# CSC 252: Computer Organization
# Spring 2018: Lecture 20

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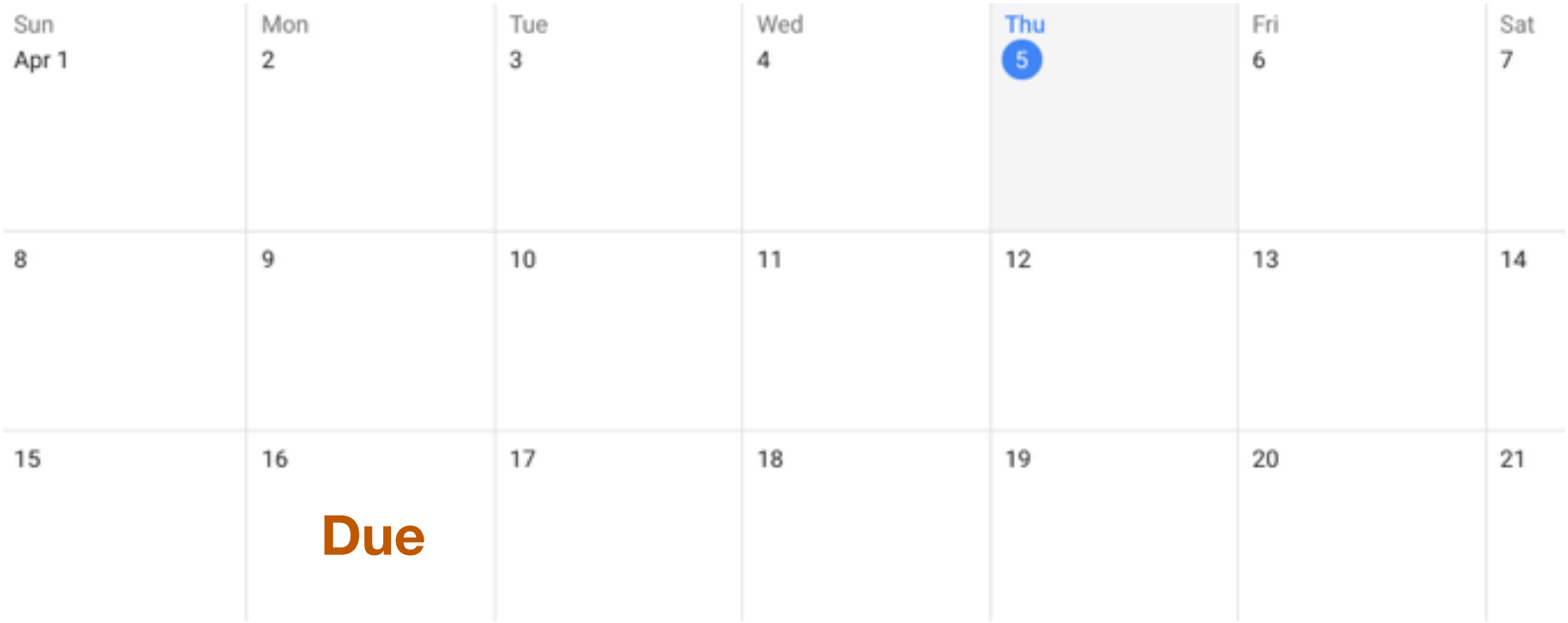
University of Rochester

**Action Items:**

- **Programming Assignment 5 is out**

# Announcement

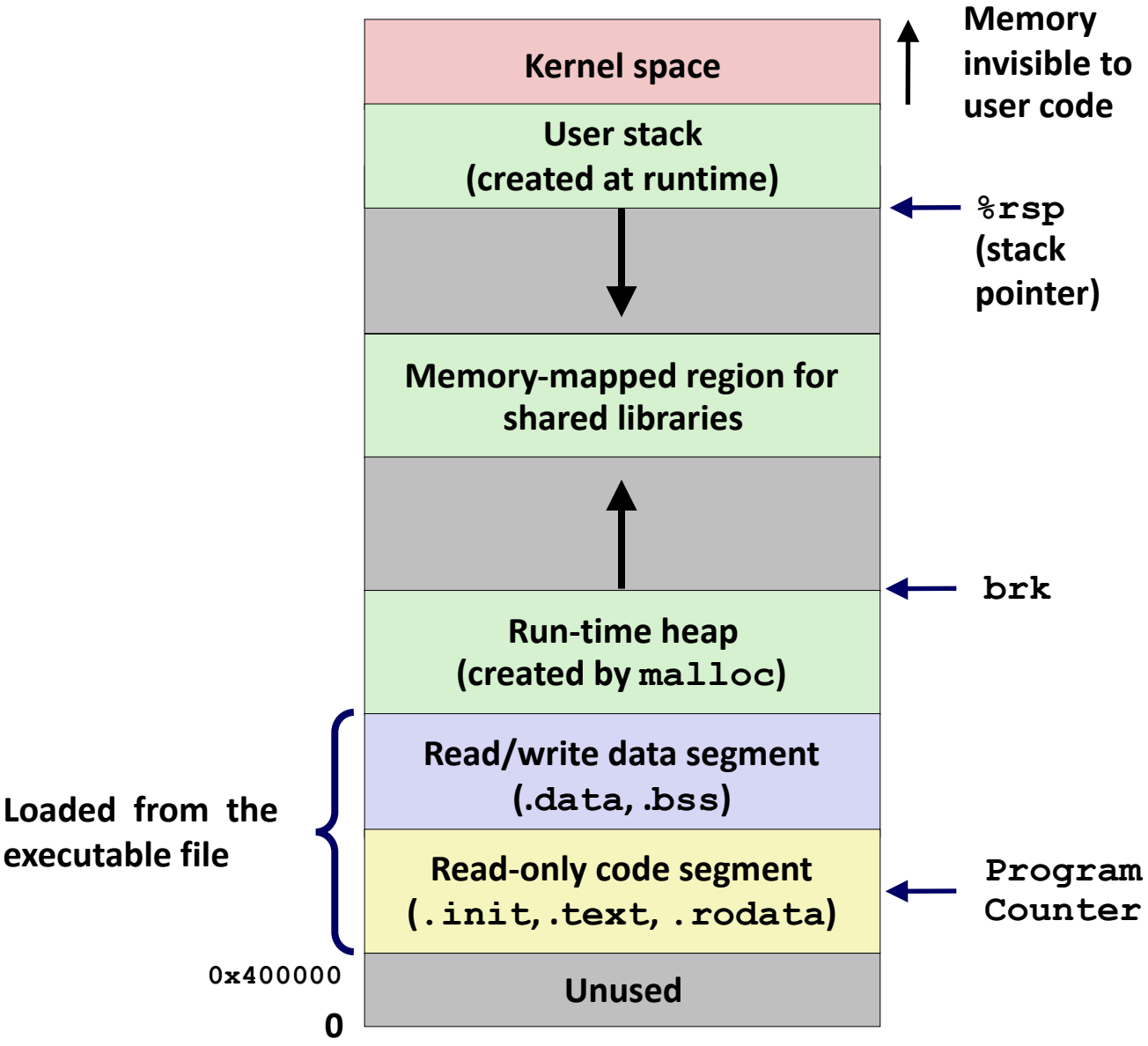
- Programming Assignment 5 is out
  - Main assignment: 11:59pm, **Monday, April 16**.



# Today

- Process Control
- Signals
- Non-local Jumps (if time permits)

# Process Address Space



# What Happens at `fork()`?

**code segment**

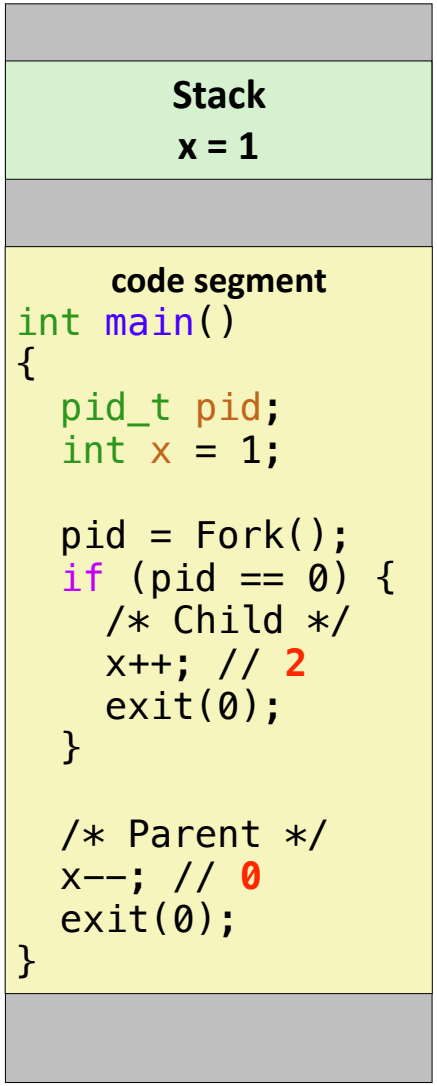
```
int main()
{
  pid_t pid;
  int x = 1;

  pid = Fork();
  if (pid == 0) {
    /* Child */
    x++; // 2
    exit(0);
  }

  /* Parent */
  x--; // 0
  exit(0);
}
```

# What Happens at `fork()`?

## Parent Address Space



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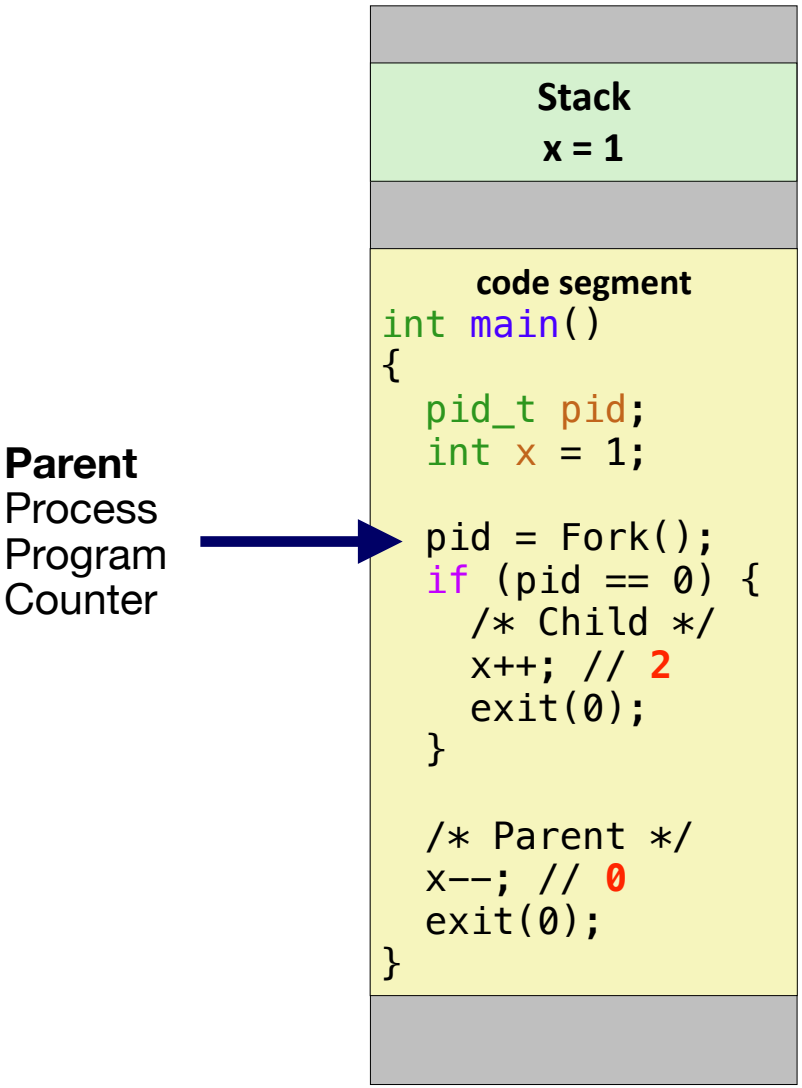

