Processes (cont.): exec, wait, signal

Computer Systems Programming, Summer 2025

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Poll Everywhere

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- How is penn-vector going?
  - I haven’t started
  - I have read the spec
  - I’ve setup the container
  - I’ve started writing code
  - I’ve started writing code and I am pretty sure I understand what is going on
  - I’m done!

Administrivia

- First Assignment (HW00 penn-vector)
  - Released already!
  - "Due" Tonight 06/02
  - Extended to be due the same time as HW01 (Friday the 6th)
  - Mostly a C refresher

- Pre semester Survey
  - Anonymous
  - Short!
  - Due Wednesday the 4th

- Some OH later today 3:30 – 7pm (Levine 307)

Administrivia

- Second Assignment (HW01 penn-shredder)
  - Releases after today's lecture
  - Due **Friday this week** 06/06
  - Intro to system calls, processes, etc.
  - Short Q&A and demo at end of class ☺

- First Check-in
  - Releases Wednesday
  - Due before lecture on the 9th

Lecture Outline

- **Processes & Fork Refresher**
- exec
- wait & process states
- Hardware interrupts
- Software signals
- Process States updated
- penn-shredder demo

Processes & Fork Summary

- Processes are instances of programs that:
  - Each have their own independent address space
  - Each process is scheduled by the OS
    - Without using some functions we have not talked about (yet), there is no way to guarantee the order processes are executed
  - Processes are created by fork() system call
    - Only difference between processes is their process id and the return value from fork() each process gets

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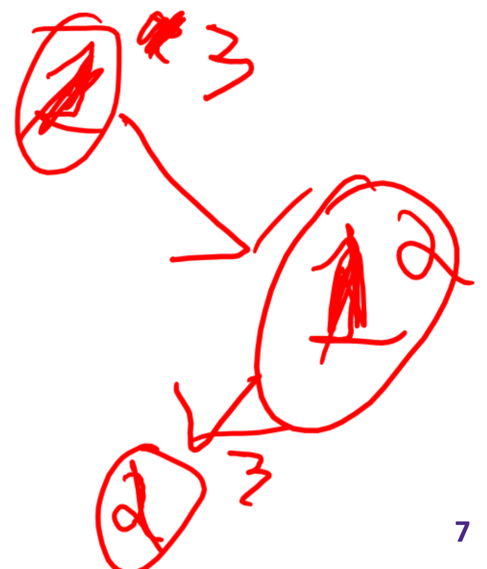
```c
int global_num = 1;

void function() {
  global_num++;
  printf("%d\n", global_num);
}

int main() {
  pid_t id = fork();

  if (id == 0) {
    function();
    id = fork();
    if (id == 0) {
      function();
    }
    return EXIT_SUCCESS;
  }

  global_num += 2;
  printf("%d\n", global_num);
  return EXIT_SUCCESS;
}
```

- How many numbers are printed? What number(s) get printed from each process?



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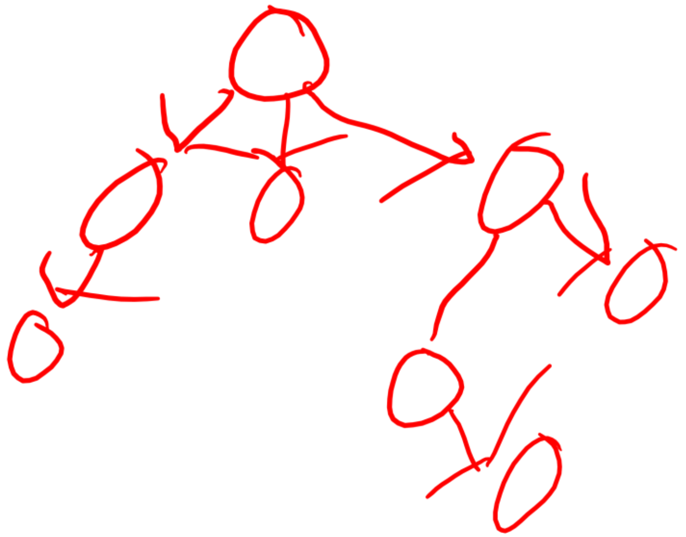
- How many times is ":)" printed?

```
int main(int argc, char* argv[]) {
  for (int i = 0; i < 4; i++) {
    fork();
  }

  printf(":)\n");
  return EXIT_SUCCESS;
}
```



Lecture Outline

- Processes & Fork Refresher
- **exec**
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exec*()

