:



Feasible total ordering:



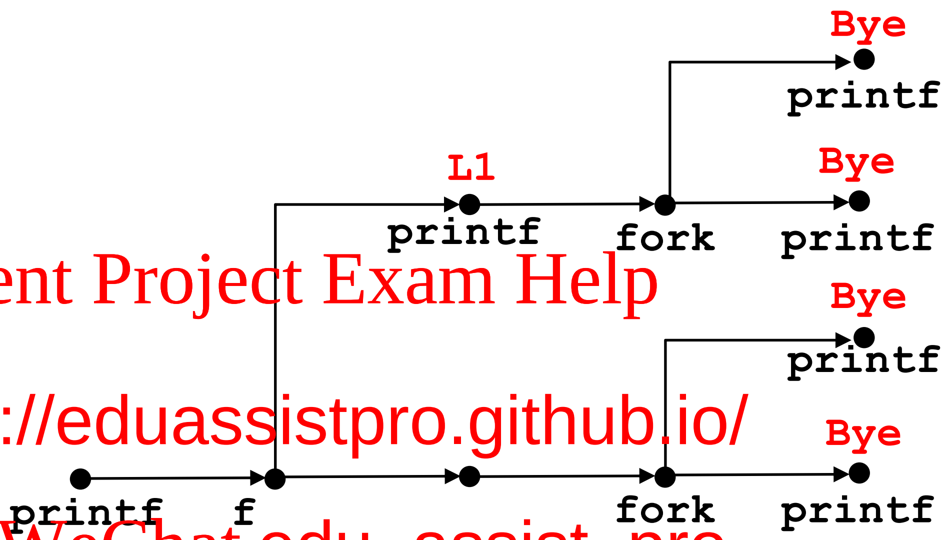
Feasible or Infeasible?



Infeasible: not a topological sort

fork Example: Two consecutive forks

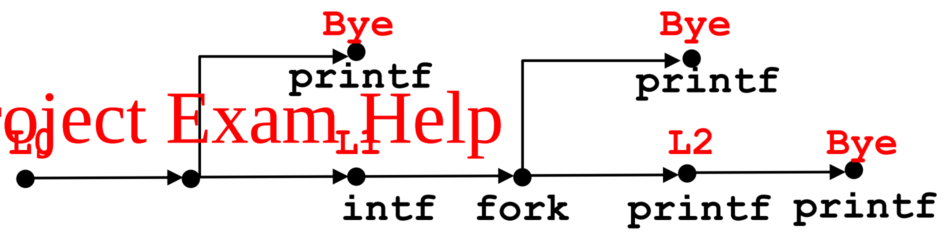
```
void fork2()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("Bye\n");
}                          forks.c
```



Feasible output:	Infeasible output:
L0	L0
L1	Bye
Bye	L1
Bye	Bye
L1	L1
Bye	Bye
Bye	Bye

`fork` Example: Nested `fork`s in parent

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



Feasible or Infeasible?

L0
Bye
L1
Bye
Bye
L2

Infeasible

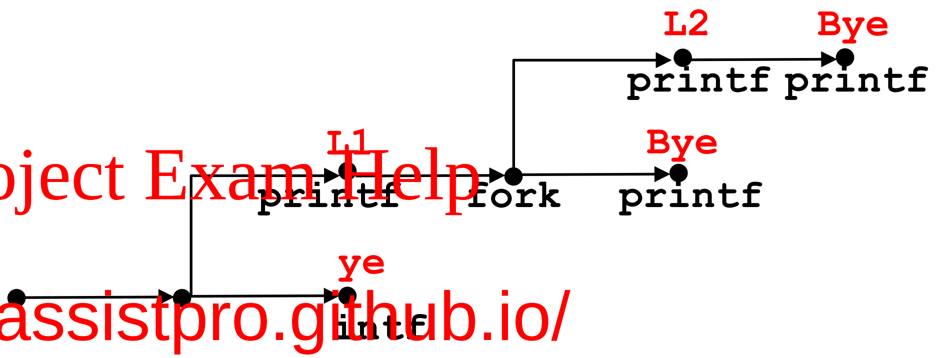
Feasible or Infeasible?