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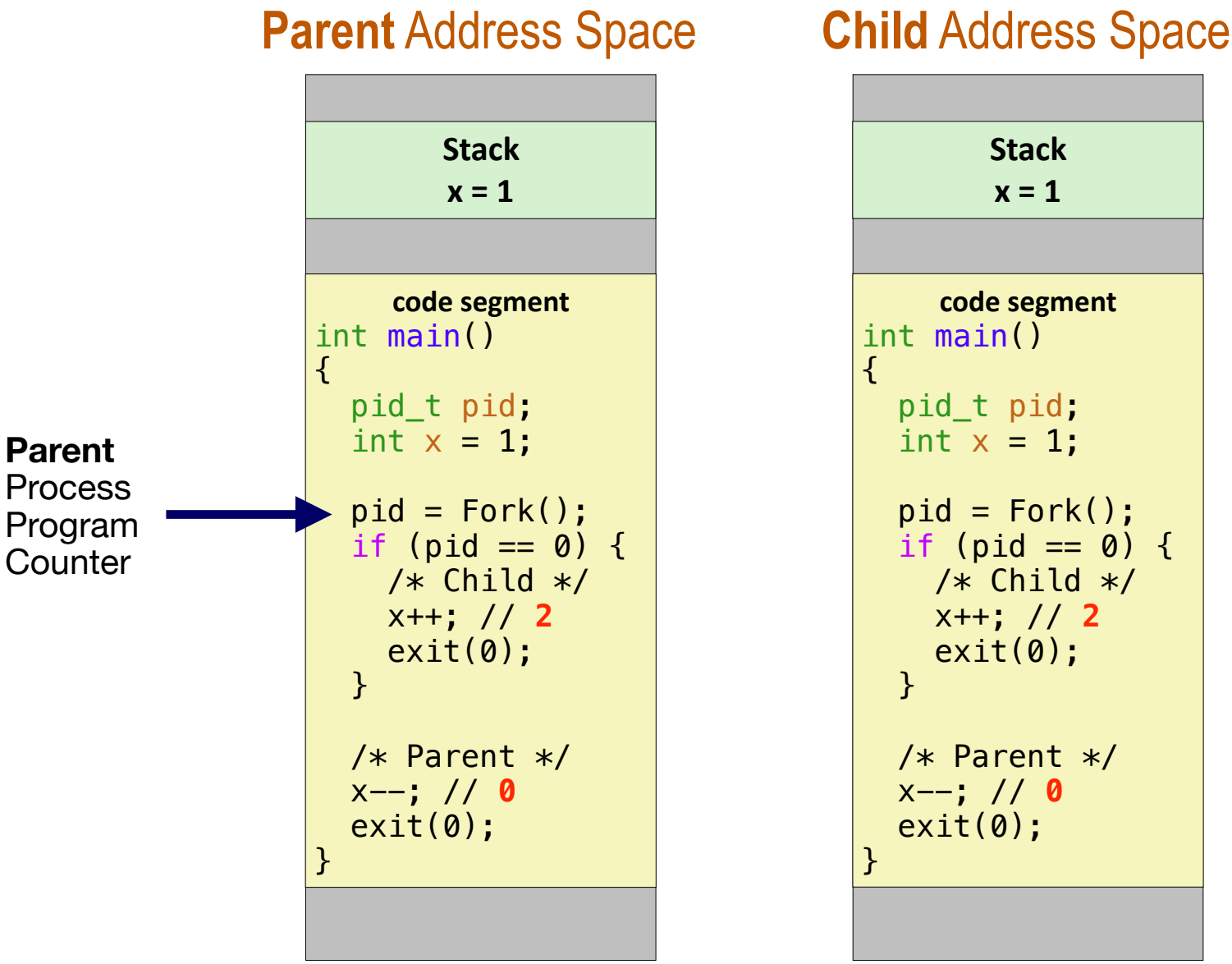

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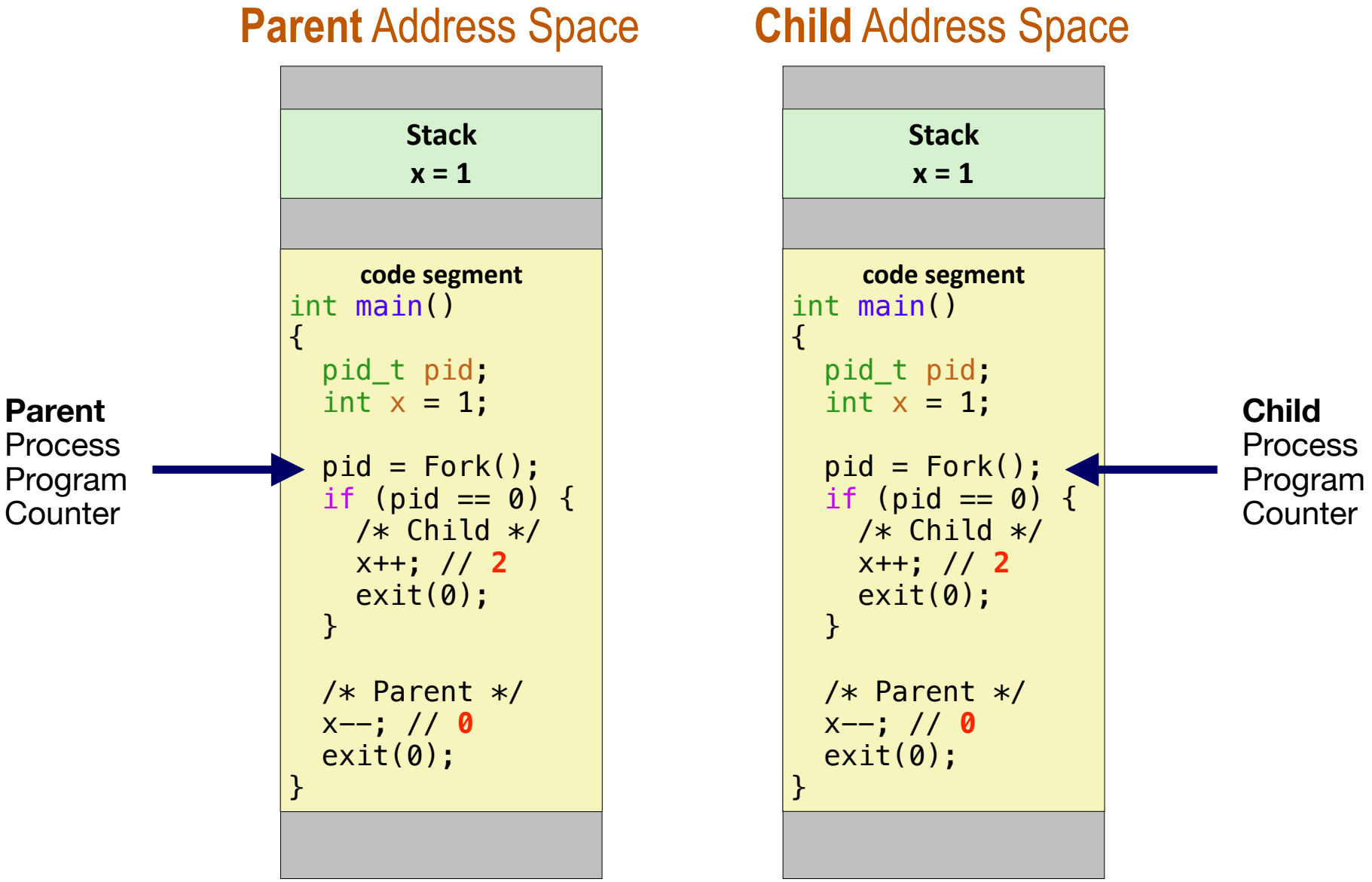
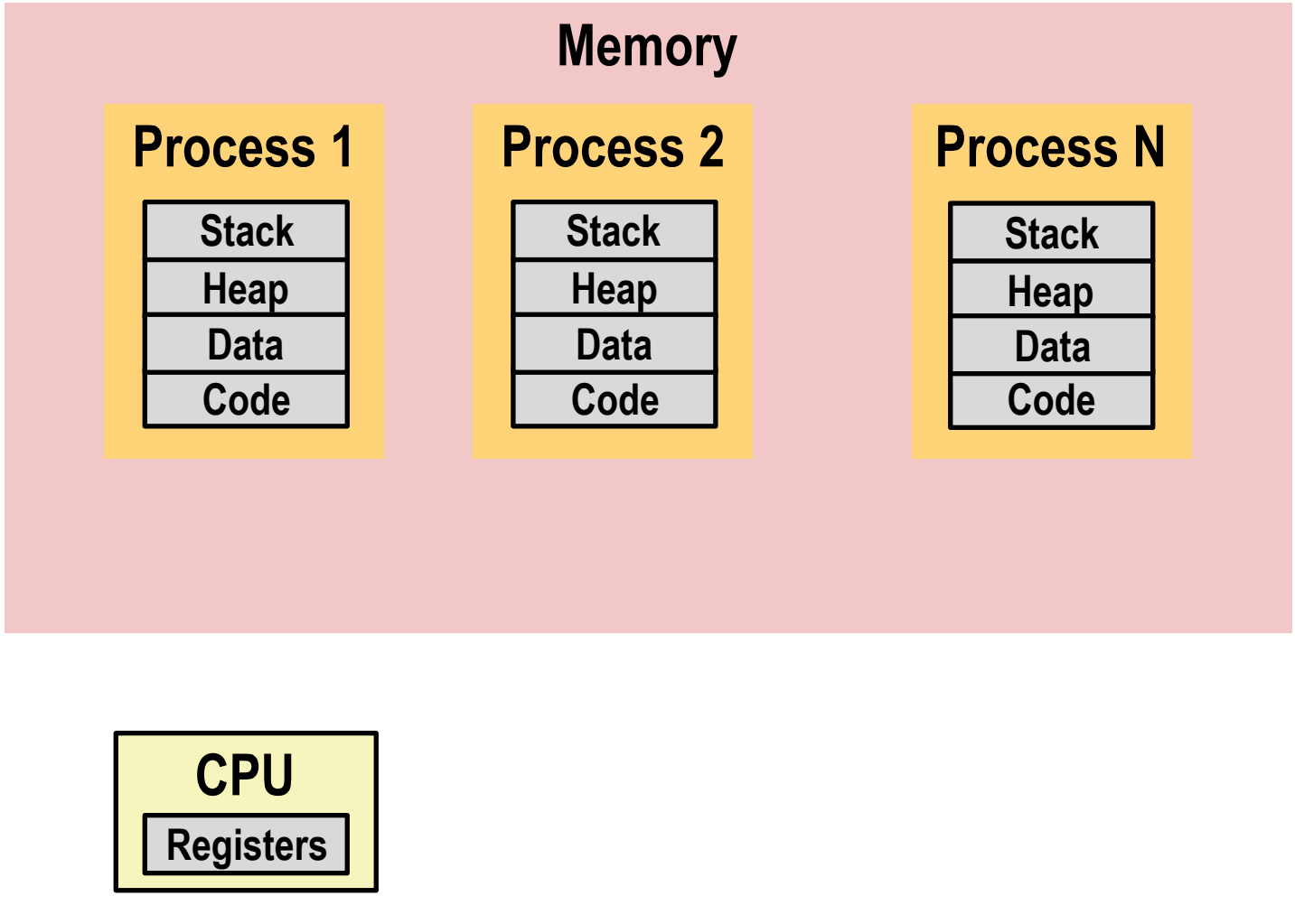


# Creating Processes

- Parent process creates a new child process by calling `fork`
- Child get an identical (but separate) copy of the parent's (virtual) address space (i.e., same stack copies, code, etc.)
- `int fork(void)`
  - Returns **0** to the child process
  - Returns **child's PID** to the parent process