- Loads in a new program for execution

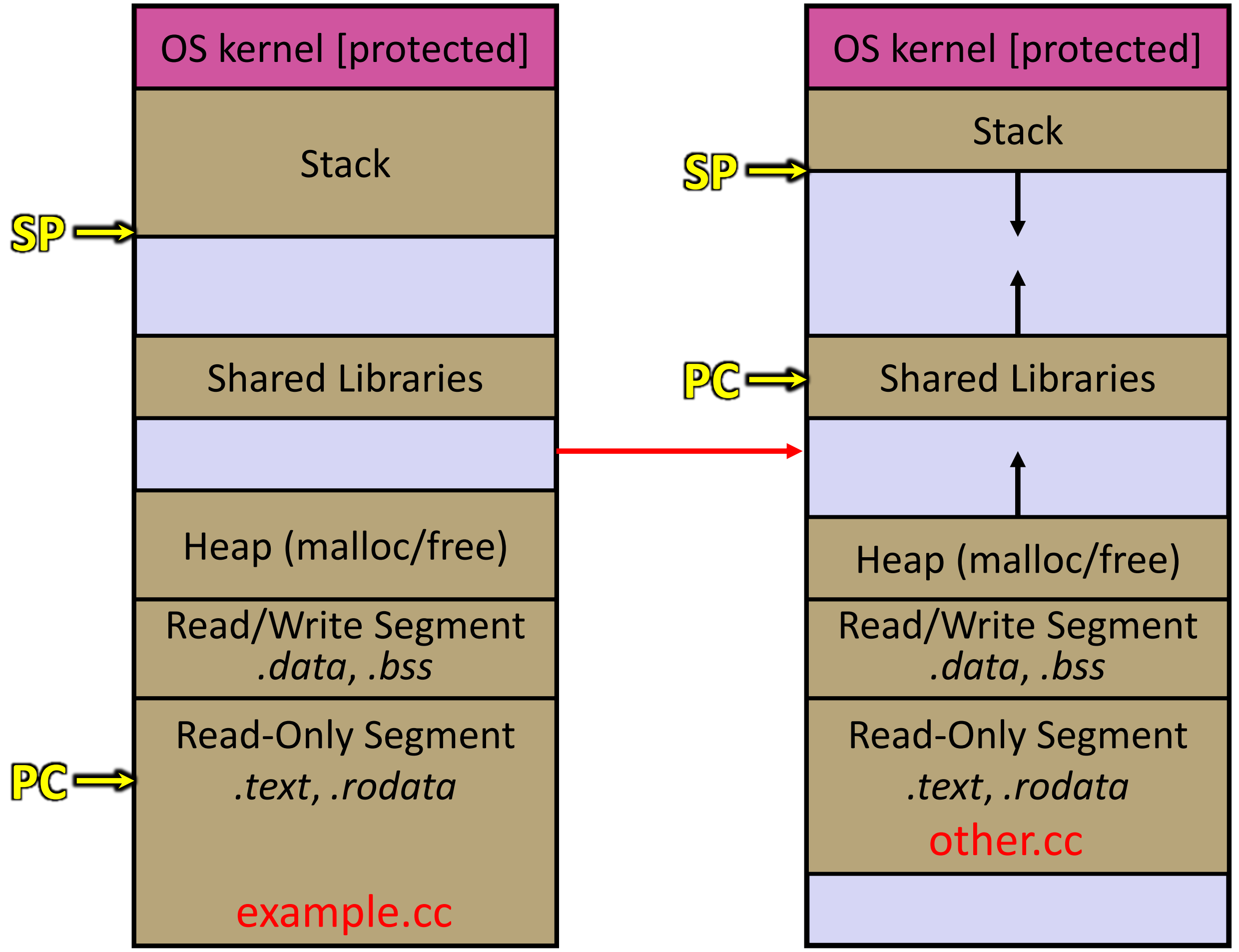
- PC, SP, registers, and memory are all reset so that the specified program can run

execve()

-
  ```
  int execve(const char *file,
             char* const argv[]
             char* const envp[]);
  ```
- Duplicates the action of the shell (terminal) in terms of finding the command/program to run
- Argv is an array of **`char*`**, the same kind of argv that is passed to `main()` in a C program
  - **`argv[0]`** MUST have the same contents as the file parameter
  - **`argv`** must have NULL as the last entry of the array
- Just pass in an array of `{ NULL };` as envp
- Returns -1 on error. Does NOT return on success

Exec Visualization

- Exec takes a process and discards or "resets" most of it



NOTE that the following DO change
- The stack
- The heap
- Globals
- Loaded code
- Registers

NOTE that the following do NOT change
- Process ID
- Open files
- The kernel

Aside: Exiting a Process

-
  ```
  void exit(int status);
  ```
  - Causes the current process to exit normally
  - Automatically called by `main()` when main returns
  - Exits with a return status (e.g. EXIT_SUCCESS or EXIT_FAILURE)
    - This is the same int returned by `main()`
  - The exit status is accessible by the parent process with `wait()` or `waitpid()`. (more on these functions next lecture)

Exec Demo

- See `exec_example.c`
  - Brief code demo to see how exec works
  - What happens when we call exec?
  - What happens to allocated memory when we call exec?

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```
int main(int argc, char* argv[]) {
  char* envp[] = { NULL };
  // fork a process to exec clang
  pid_t clang_pid = fork();

  if (clang_pid == 0) {
    // we are the child
    char* clang_argv[] = {"/bin/clang", "-o",
                          "hello","hello_world.c", NULL};
    execve(clang_argv[0], clang_argv, envp);
    exit(EXIT_FAILURE);
  }

  // fork to run the compiled program
  pid_t hello_pid = fork();
  if (hello_pid == 0) {
    // the process created by fork
    char* hello_argv[] = {"./hello", NULL};
    execve(hello_argv[0], hello_argv, envp);
    exit(EXIT_FAILURE);
  }
  return EXIT_SUCCESS;
}
```

This code is broken. It compiles, but it doesn't do what we want. It is trying to compile some code and then run it.

Why is this broken?

- Clang is a C compiler
- Assume exec'ing the compiler works (hello_world.c compiles correctly)
- Assume I gave the correct args to exec in both cases

utograder.c

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$$\begin{tikzcd}
\text{main()} \arrow[d] & \\
\text{fork()} \arrow[r] \arrow[dd] & \text{execve(compile hello\_world)} \arrow[d] \\
 & \text{exit()} \\
\text{fork()} \arrow[r] \arrow[d] & \text{execve(run hello\_world)} \arrow[d] \\
\text{exit()} & \text{exit()}
\end{tikzcd}$$

This code is broken. It compiles, but it doesn’t do what we want. Why?

- Clang is a C compiler
- Assume it compiles
- Assume I gave the correct args to exec

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- In each of these, how often is `":) \n"` printed? Assume functions don't fail

```
int main(int argc, char* argv[]) {
  char* envp[] = { NULL };

  pid_t pid = fork();
  if (pid == 0) {
    // we are the child
    char* argv[] = {"/bin/echo",
                    "hello",
                    NULL};
    execve(argv[0], argv, envp);
  }

   printf(":) \n");

  return EXIT_SUCCESS;
}
```

```
int main(int argc, char* argv[]) {
  char* envp[] = { NULL };

  pid_t pid = fork();
  if (pid == 0) {
    // we are the child
    return EXIT_SUCCESS;
  }

   printf(":) \n");

  return EXIT_SUCCESS;
}
```

Lecture Outline

- Processes & Fork Refresher
- exec
- **wait & process states**
- Hardware interrupts
- Software signals
- Process States updated
- penn-shredder demo

From a previous poll:

```c
int main(int argc, char* argv[]) {
  char* envp[] = { NULL };