L0
L1
Bye
Bye
L2
Bye

Feasible

fork Example: Nested forks in children

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



Feasible or Infeasible?	Feasible or Infeasible?
L0	L0
Bye	Bye
L1	L1
Bye	L2
Bye	Bye
L2	Bye
Infeasible	Feasible

No Quiz Today

…But let's k now

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 pa g `wait` or `waitpid`)
  - Parent is given exit status informati
  - Kernel then deletes zombie child pr
- **What if parent doesn’t reap?**
  - If any parent terminates without reaping a child, then the orphaned child should be reaped by **`init`** process (pid == 1)
    - Unless ppid == 1! Then need to reboot…
  - 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 =
Terminating Child, PID
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
```

shows child process as "defunct" (i.e., a zombie)

- Killing parent allows child to be reaped by **`init`**

Non-terminating 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);
```

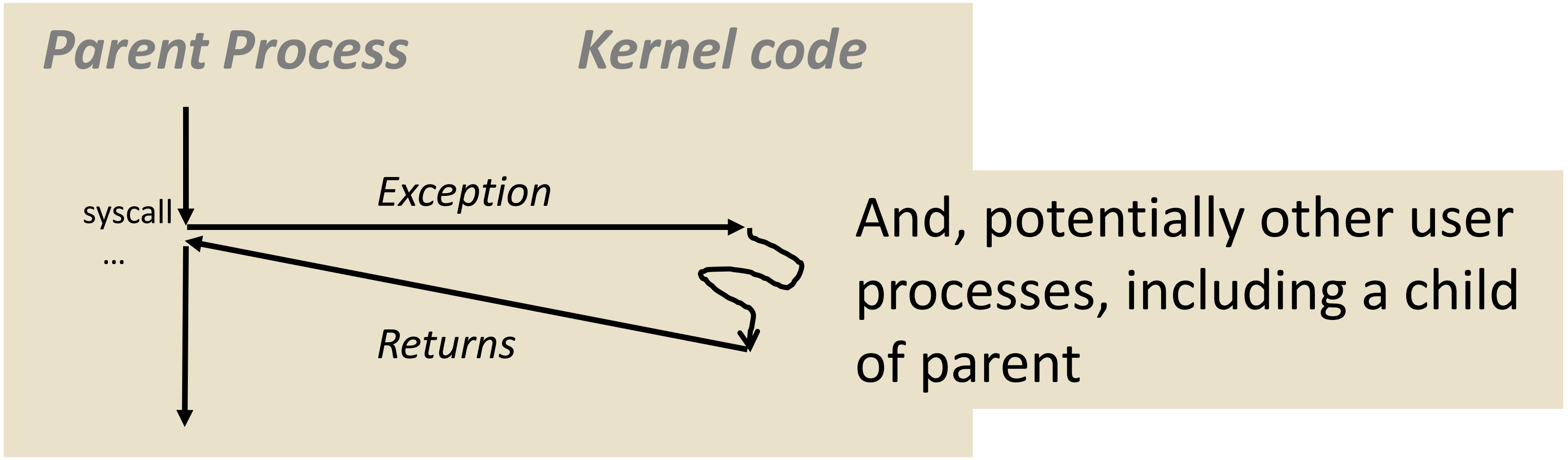
```
linux> ./forks 8
Terminating Parent, PID = 6675
Running Child, PID = 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6676 ttyp9    00:00:06 forks
 6677 ttyp9    00:00:00 ps
linux> kill 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6678 ttyp9   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

- till 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
  - Implemented as


Parent Process
Kernel code
syscall
…
Exception
Returns
And, potentially other user processes, including a child of parent

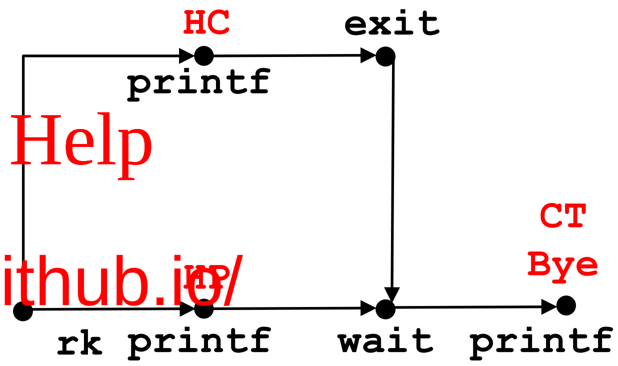
`wait`: Synchronizing with Children

- **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 t t terminated
  - If **`child_stat`** r it points to will be set to a value that indicates reason the ed 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