# Multiprocessing Illustration



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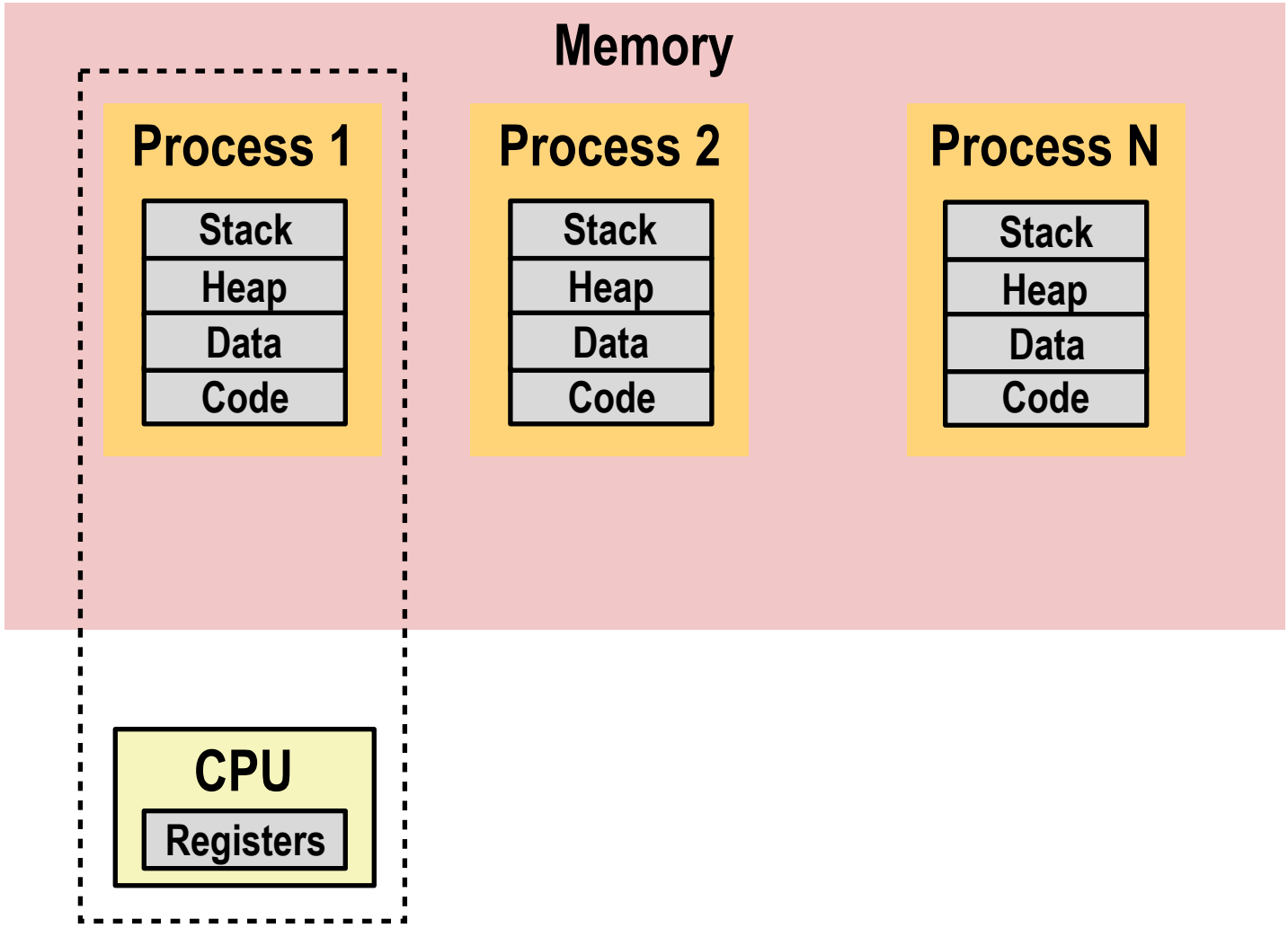

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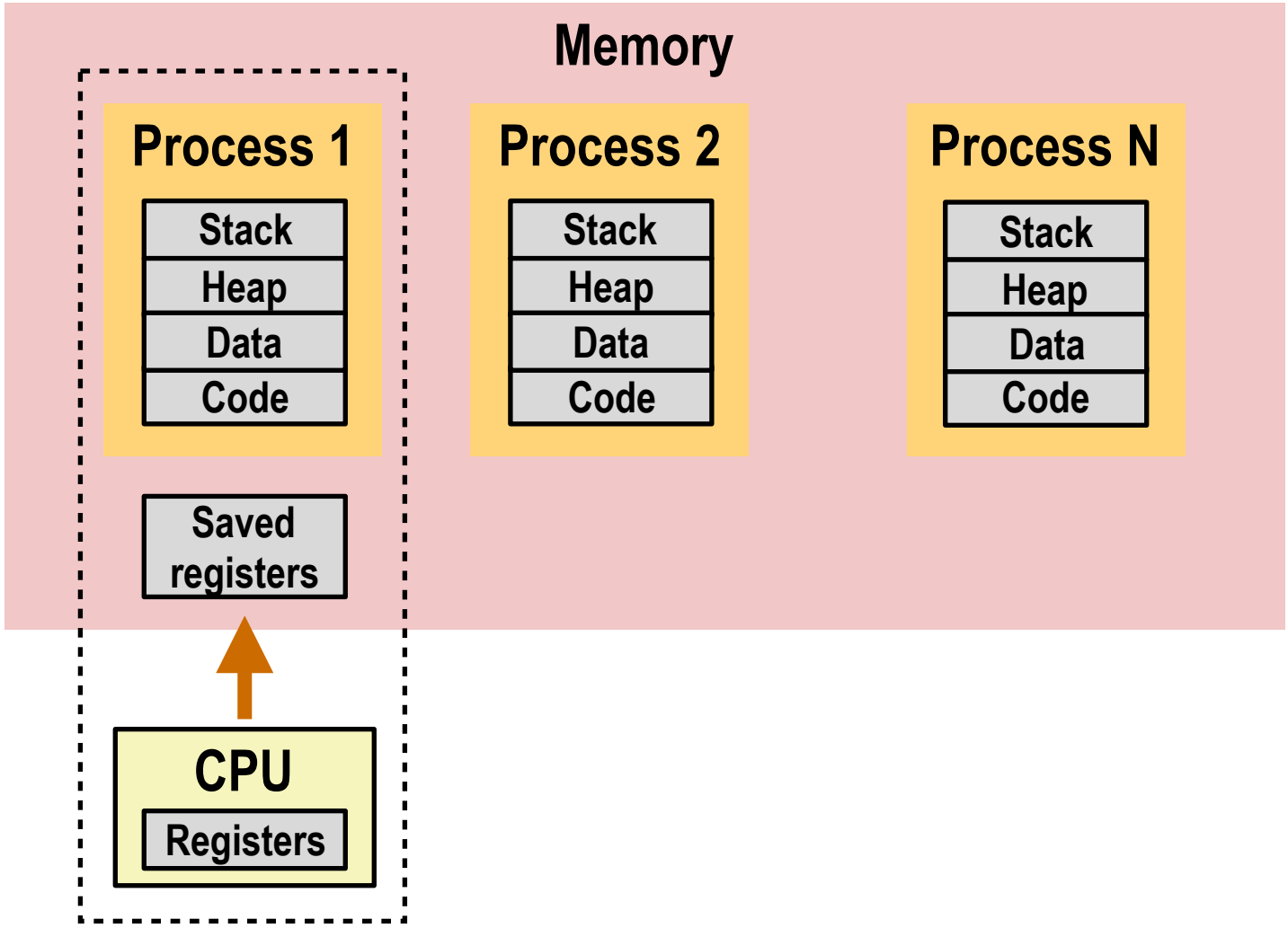

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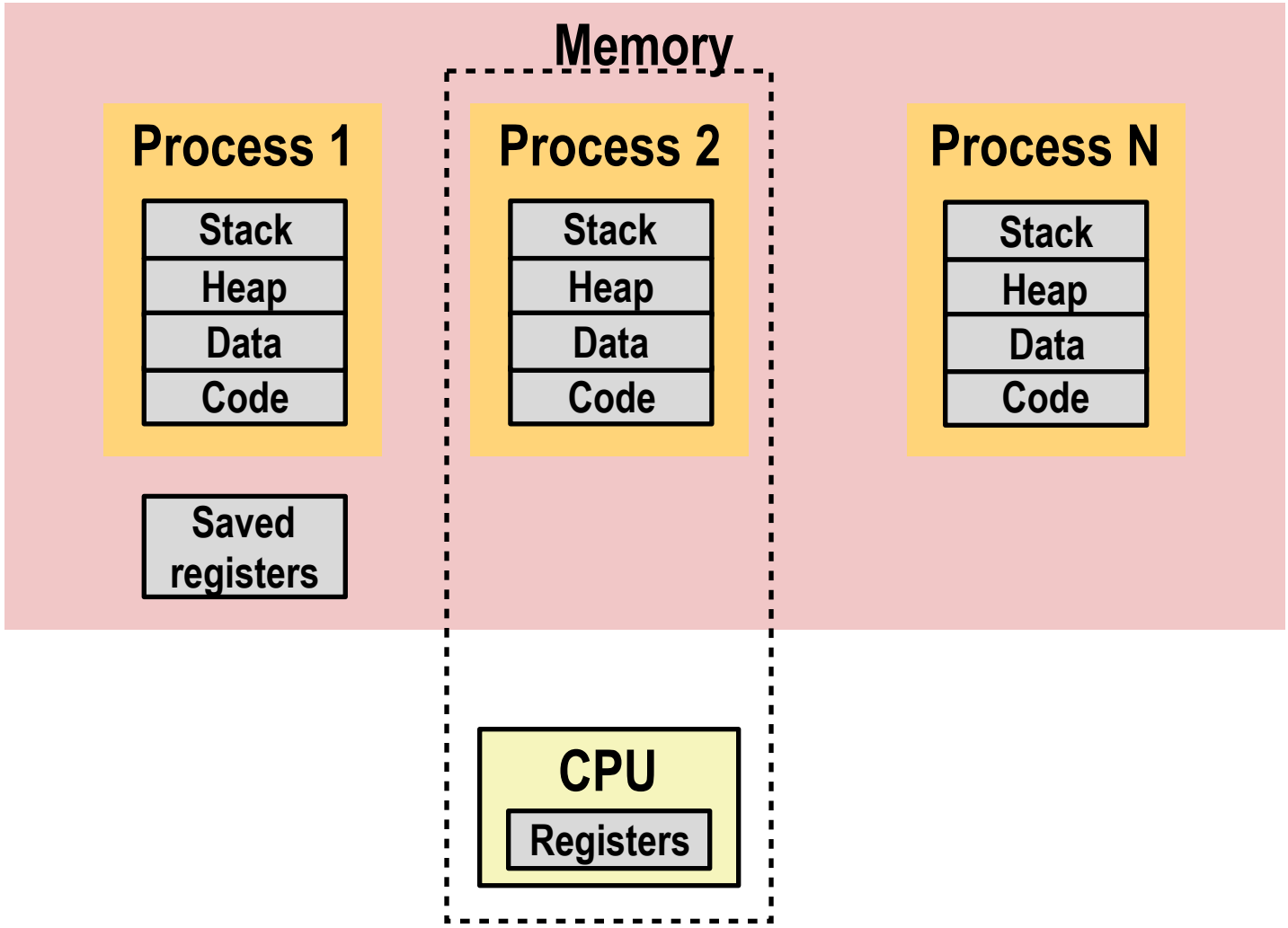