  // fork a process to exec clang
  pid_t clang_pid = fork();
  if (clang_pid == 0) {
    // we are the child
    char* clang_argv[] = {"/bin/clang", "-o",
              "hello","hello_world.c", NULL};
    execve(clang_argv[0], clang_argv, envp);
    exit(EXIT_FAILURE);
  }

  // fork to run the compiled program
  pid_t hello_pid = fork();
  if (hello_pid == 0) {
    // the process created by fork
    char* hello_argv[] = {"./hello", NULL};
    execve(hello_argv[0], hello_argv, envp);
    exit(EXIT_FAILURE);
  }
  return EXIT_SUCCESS;
}
```

broken_autograder.c

This code is broken. It compiles, but it doesn't **always** do what we want. Why?

- Clang is a C compiler
- Assume it compiles
- Assume I gave the correct args to exec

"waiting" for updates on a Process

Usual change in status is to "terminated"

-
  ```
  pid_t wait(int *wstatus);
  ```
  - Calling process waits for any child process to change status
    - Also cleans up the child process if it was a zombie/terminated
  - Gets the exit status of child process through output parameter **`wstatus`**
  - Returns process ID of child who was waited for or `-1` on error

Execution Blocking

- When a process calls **`wait()`** and there is a process to wait on, the calling process **blocks**

- If a process **blocks** or is **blocking** it is not scheduled for execution.
  - It is not run until some condition "unblocks" it
  - For **`wait()`**, it unblocks once there is a status update in a child