```
void fork9() {
    int child_status;

    if (fork() == 0) {
        printf("HC: hello from child\n");
        exit(0);
    } else {
        printf("HP: he[illegible]
        wait(&child_status);
        printf("CT: child has terminat[illegible]
    }
    printf("Bye\n");
}
                                        forks.c
```



Feasible output(s):

HC	HP
HP	HC
CT	CT
Bye	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

```
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)

```
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);
    }
}
```

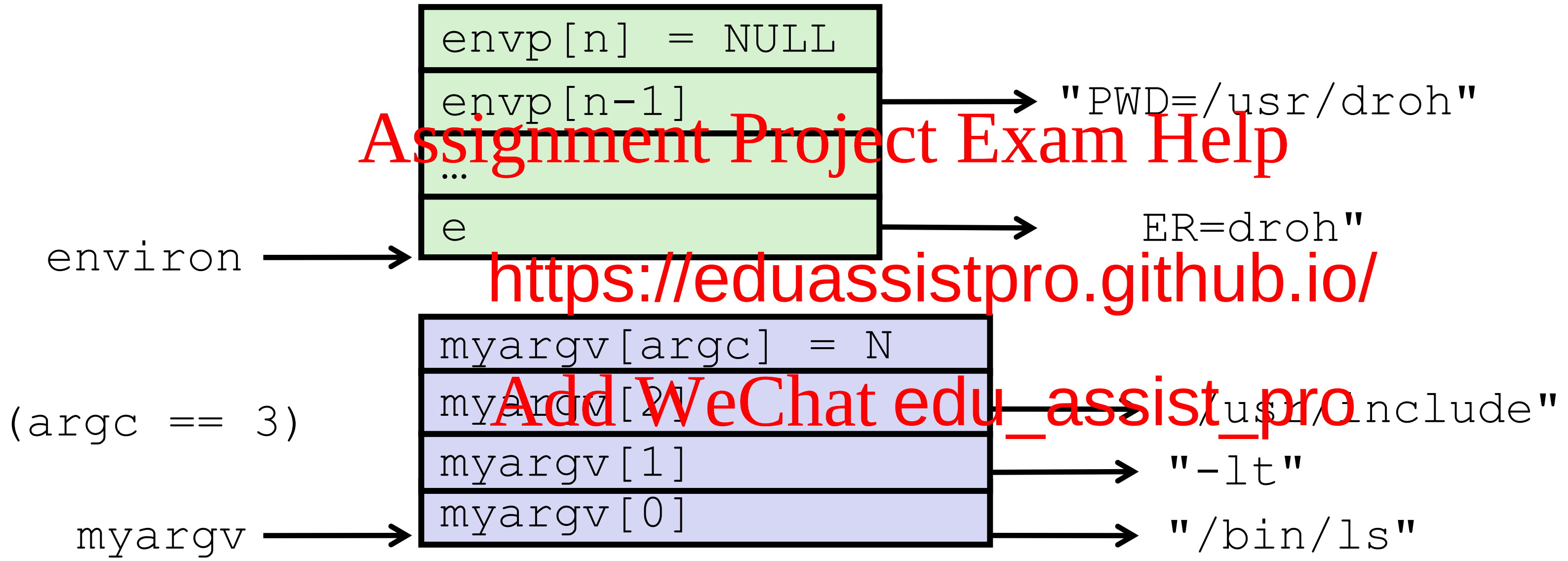
forks.c

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., `#!/bi`
  - …with argument l
    - By convention `argv[0]==fil`
  - …and environment variable list `en`
    - "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