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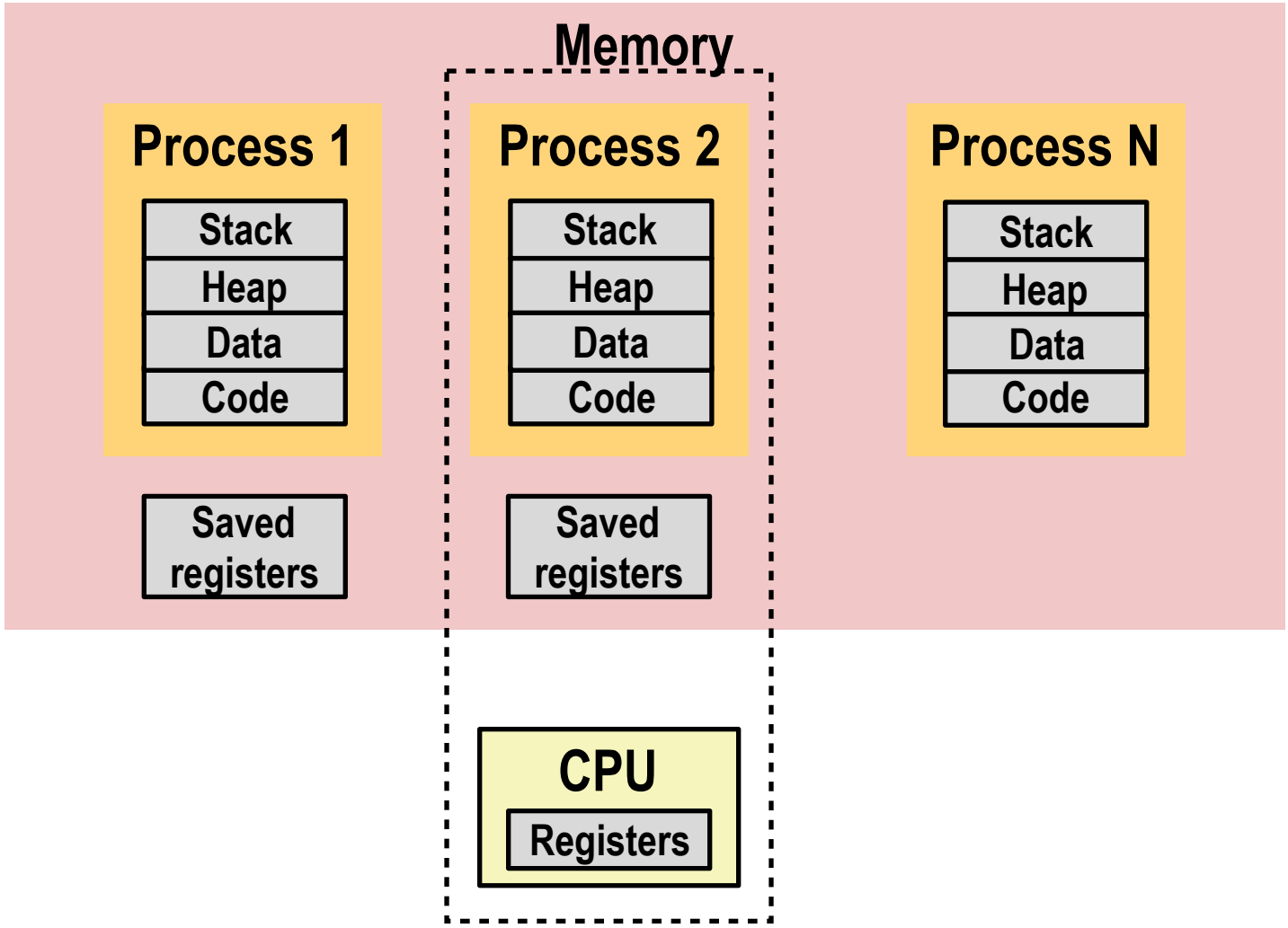

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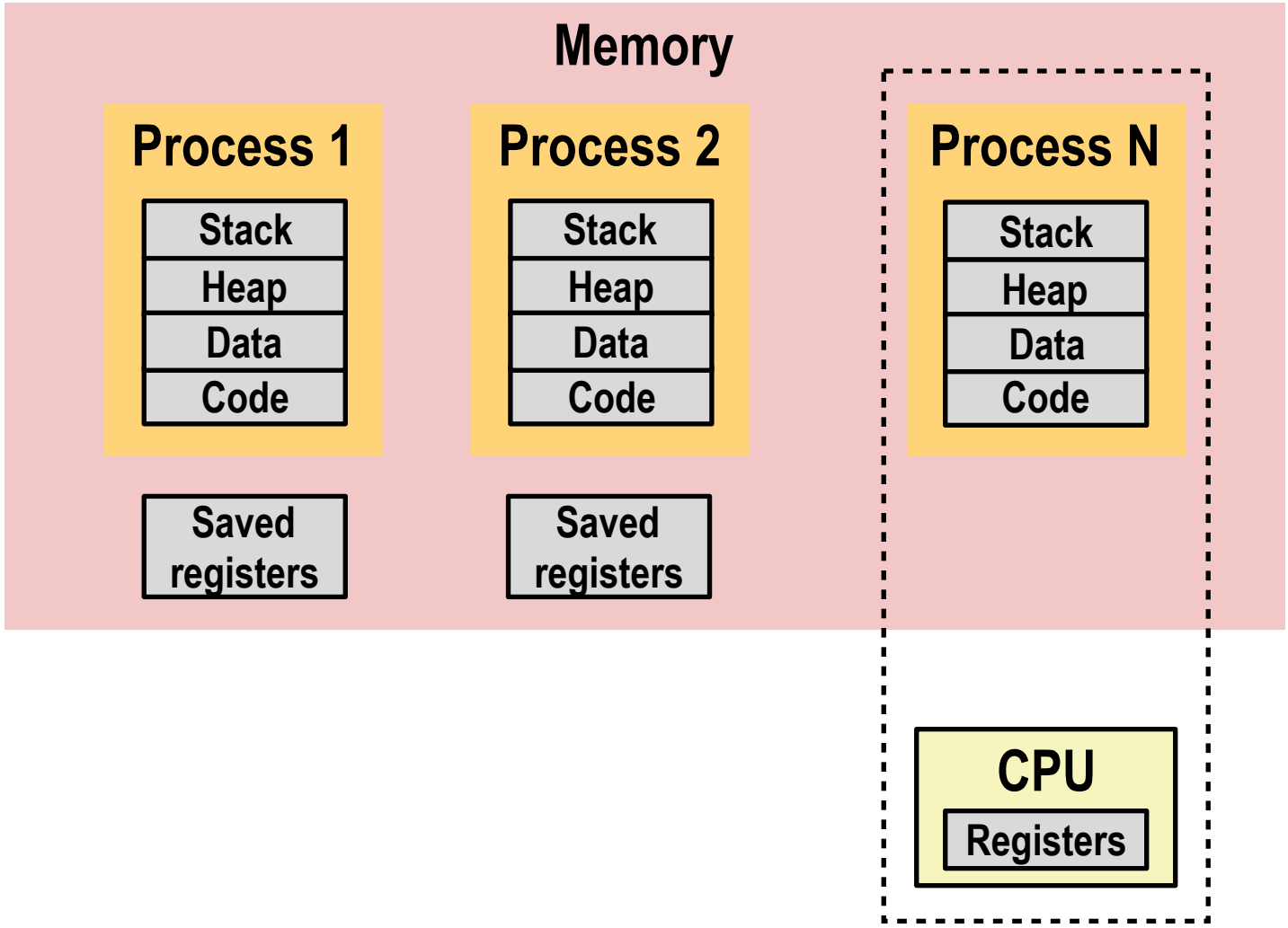

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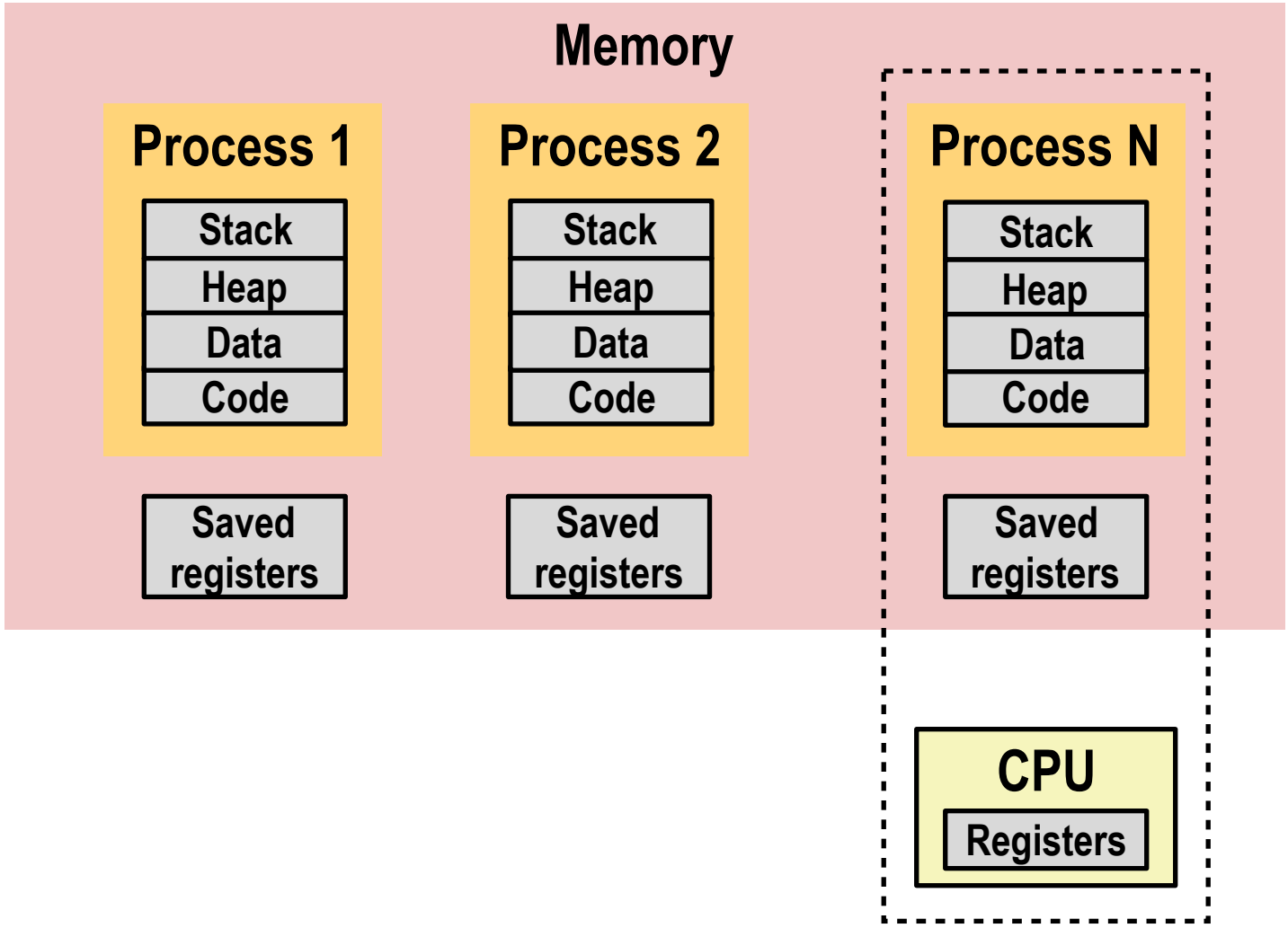