Fixed code from broken_autograder.c

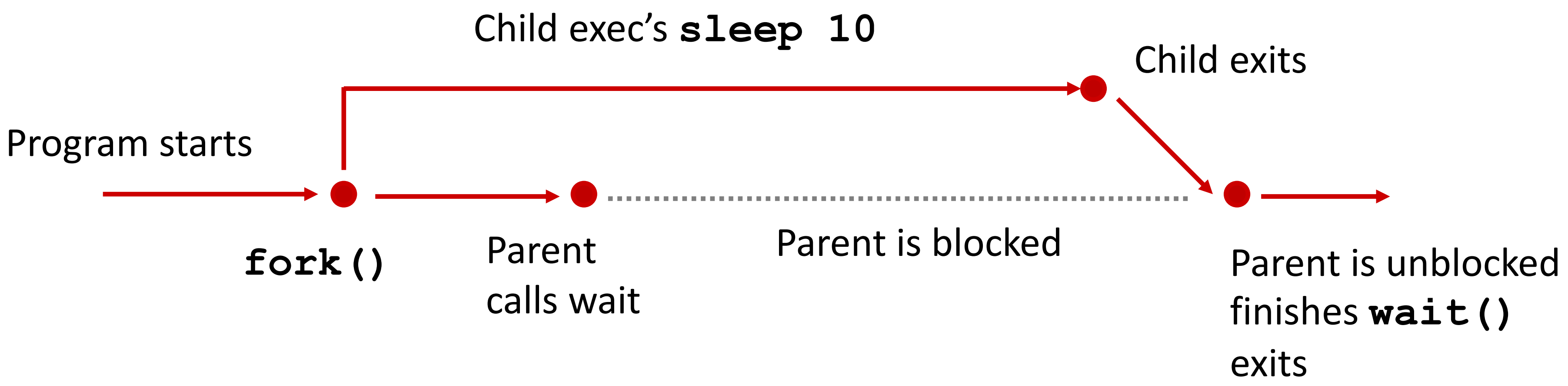
```c
int main(int argc, char* argv[]) {
  char* envp[] = { NULL };
  // fork a process to exec clang
  pid_t clang_pid = fork();
  if (clang_pid == 0) {
    // we are the child
    char* clang_argv[] = {"/bin/clang", "-o",
                "hello","hello_world.c", NULL};
    execve(clang_argv[0], clang_argv, envp);
    exit(EXIT_FAILURE);
  }
  wait(NULL); // should error check, not enough slide space :(
  // fork to run the compiled program
  pid_t hello_pid = fork();
  if (hello_pid == 0) {
    // the process created by fork
    char* hello_argv[] = {"./hello", NULL};
    execve(hello_argv[0], hello_argv, envp);
    exit(EXIT_FAILURE);