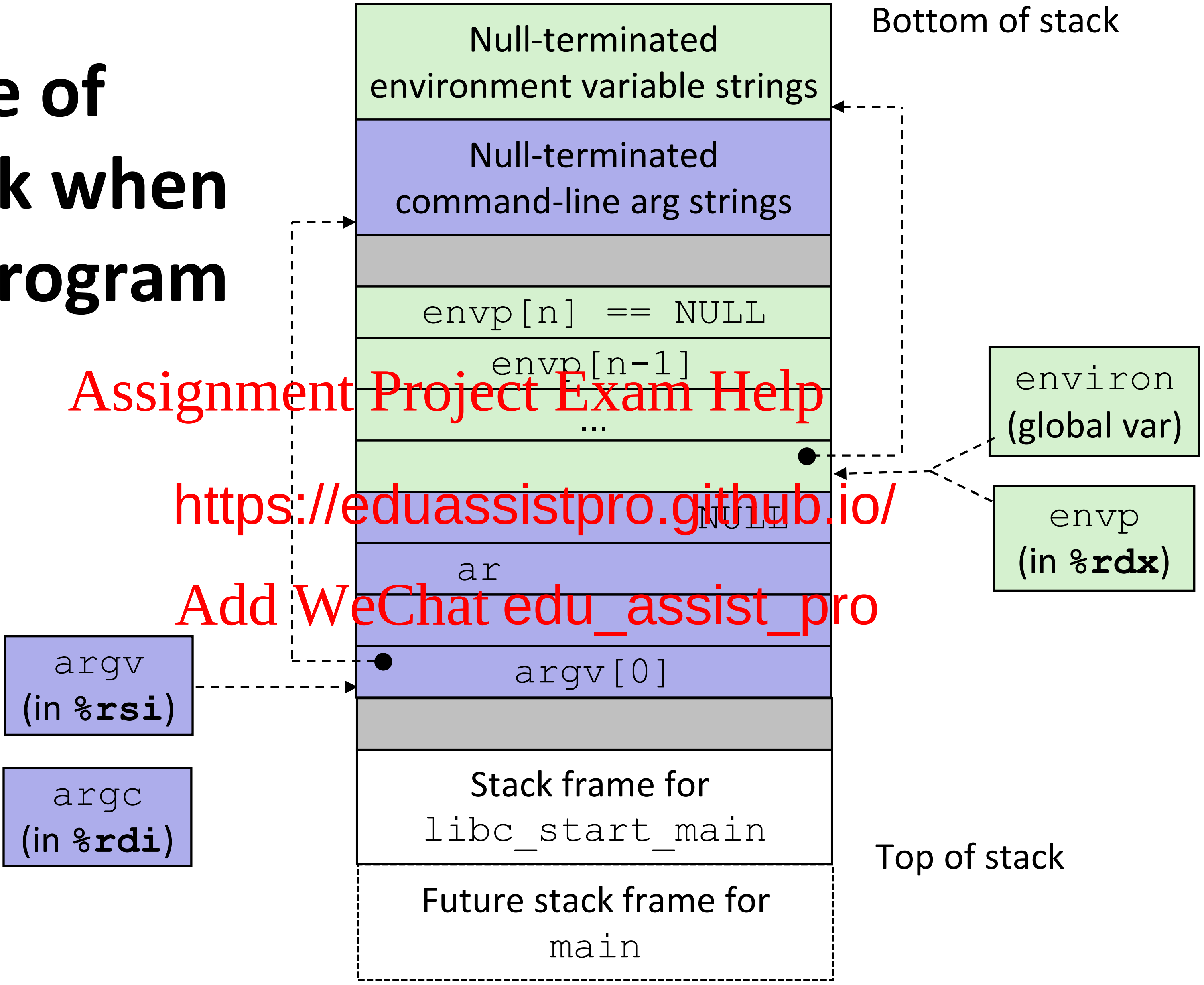
execve Example

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

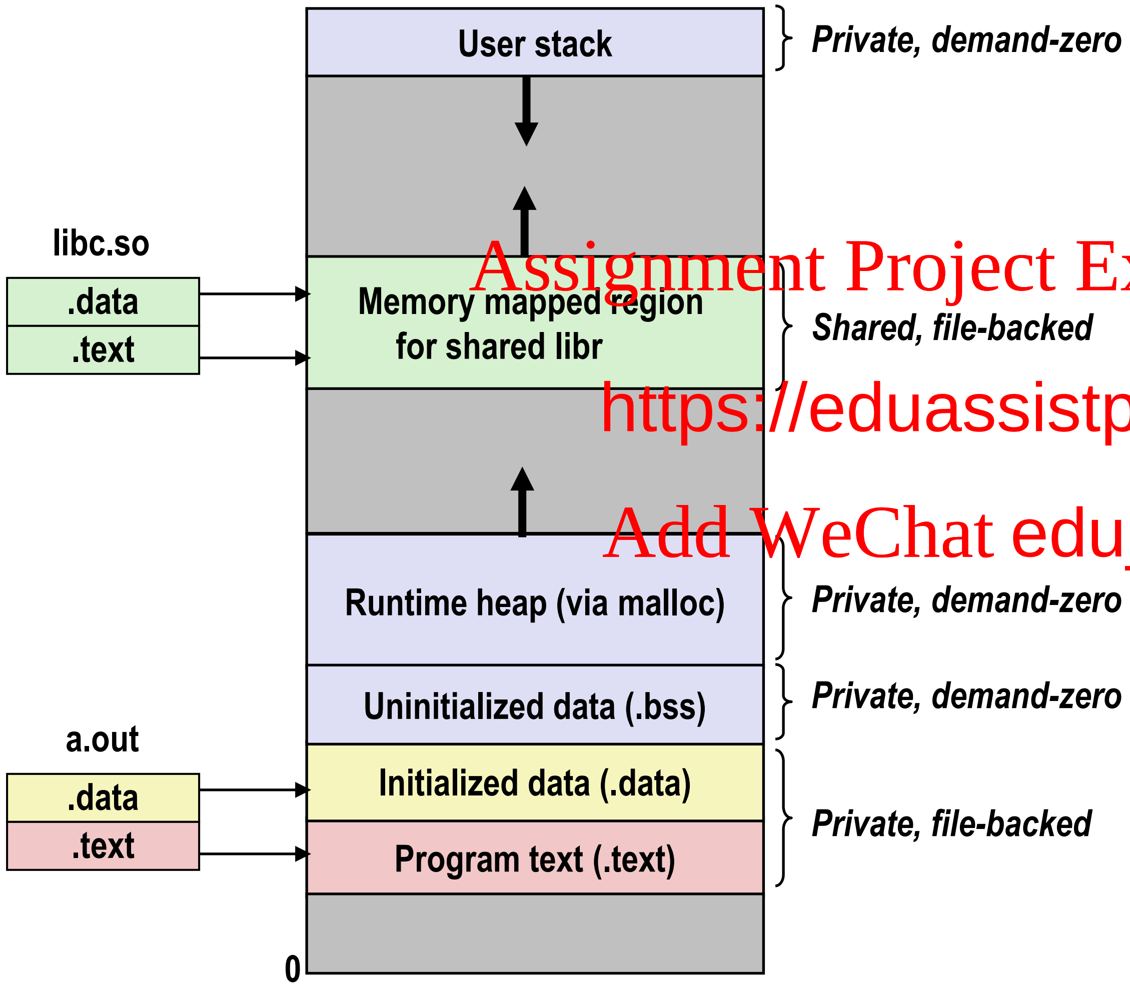


```
if ((pid = Fork()) == 0) {   /* Child runs program */
    if (execve(myargv[0], myargv, environ) < 0) {
        printf("%s: Command not found.\n", myargv[0]);
        exit(1);
    }
}
```

Structure of the stack when a new program starts


Bottom of stack
Null-terminated environment variable strings
Null-terminated command-line arg strings
envp[n] == NULL
envp[n-1]
...
NULL
ar
argv[0]
Stack frame for libc_start_main
Future stack frame for main
Top of stack
environ (global var)
envp (in %rdx)
argv (in %rsi)
argc (in %rdi)

The **execve** Function Revisited



- To load and run a new program `a.out` in the current process using `execve`:
- Free `vm_area_struct`'s nd page tables for old areas
- ate `vm_area_struct`'s page tables for new as
  - Programs and initialized data backed by object files.
  - `.bss` and stack backed by anonymous files.
- Set PC to entry point in `.text`
  - Linux will fault in code and data pages as needed.

Summary

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

- **Processes**
  - At any given tim rocesses
  - Only one can execute at a time on
  - 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 ret
- **Reaping and waiting for process**
  - Call `wait` or `waitpid`
- **Loading and running programs**
  - Call `execve` (or variant)
  - One call, (normally) no return

Making `fork` More Nondeterministic

- Problem
  - Linux scheduler does not create much run-to-run variance
  - Hides potential race conditions in nondeterministic programs
    - E.g., does `fork` return to child first, or to parent?
- Solution
  - Create custom inserts random delays along different branches
    - E.g., for parent and child in `fo`
  - Use runtime interpositioning to have program use special version of library code

Variable delay `fork`

```
/* fork wrapper function */
pid_t fork(void) {
    initialize();
    int parent_delay = choose_delay();
    int child_delay = choose_delay();
    pid_t parent_pid = getpid();
    pid_t child_pid_or_zero = real_fork();
    if (child_pid_or_ze
        /* Parent */
        if (verbose) {
            printf(
"Fork.  Child pid=%d, delay = %dms.  Pa                          delay = %dms\n",
                   child_pid_or_zero, c
                   parent_pid, parent_delay);
            fflush(stdout);
        }
        ms_sleep(parent_delay);
    } else {
        /* Child */
        ms_sleep(child_delay);
    }
    return child_pid_or_zero;
}
```

myfork.c