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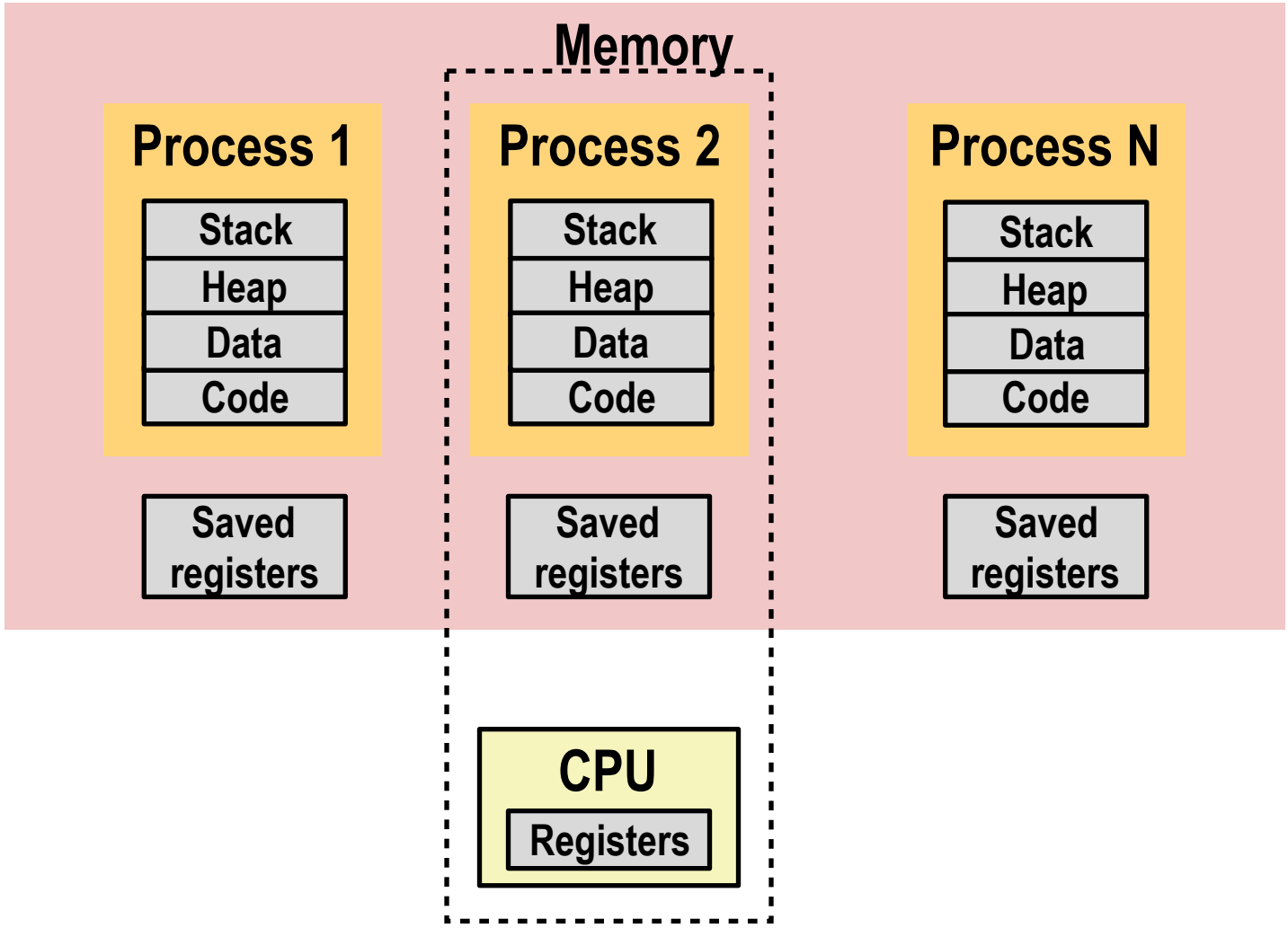

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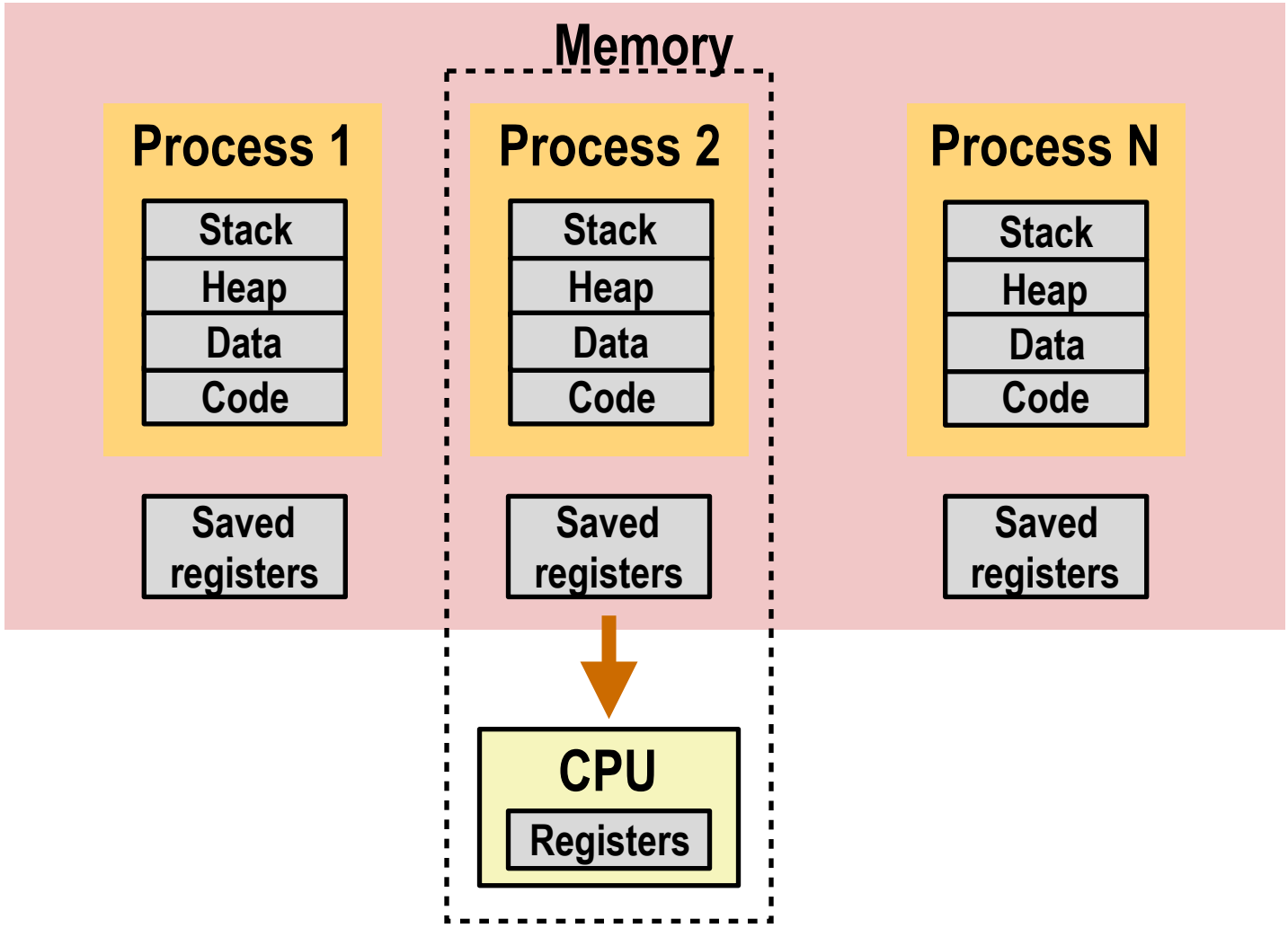

# `execve`: Loading and Running Programs

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

```
char *myargv[] = {"/bin/ls", "-lt", "/usr/include"};
char *environ[] = {"USER=droh", "PWD="/usr/droh"};

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

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- Overwrites code, data, and stack
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- Called once and never returns
  - …except if there is an error

# Summary

- 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
- 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

# Today

- Process Control
- Signals
- Non-local Jumps (if time permits)

# Signals

- A signal is a small message that notifies a process that an event of some type has occurred in the system
  - Sent from the **OS kernel**
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| *ID* | *Name* | *Default Action* | *Corresponding Event* |
|---|---|---|---|
| 2 | SIGINT | Terminate | User typed ctrl-c |
| 9 | SIGKILL | Terminate | Kill program (cannot override or ignore) |
| 11 | SIGSEGV | Terminate | Segmentation violation |
| 14 | SIGALRM | Terminate | Timer signal |
| 17 | SIGCHLD | Ignore | Child stopped or terminated |

# Signal Concepts: Sending a Signal

- Kernel sends (delivers) a signal to a destination process by updating some state in the context of the destination process
- Kernel sends a signal for one of the following reasons:

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- Kernel sends a signal for one of the following reasons:
  - Kernel has detected a system event such as:
    - Exception: divide-by-zero (SIGFPE)
    - Interrupt: user pressing Ctrl + C (SIGINT)
    - The termination of a child process (SIGCHLD)
  - Another process has invoked the `kill` system call to explicitly request the kernel to send a signal to the destination process.
    - Note: `kill` doesn't mean you are going to kill the target process. It is just a system call that allows you to send signals. Of course the signal you send could be SIGKILL.

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  - Catch the signal by executing a user-level function called signal handler
    - Similar to a hardware exception handler being called in response to an asynchronous interrupt:

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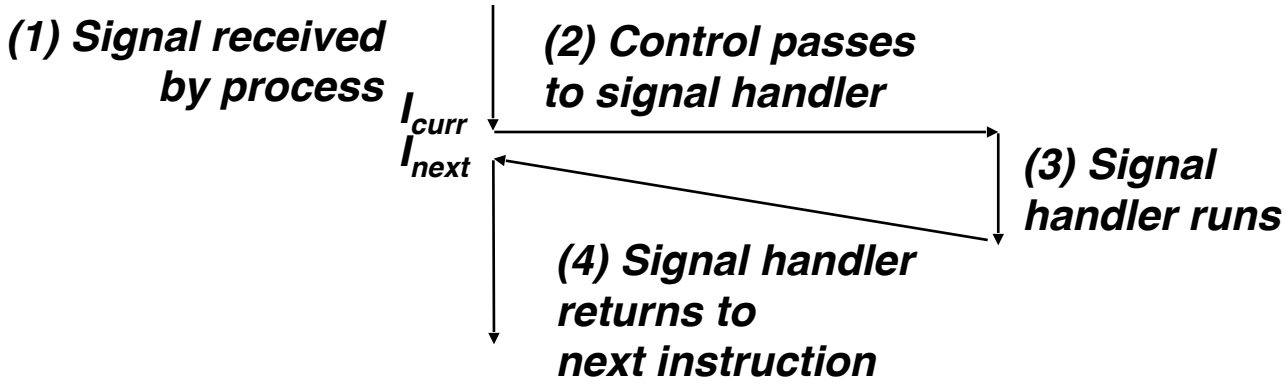

# Sending Signals with `/bin/kill` Program

- `/bin/kill` program sends arbitrary signal to a process
- Examples
  - **`/bin/kill -9 24818`**
    Send SIGKILL to process 24818
  - `/bin/kill` itself doesn't kill the process. 9 is the ID for the SIGKILL signal, which kills the process

```
linux> ./forks 16
Child1: pid=24818 pgrp=24817
Child2: pid=24819 pgrp=24817

linux> ps
  PID TTY          TIME CMD
24788 pts/2    00:00:00 tcsh
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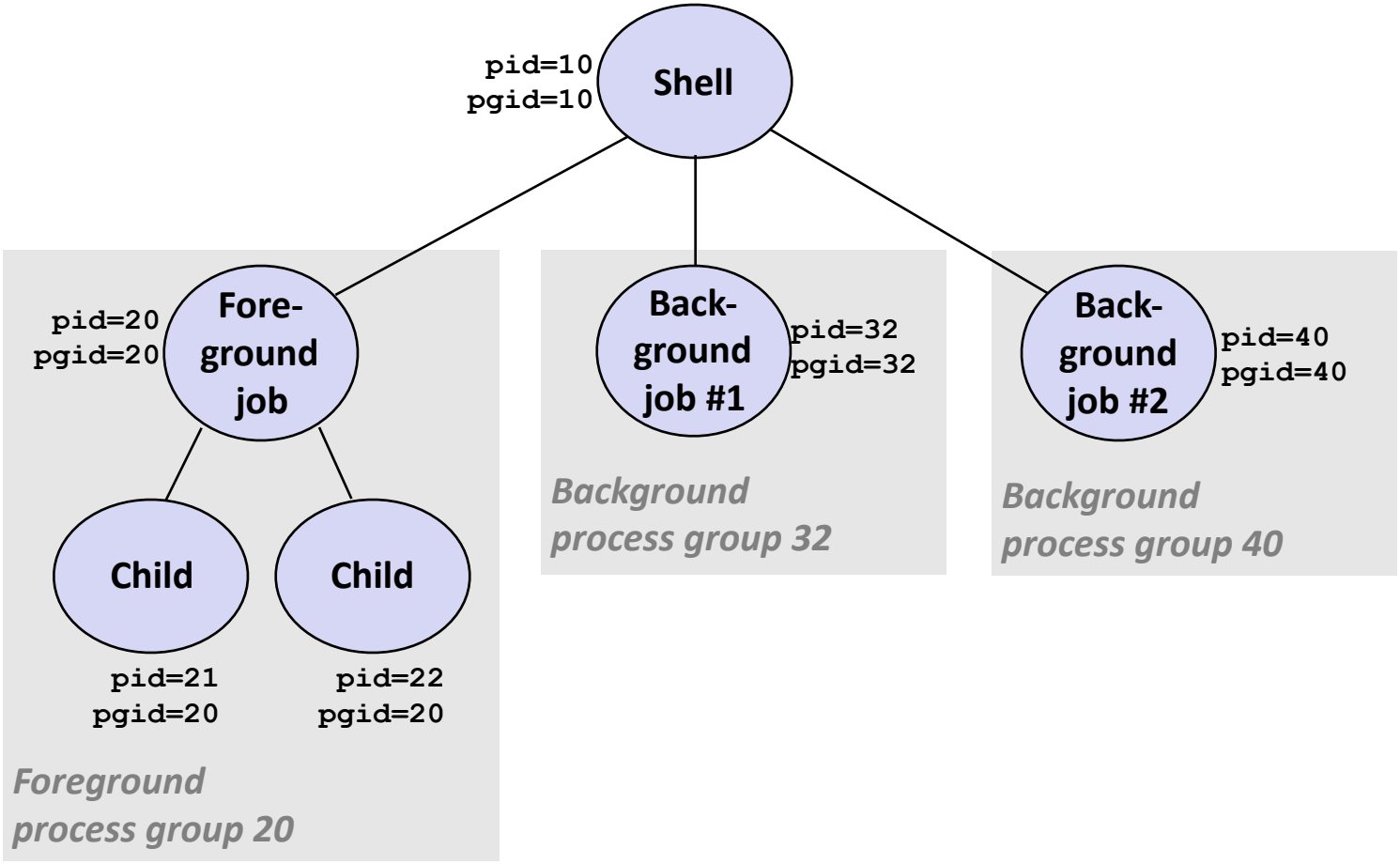
# Process Groups