  }
  return EXIT_SUCCESS;
}
```

autograder.c

Demo: `wait_example`

- See `wait_example.c`
  - Brief demo to see how a process blocks when it calls wait()
  - Makes use of **`fork()`**, **`execve()`**, and **`wait()`**

- Execution timeline:


Child exec's **sleep 10**
Child exits
Program starts
fork()
Parent calls wait
Parent is blocked
Parent is unblocked finishes **wait()** exits

discuss

- Can a child finish before parent calls wait?

What if the child finishes first?

- In the timeline I drew, the parent called wait before the child executed.
  - In the program, it is extremely likely this happens if the child is calling **`sleep 10`**
  - What happens if the child finishes before the parent calls wait?
    Will the parent not see the child finish?

Process Tables & Process Control Blocks

- The operating system maintains a table of all processes that aren't "completely done"

- Each process in this table has a **p**rocess **c**ontrol **b**lock (**PCB**) to hold information about it.
- A PCB can contain:
  - Process ID
  - Parent Process ID
  - Child process IDs
  - Process Group ID
  - Status (e.g. running/zombie/etc)
  - Other things (file descriptors, register values, etc)

Zombie Process

- Answer: processes that are terminated become “zombies”
  - Zombie processes deallocate their address space, don’t run anymore
  - still “exists”, has a PCB still, so that a parent can check its status one final time