- Every process belongs to exactly one process group



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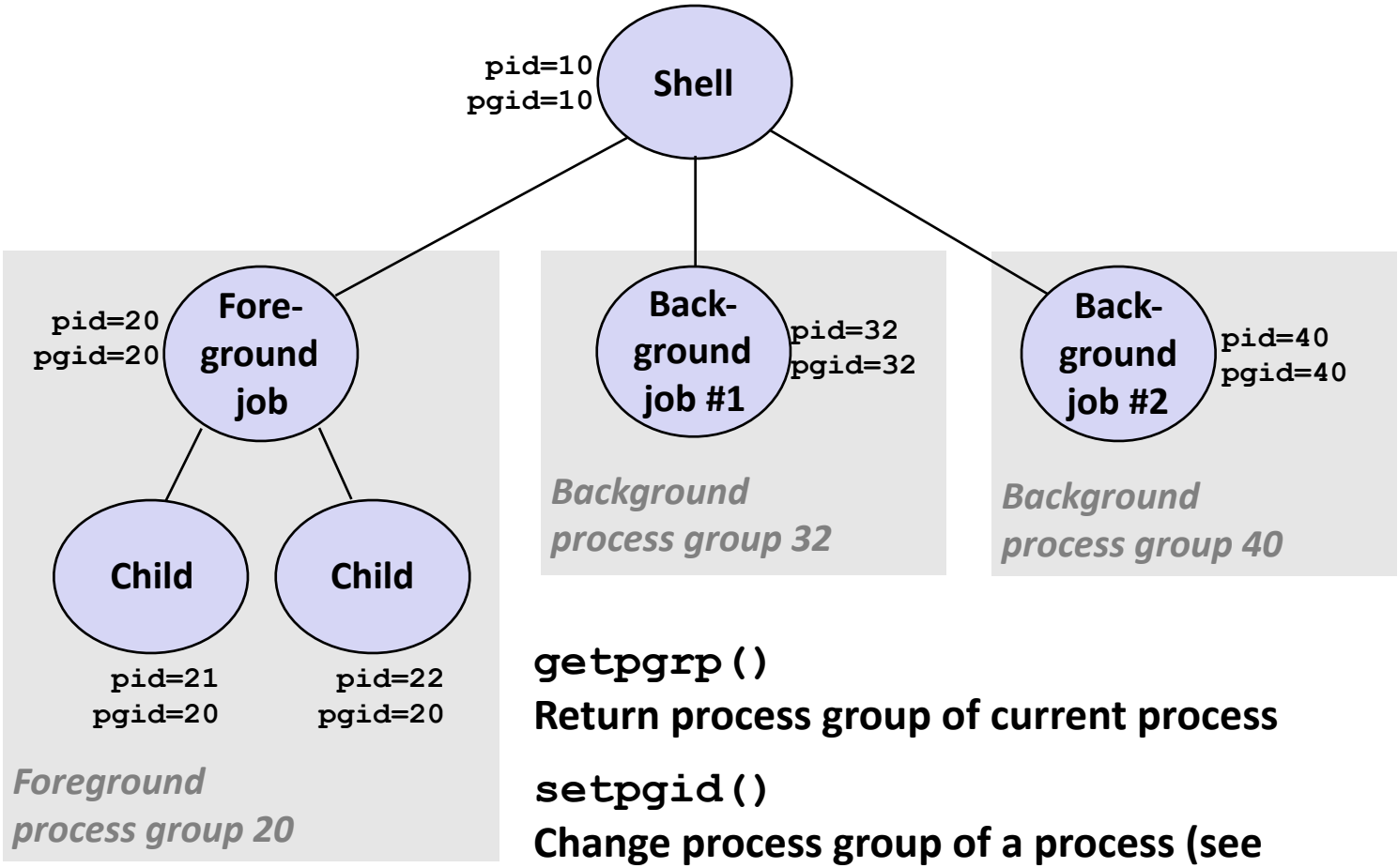


**`getpgrp()`**
**Return process group of current process**

**`setpgid()`**
**Change process group of a process (see text for details)**

# Sending Signals with `/bin/kill` Program

- `/bin/kill` program sends arbitrary signal to a process or process group

- Examples
  - **`/bin/kill -9 -24817`**
    Send SIGKILL to every process in process group 24817

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# Sending Signals from the Keyboard

- Typing ctrl-c causes the kernel to send a SIGINT to every job in the foreground process group.
  - SIGINT – default action is to terminate each process
- Typing ctrl-z causes the kernel to send a SIGTSTP to every job in the foreground process group.
  - SIGTSTP – default action is to stop (suspend) each process

# Example of `ctrl-c` and `ctrl-z`

```
bluefish> ./forks 17
Child: pid=28108 pgrp=28107
Parent: pid=28107 pgrp=28107

<types ctrl-z>
Suspended
bluefish> ps w
  PID TTY      STAT   TIME COMMAND
27699 pts/8    Ss     0:00 -tcsh
28107 pts/8    T      0:01 ./forks 17
28108 pts/8    T      0:01 ./forks 17
28109 pts/8    R+     0:00 ps w

bluefish> fg
./forks 17
<types ctrl-c>
bluefish> ps w
  PID TTY      STAT   TIME COMMAND
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28110 pts/8    R+     0:00 ps w
```

**STAT (process state) Legend:**

***First letter:***

**S: sleeping**

**T: stopped**

**R: running**

***Second letter:***

**s: session leader**

**+: foreground proc group**

**See “man ps” for more details**

# Sending Signals from the Keyboard

- Can you guess how it might be implemented?
  - Ctrl + C sends a keyboard interrupt to the CPU, which triggers an interrupt handler
  - The interrupt handler, executed by the kernel, triggers certain piece of the kernel, which generates the signal, which is then delivered to the target process

# Sending Signals with `kill` Function

```
void fork12()
{
    pid_t pid[N];
    int i;
    int child_status;

    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0) {
            /* Child: Infinite Loop */
            while(1)
                ;
        }

    for (i = 0; i < N; i++) {
        printf("Killing process %d\n", pid[i]);
        kill(pid[i], SIGINT);
    }

    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 terminated abnormally\n", wpid);
    }
}
```

*forks.c*

# Pending and Blocked Signals

- A signal is pending if sent but not yet received
  - There can be at most one pending signal of any particular type
  - That is: *Signals are not queued*
    - If a process has a pending signal of type k, then subsequent signals of type k that are sent to that process are discarded
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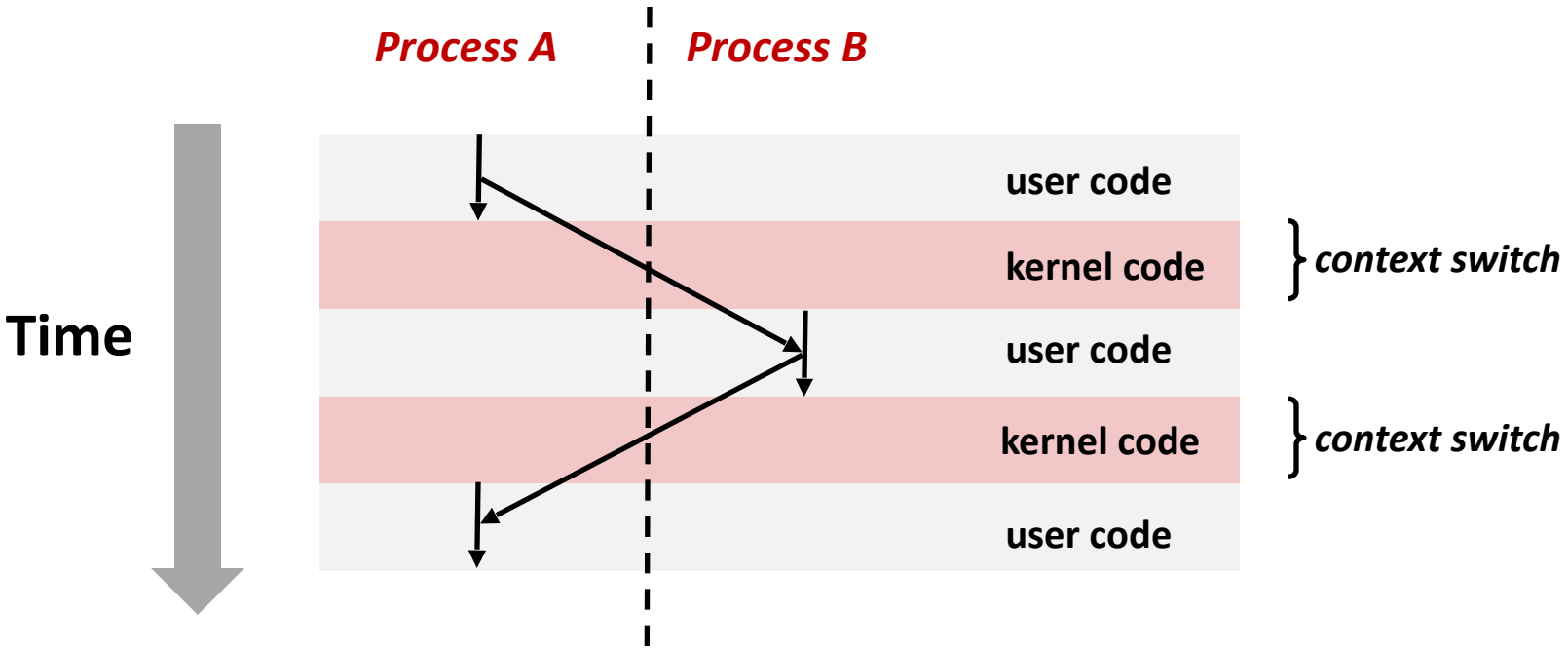
- A process can block the receipt of certain signals
  - Blocked signals can be delivered, but will not be received *until the signal is unblocked*

# Pending/Blocked Bits

- Kernel maintains pending and blocked bit vectors in the context of each process
  - pending: represents the set of pending signals
    - Kernel sets bit k in pending when a signal of type k is delivered
    - Kernel clears bit k in pending when a signal of type k is received
  - blocked: represents the set of blocked signals
    - Can be set and cleared by using the `sigprocmask` function
    - Also referred to as the signal mask.

# Receiving Signals

- Kernel handles signals delivered to a process *p* when it switches *p* from kernel mode to user mode (e.g., after a context switch)



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  - Repeat for all nonzero k in pnb
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# Default Actions

- Each signal type has a predefined default action, which is one of:
  - The process terminates
  - The process stops until restarted by a SIGCONT signal
  - The process ignores the signal

# Installing Signal Handlers

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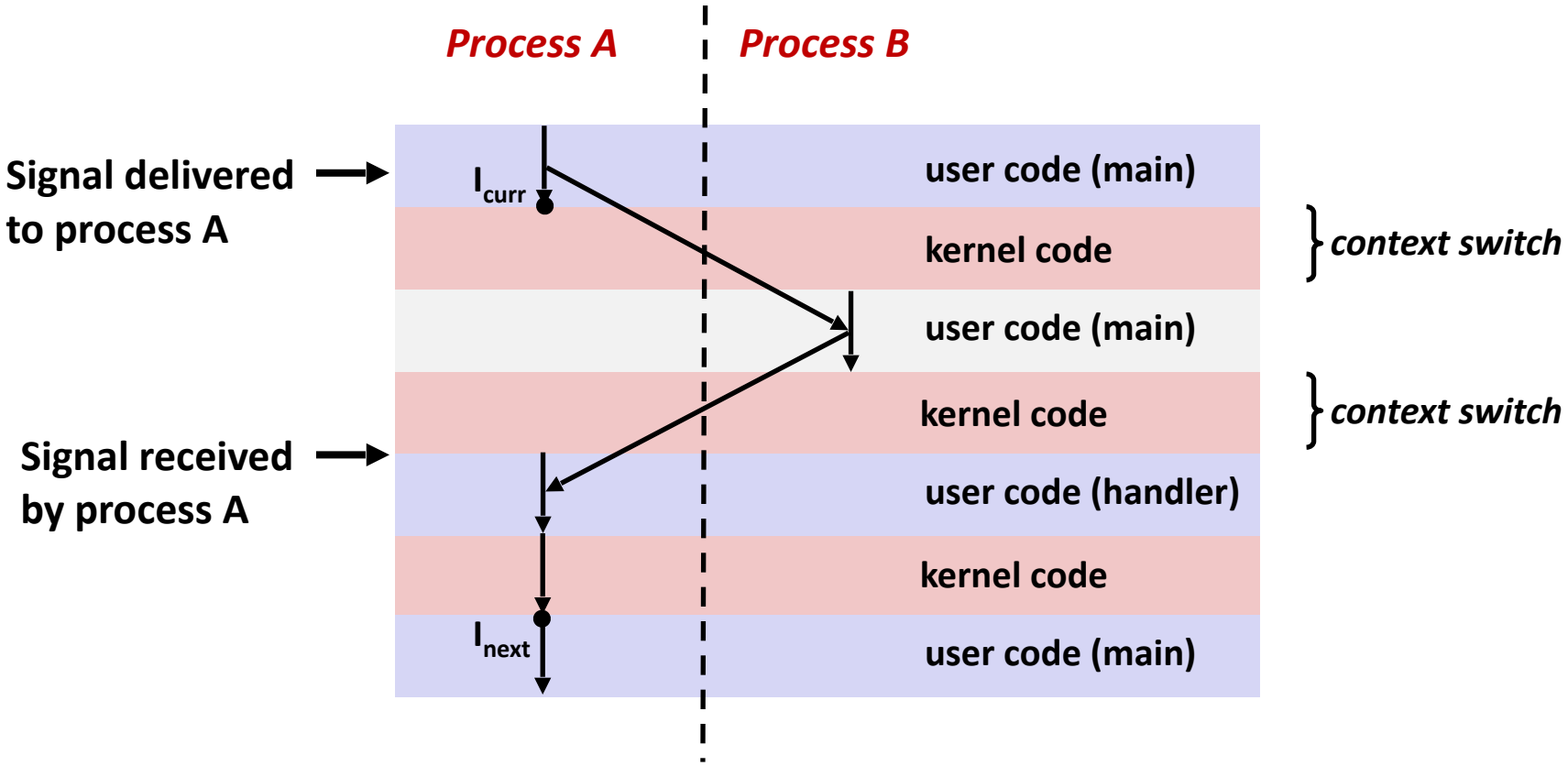
- Different values for handler:
  - SIG_IGN: ignore signals of type signum
  - SIG_DFL: revert to the default action on receipt of signals of type signum
  - Otherwise, handler is the address of a user-level function (signal handler)
    - Called when process receives signal of type signum
    - Referred to as "installing" the handler
    - Executing handler is called "catching" or "handling" the signal
    - When the handler executes its return statement, control passes back to instruction in the control flow of the process that was interrupted by receipt of the signal

# Signal Handling Example

```c
void sigint_handler(int sig) /* SIGINT handler */
{
    printf("So you think you can stop the bomb with ctrl-c, do you?\n");
    sleep(2);
    printf("Well...");
    fflush(stdout);
    sleep(1);
    printf("OK. :-)\n");
    exit(0);
}

int main()
{
    /* Install the SIGINT handler */
    if (signal(SIGINT, sigint_handler) == SIG_ERR)
        unix_error("signal error");

    /* Wait for the receipt of a signal */
    pause();

    return 0;
}
```

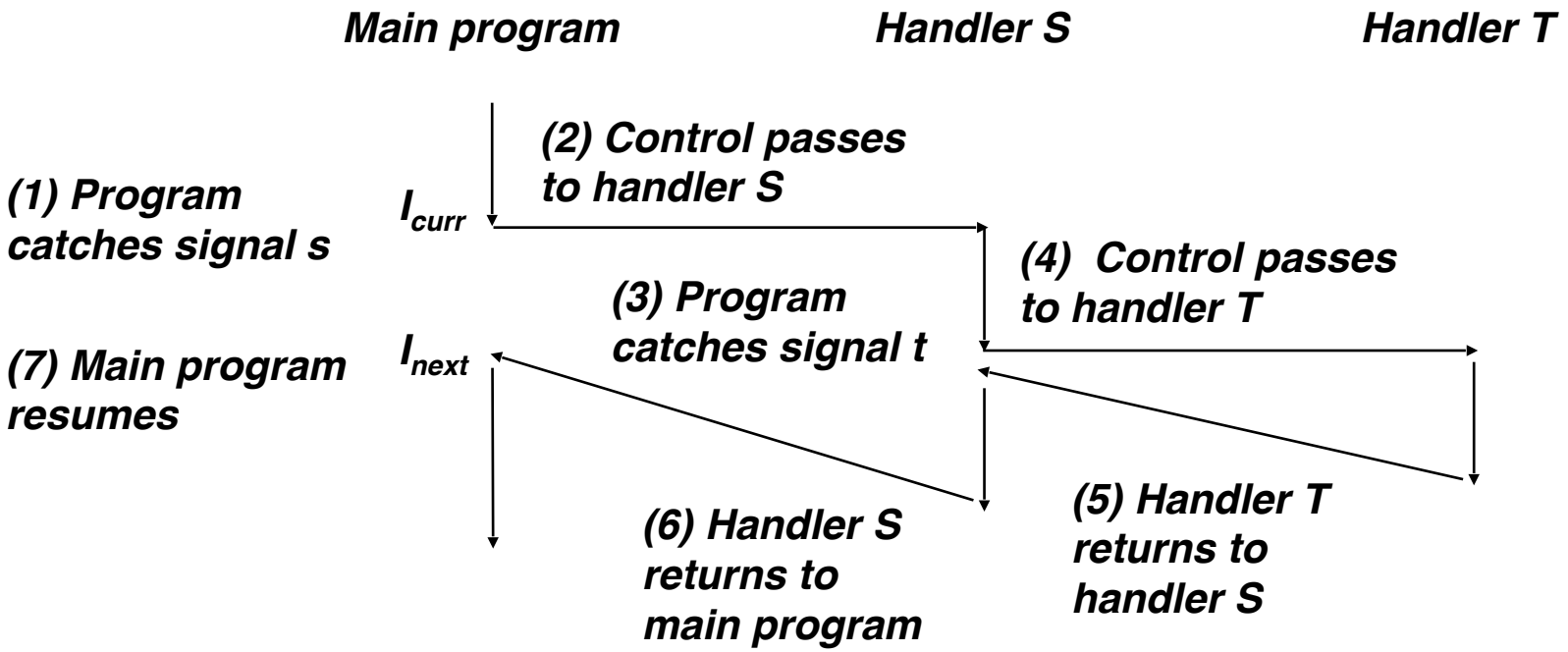
sigint.c

# View Signal Handlers as Concurrent Flows



# Nested Signal Handlers

- Handlers can be interrupted by other handlers



# Blocking Signals

```
sigset_t mask, prev_mask;

sigemptyset(&mask);
sigaddset(&mask, SIGINT);

/* Block SIGINT and save previous blocked set */
sigprocmask(SIG_BLOCK, &mask, &prev_mask);

/* Code region that will not be interrupted by SIGINT */

/* Restore previous blocked set, unblocking SIGINT */
sigprocmask(SIG_SETMASK, &prev_mask, NULL);
```

- Explicit blocking and unblocking signal
  - `sigprocmask` function
  - `sigemptyset` – Create empty set
  - `sigfillset` – Add every signal number to set
  - `sigaddset` – Add signal number to set
  - `sigdelset` – Delete signal number from set

# Safe Signal Handling

- Handlers are tricky because they are concurrent with main program and may share the same global data structures.

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static int x = 5;
void handler(int sig)
{
    x = 10;
}

int main(int argc, char **argv)
{
    int pid;
    Signal(SIGCHLD, handler);

    if ((pid = Fork()) == 0) { /* Child */
        Execve("/bin/date", argv, NULL);
    }

    if (x == 5)
        y = x * 2; // You'd expect y == 10
    exit(0);
}
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- Parent process executes and finishes `if (x == 5)`

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What if the following happens:

- Parent process executes and finishes `if (x == 5)`
- Context switch to child, which then terminates, sends a SIGCHLD signal
- Another context switch back to parent, and now the kernel needs to execute the SIGCHLD handler

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What if the following happens:

- Parent process executes and finishes `if (x == 5)`
- Context switch to child, which then terminates, sends a SIGCHLD signal
- Another context switch back to parent, and now the kernel needs to execute the SIGCHLD handler
- When return to parent process, **y == 20**!

# Safe Signal Handling

- Handlers are tricky because they are concurrent with main program and may share the same global data structures.
  - Programmers have no control over the execution ordering between the main program and the signal handler, that is:
    - when a signal happens/delivers (depends on user or other process)
    - when the signal handler will be executed (depends on kernel)
  - If not careful, shared data structures can be corrupted

# Fixing the Signal Handling Bug

```
static int x = 5;
void handler(int sig)
{
    x = 10;
}

int main(int argc, char **argv)
{
    int pid;
    sigset_t mask_all, prev_all;
    sigfillset(&mask_all);
    signal(SIGCHLD, handler);

    if ((pid = Fork()) == 0) { /* Child */
        Execve("/bin/date", argv, NULL);
    }

    Sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
    if (x == 5)
        y = x * 2; // You'd expect y == 10
    Sigprocmask(SIG_SETMASK, &prev_all, NULL);

    exit(0);
}
```

- Block all signals before accessing a shared, global data structure.
- Can't use a lock (later in this course)

# Async-Signal-Safety

- Function is async-signal-safe if either reentrant (e.g., no access to global variables) or non-interruptible by signals.

# Async-Signal-Safety

- Function is async-signal-safe if either reentrant (e.g., no access to global variables) or non-interruptible by signals.
- Posix guarantees 117 functions to be async-signal-safe
  - Source: “man 7 signal”
  - Popular functions on the list:
    - `_exit`, `write`, `wait`, `waitpid`, `sleep`, `kill`
  - Popular functions that are not on the list:
    - `printf`, `sprintf`, `malloc`, `exit`
    - Unfortunate fact: `write` is the only async-signal-safe output function

# Another Unsafe Signal Handler Example

# Another Unsafe Signal Handler Example

- Assume a program wants to do the following:
  - The parent creates multiple child processes
  - When each child process is created, add the child PID to a queue
  - When a child process terminates, the parent process removes the child PID from the queue

# Another Unsafe Signal Handler Example

- Assume a program wants to do the following:
  - The parent creates multiple child processes
  - When each child process is created, add the child PID to a queue
  - When a child process terminates, the parent process removes the child PID from the queue
- One possible implementation:
  - An array for keeping the child PIDs
  - Use a loop to fork child, and add PID to the array after fork
  - Install a handler for SIGCHLD in parent process
  - The SIGCHLD handler removes the child PID

# First Attempt

```
void handler(int sig)
{
    pid_t pid;

    while ((pid = wait(NULL)) > 0) { /* Reap child */
        deletejob(pid); /* Delete the child from the job list */
    }
}

int main(int argc, char **argv)
{
    int pid;

    Signal(SIGCHLD, handler);
    initjobs(); /* Initialize the job list */

    while (1) {
        if ((pid = Fork()) == 0) { /* Child */
            Execve("/bin/date", argv, NULL);
        }
        addjob(pid);  /* Add the child to the job list */
    }
    exit(0);
}
```

# Second Attempt

```
void handler(int sig)
{
    sigset_t mask_all, prev_all;
    pid_t pid;

    sigfillset(&mask_all);
    while ((pid = wait(NULL)) > 0) {
        sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
        deletejob(pid);
        sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
}
int main(int argc, char **argv)
{
    int pid;
    sigset_t mask_all, prev_all;

    sigfillset(&mask_all);
    signal(SIGCHLD, handler);
    initjobs(); /* Initialize the job list */

    while (1) {
        if ((pid = Fork()) == 0) {
            Execve("/bin/date", argv, NULL);
        }
        sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
        addjob(pid);
        sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
    exit(0);
}
```

# Second Attempt

```
void handler(int sig)
{
    sigset_t mask_all, prev_all;
    pid_t pid;

    sigfillset(&mask_all);
    while ((pid = wait(NULL)) > 0) {
        sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
        deletejob(pid);
        sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
}
int main(int argc, char **argv)
{
    int pid;
    sigset_t mask_all, prev_all;

    sigfillset(&mask_all);
    signal(SIGCHLD, handler);
    initjobs(); /* Initialize the job list */

    while (1) {
        if ((pid = Fork()) == 0) {
            Execve("/bin/date", argv, NULL);
        }
        sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
        addjob(pid);
        sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
    exit(0);
}
```

The following can happen:

# Second Attempt

```
void handler(int sig)
{
    sigset_t mask_all, prev_all;
    pid_t pid;

    sigfillset(&mask_all);
    while ((pid = wait(NULL)) > 0) {
        sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
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int main(int argc, char **argv)
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    int pid;
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    while (1) {
        if ((pid = Fork()) == 0) {
            Execve("/bin/date", argv, NULL);
        }
        sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
        addjob(pid);
        sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
    exit(0);
}
```

The following can happen:

- Child runs, and terminates

# Second Attempt

```
void handler(int sig)
{
    sigset_t mask_all, prev_all;
    pid_t pid;

    sigfillset(&mask_all);
    while ((pid = wait(NULL)) > 0) {
        sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
        deletejob(pid);
        sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
}
int main(int argc, char **argv)
{
    int pid;
    sigset_t mask_all, prev_all;

    sigfillset(&mask_all);
    signal(SIGCHLD, handler);
    initjobs(); /* Initialize the job list */

    while (1) {
        if ((pid = Fork()) == 0) {
            Execve("/bin/date", argv, NULL);
        }
        sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
        addjob(pid);
        sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
    exit(0);
}
```

The following can happen:

- Child runs, and terminates
- Kernel sends SIGCHLD

# Second Attempt

```
void handler(int sig)
{
    sigset_t mask_all, prev_all;
    pid_t pid;

    sigfillset(&mask_all);
    while ((pid = wait(NULL)) > 0) {
        sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
        deletejob(pid);
        sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
}
int main(int argc, char **argv)
{
    int pid;
    sigset_t mask_all, prev_all;

    sigfillset(&mask_all);
    signal(SIGCHLD, handler);
    initjobs(); /* Initialize the job list */

    while (1) {
        if ((pid = Fork()) == 0) {
            Execve("/bin/date", argv, NULL);
        }
        sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
        addjob(pid);
        sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
    exit(0);
}
```

The following can happen:

- Child runs, and terminates
- Kernel sends SIGCHLD
- Context switch to parent, but before it can run, kernel has to handle SIGCHLD first

# Second Attempt

```
void handler(int sig)
{
    sigset_t mask_all, prev_all;
    pid_t pid;

    sigfillset(&mask_all);
    while ((pid = wait(NULL)) > 0) {
        sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
        deletejob(pid);
        sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
}
int main(int argc, char **argv)
{
    int pid;
    sigset_t mask_all, prev_all;

    sigfillset(&mask_all);
    signal(SIGCHLD, handler);
    initjobs(); /* Initialize the job list */

    while (1) {
        if ((pid = Fork()) == 0) {
            Execve("/bin/date", argv, NULL);
        }
        sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
        addjob(pid);
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    }
    exit(0);
}
```

The following can happen:

- Child runs, and terminates
- Kernel sends SIGCHLD
- Context switch to parent, but before it can run, kernel has to handle SIGCHLD first
- The handler deletes the job, which does nothing

# Second Attempt

```
void handler(int sig)
{
    sigset_t mask_all, prev_all;
    pid_t pid;

    sigfillset(&mask_all);
    while ((pid = wait(NULL)) > 0) {
        sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
        deletejob(pid);
        sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
}
int main(int argc, char **argv)
{
    int pid;
    sigset_t mask_all, prev_all;

    sigfillset(&mask_all);
    signal(SIGCHLD, handler);
    initjobs(); /* Initialize the job list */

    while (1) {
        if ((pid = Fork()) == 0) {
            Execve("/bin/date", argv, NULL);
        }
        sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
        addjob(pid);
        sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
    exit(0);
}
```

The following can happen:

- Child runs, and terminates
- Kernel sends SIGCHLD
- Context switch to parent, but before it can run, kernel has to handle SIGCHLD first
- The handler deletes the job, which does nothing
- The parent process resumes and adds a terminated child to job list

# Third Attempt (The Correct One)

```
int main(int argc, char **argv)
{
    int pid;
    sigset_t mask_all, mask_one, prev_one;

    Sigfillset(&mask_all);
    Sigemptyset(&mask_one);
    Sigaddset(&mask_one, SIGCHLD);
    Signal(SIGCHLD, handler);
    initjobs(); /* Initialize the job list */

    while (1) {
        Sigprocmask(SIG_BLOCK, &mask_one, &prev_one); /* Block SIGCHLD */
        if ((pid = Fork()) == 0) { /* Child process */
            Sigprocmask(SIG_SETMASK, &prev_one, NULL); /* Unblock SIGCHLD */
            Execve("/bin/date", argv, NULL);
        }
        Sigprocmask(SIG_BLOCK, &mask_all, NULL); /* Parent process */
        addjob(pid);  /* Add the child to the job list */
        Sigprocmask(SIG_SETMASK, &prev_one, NULL);  /* Unblock SIGCHLD */
    }
    exit(0);
}
```

# Today

- Process Control
- Signals
- Non-local Jumps (if time permits)

# `setjmp/longjmp` Example

Goal: return directly to original caller from a deeply-nested function

```
/* Deeply nested function foo */
void foo(void)
{
    if (error1)
        longjmp(buf, 1);
    bar();
}

void bar(void)
{
    if (error2)
        longjmp(buf, 2);
}
```

```
jmp_buf buf;

int error1 = 0;
int error2 = 1;

void foo(void), bar(void);

int main()
{
    switch(setjmp(buf)) {
    case 0:
        foo();
        break;
    case 1:
        printf("Error1\n");
        break;
    case 2:
        printf("Error2\n");
        break;
    default:
        printf("Unknown error\n");
    }
    exit(0);
}
```

# Nonlocal Jumps: `setjmp/longjmp`

- Powerful (but dangerous) user-level mechanism for transferring control to an arbitrary location
  - Controlled to way to break the procedure call / return discipline
  - Useful for error recovery and signal handling

- `int setjmp(jmp_buf j)`
  - Must be called before longjmp
  - Identifies a return site for a subsequent longjmp
  - Called once, returns one or more times

- Implementation:
  - Remember where you are by storing the current register context, stack pointer, and PC value in jmp_buf
  - Return 0

# `setjmp/longjmp`

- `void longjmp(jmp_buf j, int i)`
  - Meaning:
    - return from the **`setjmp`** remembered by jump buffer **`j`** again ...
    - … this time returning `i` instead of 0
  - Called after **`setjmp`**
  - Called once, but never returns

# `setjmp/longjmp`

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  - Meaning:
    - return from the **`setjmp`** remembered by jump buffer **`j`** again ...
    - … this time returning `i` instead of 0
  - Called after **`setjmp`**
  - Called once, but never returns

- `longjmp` Implementation:
  - Restore register context (stack pointer, base pointer, PC value) from jump buffer **`j`**
  - Set **`%eax`** (the return value) to **`i`**
  - Jump to the location indicated by the PC stored in jump buf **`j`**

# Limitations of Nonlocal Jumps

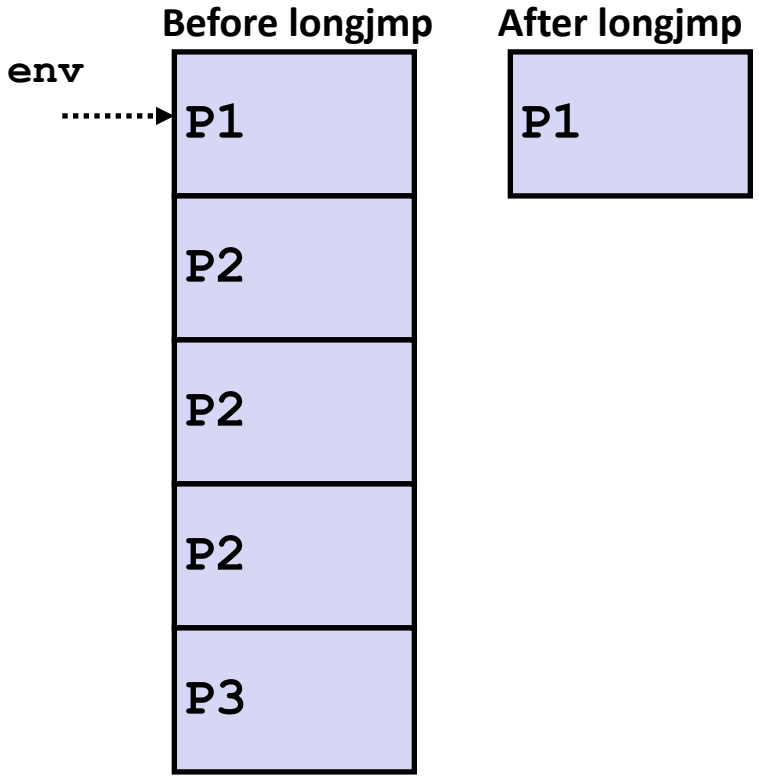
- Works within stack discipline
  - Can only long jump to environment of function that has been called but not yet completed

```
jmp_buf env;

P1()
{
  if (setjmp(env)) {
    /* Long Jump to here */
  } else {
    P2();
  }
}

P2()
{  . . . P2(); . . . P3(); }

P3()
{
  longjmp(env, 1);
}
```



# Limitations of Nonlocal Jumps

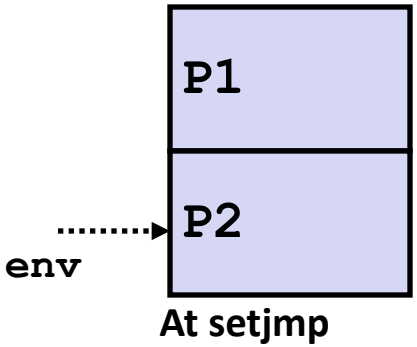
- This example violates stack principle

```
jmp_buf env;

P1()
{
  P2(); P3();
}

P2()
{
   if (setjmp(env)) {
    /* Long Jump to here */
  }
}

P3()
{
  longjmp(env, 1);
}
```



# Limitations of Nonlocal Jumps

- This example violates stack principle

```
jmp_buf env;

P1()
{
  P2(); P3();
}

P2()
{
   if (setjmp(env)) {
    /* Long Jump to here */
  }
}

P3()
{
  longjmp(env, 1);
}
```