  - If the parent call’s wait(), the zombie becomes “reaped” all information related to it has been freed (No more PCB entry)

Diagram: wait_example.c

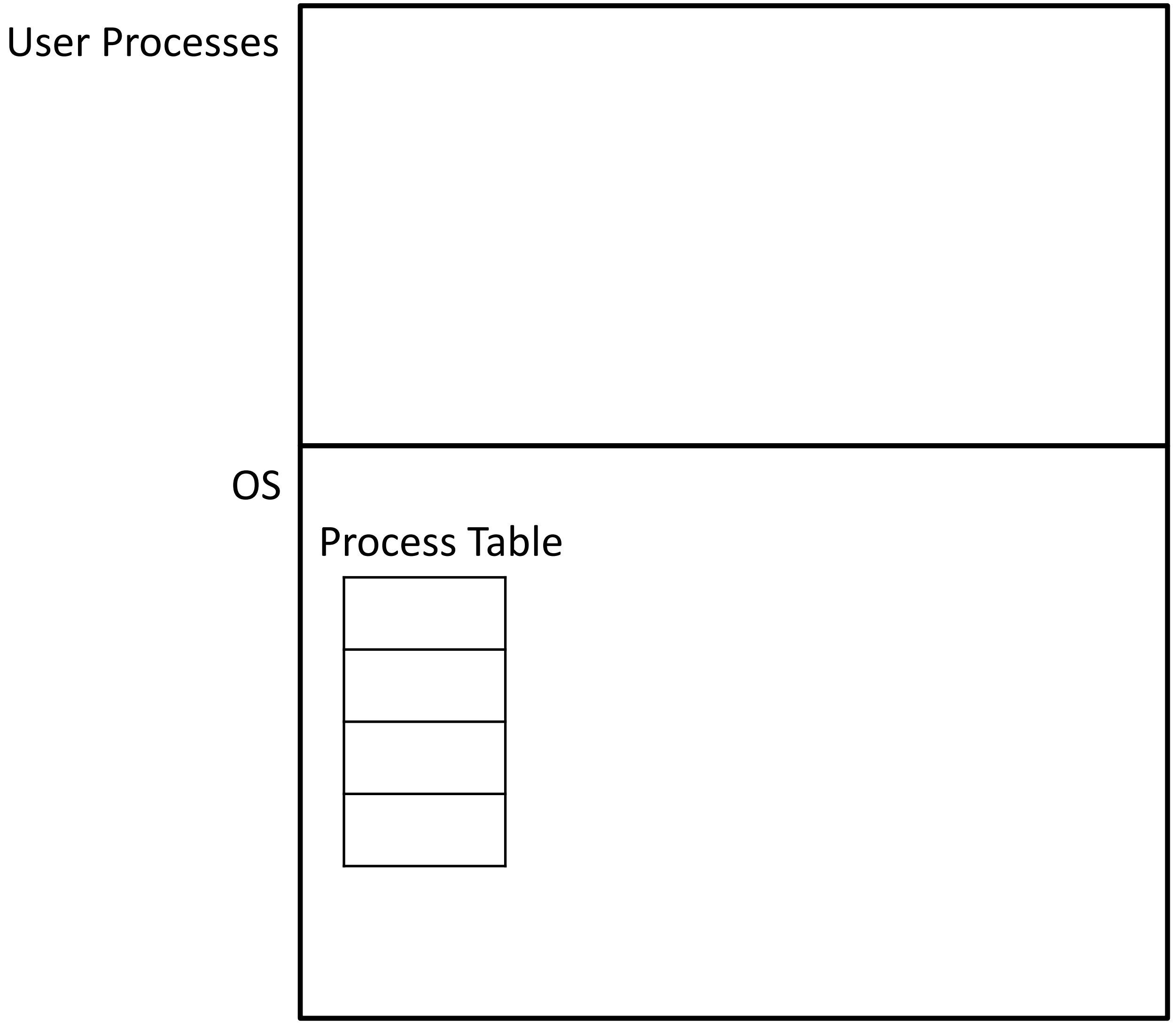


Diagram: wait_example.c

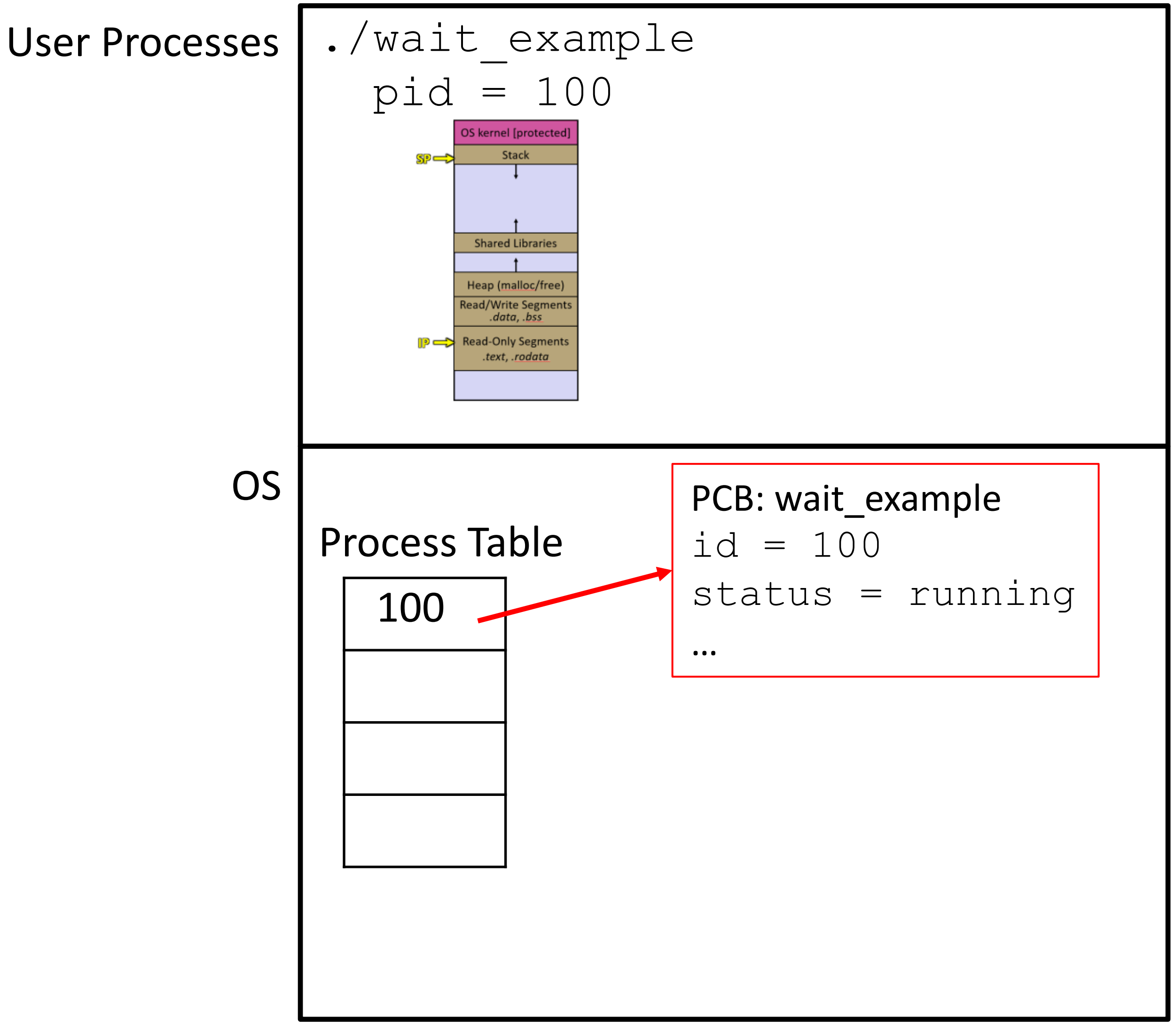


Diagram: wait_example.c

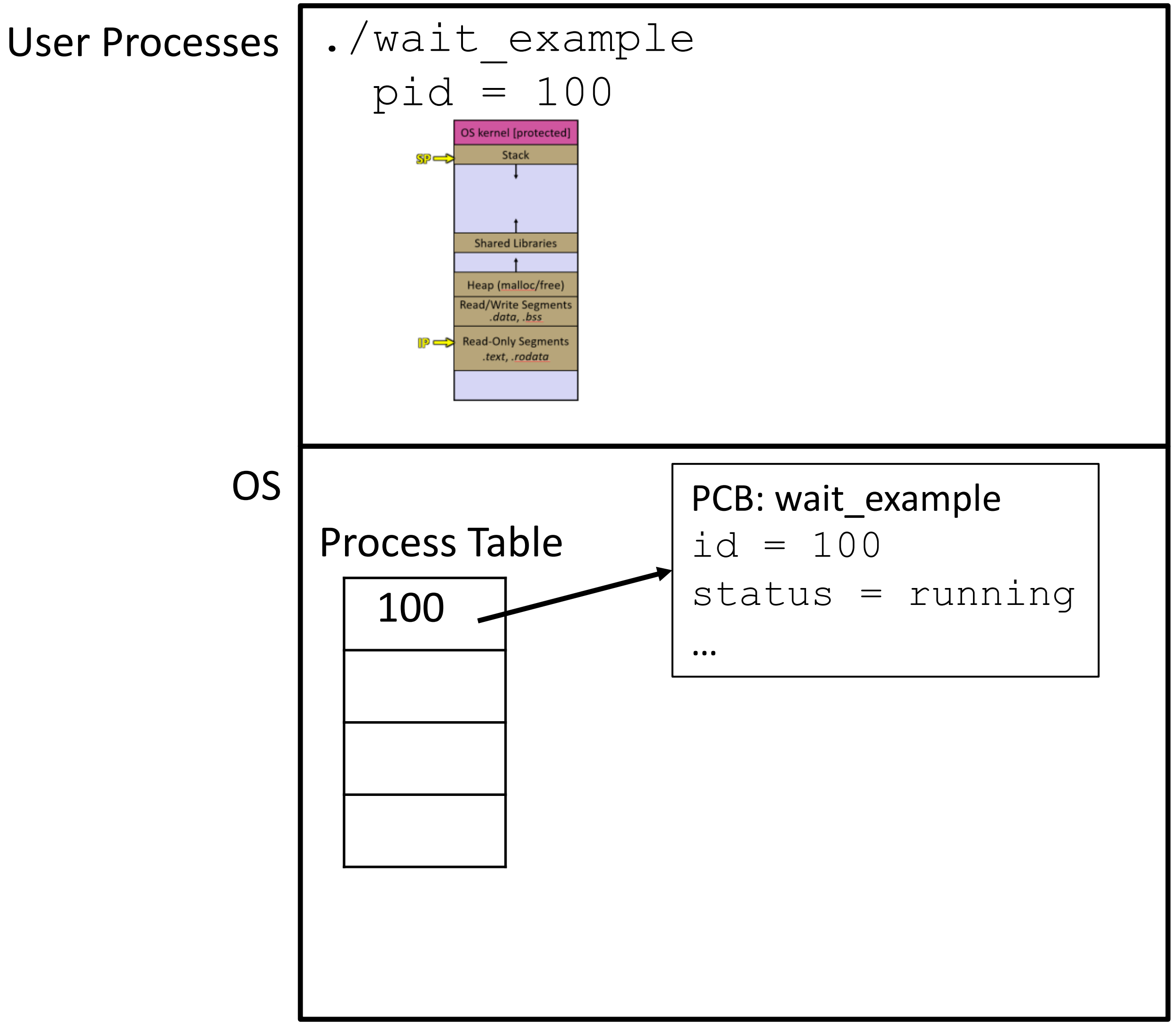
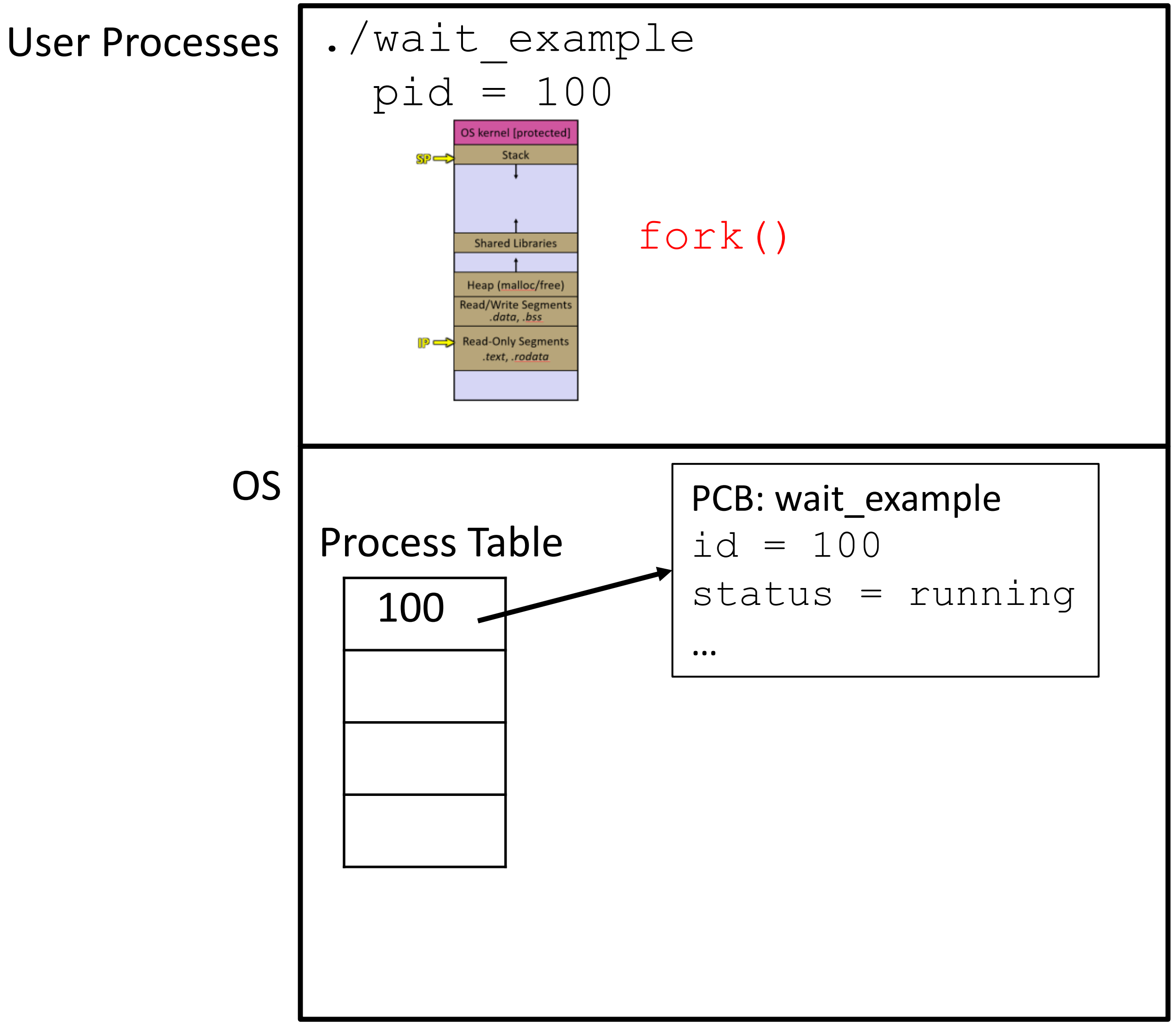


Diagram: wait_example.c



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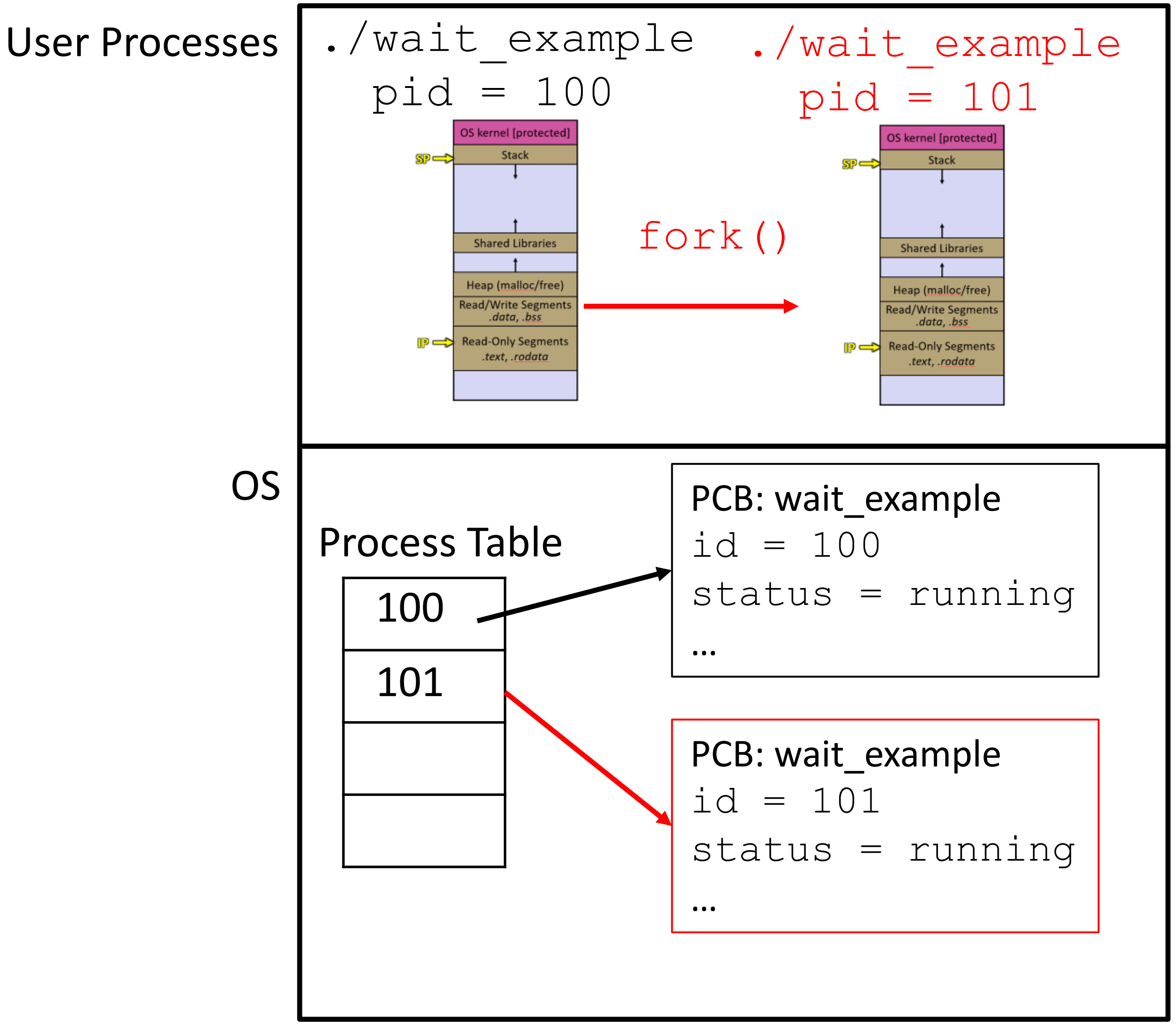

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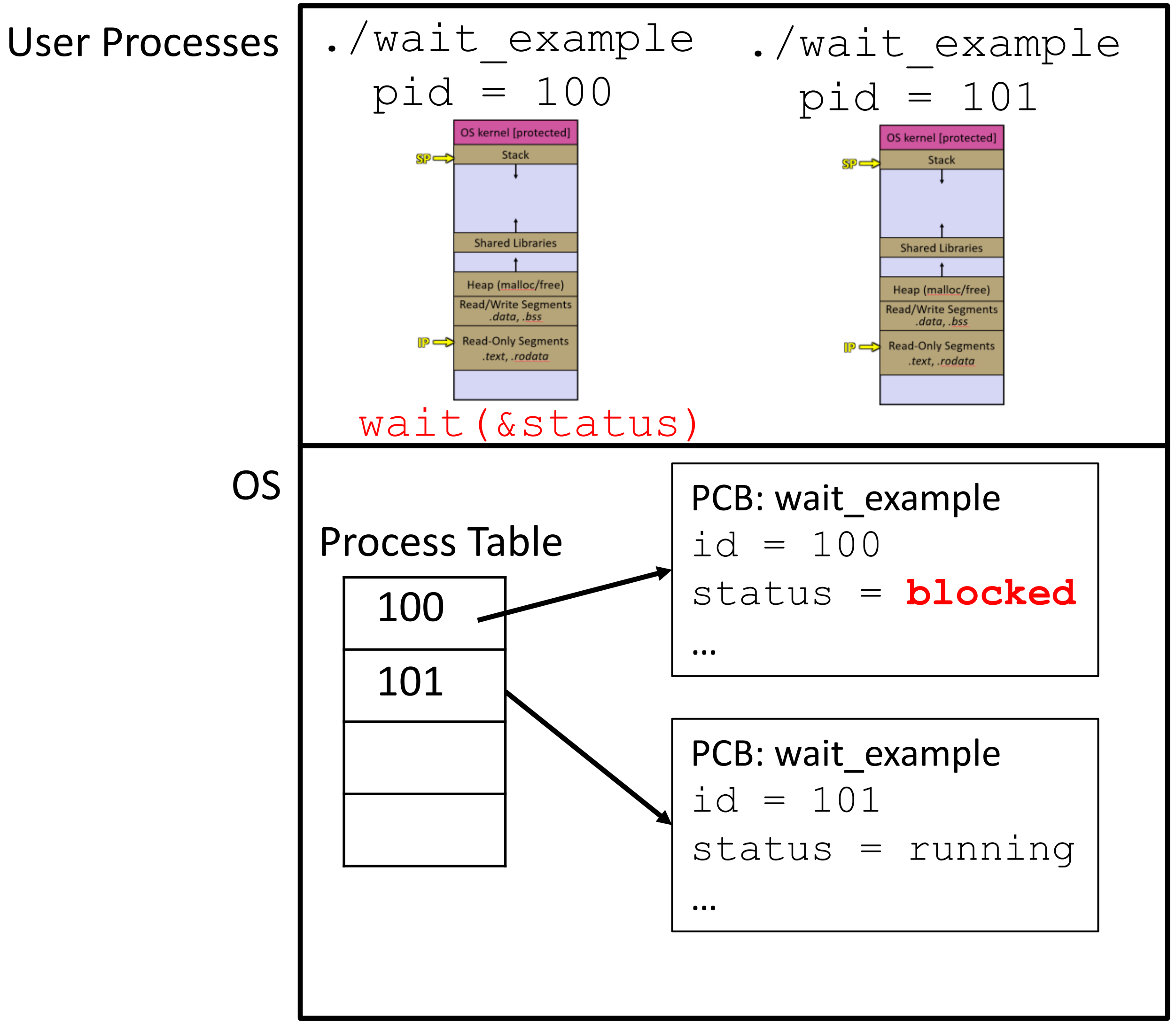


Diagram: wait_example.c

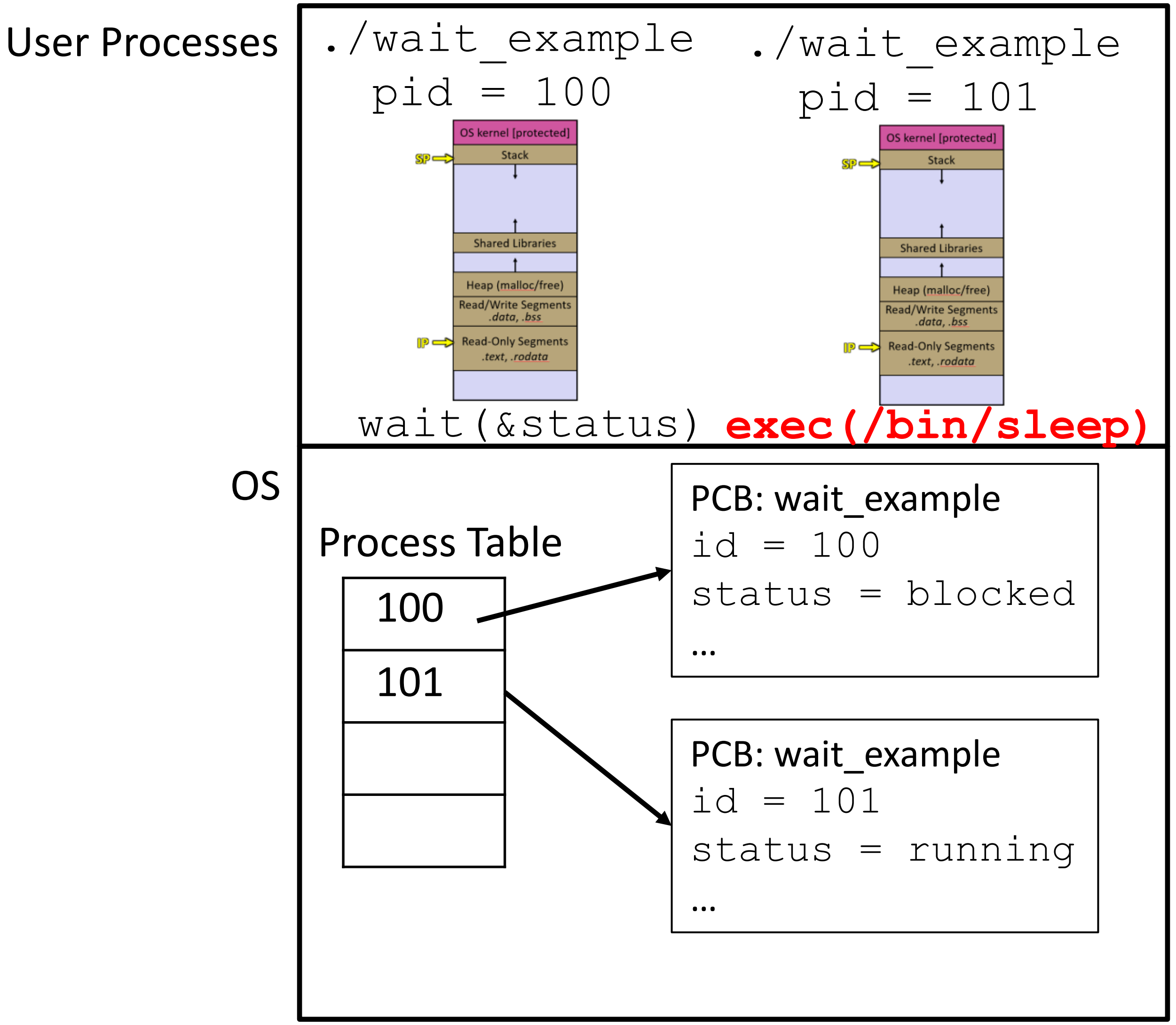


Diagram: wait_example.c

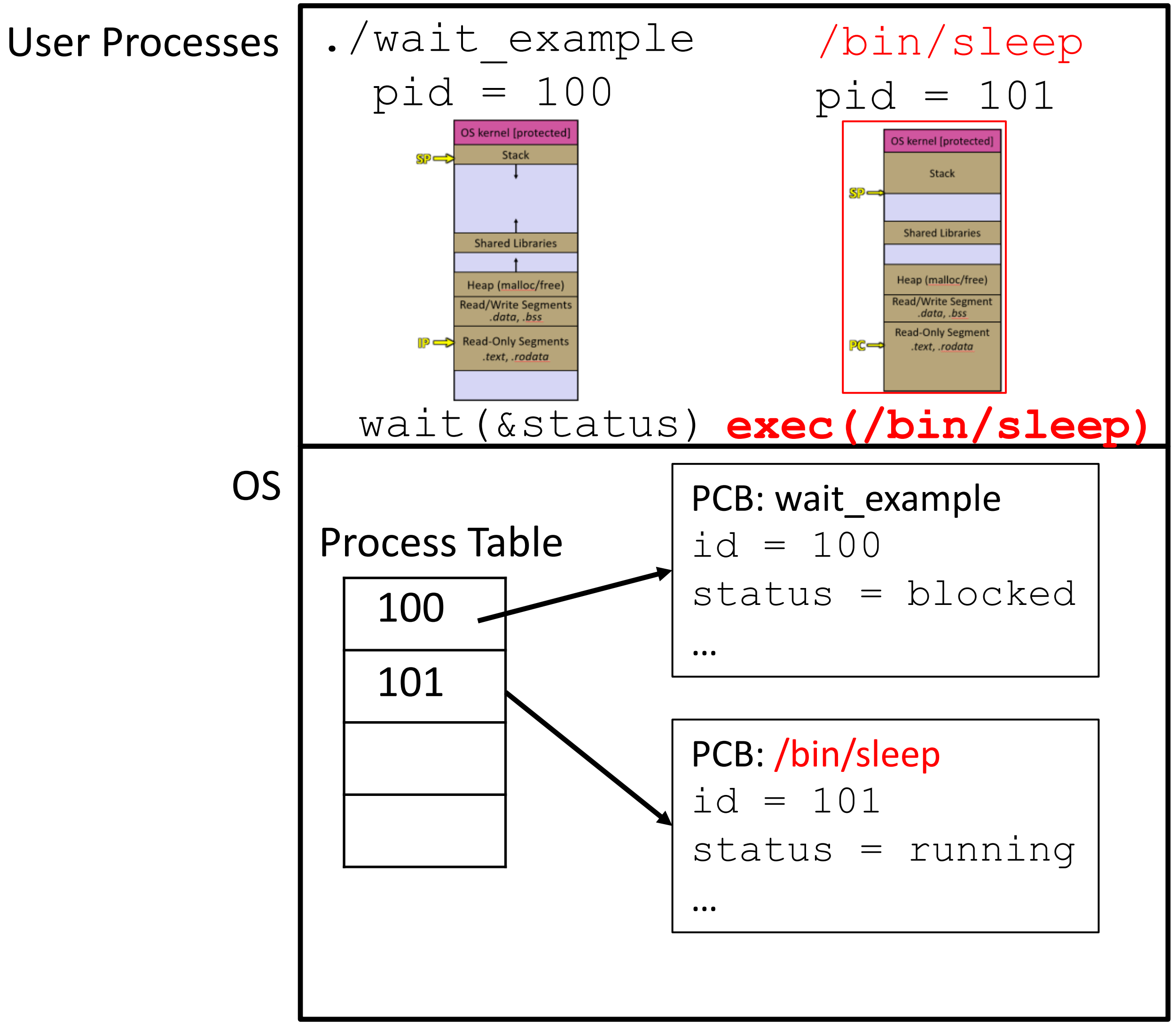


Diagram: wait_example.c

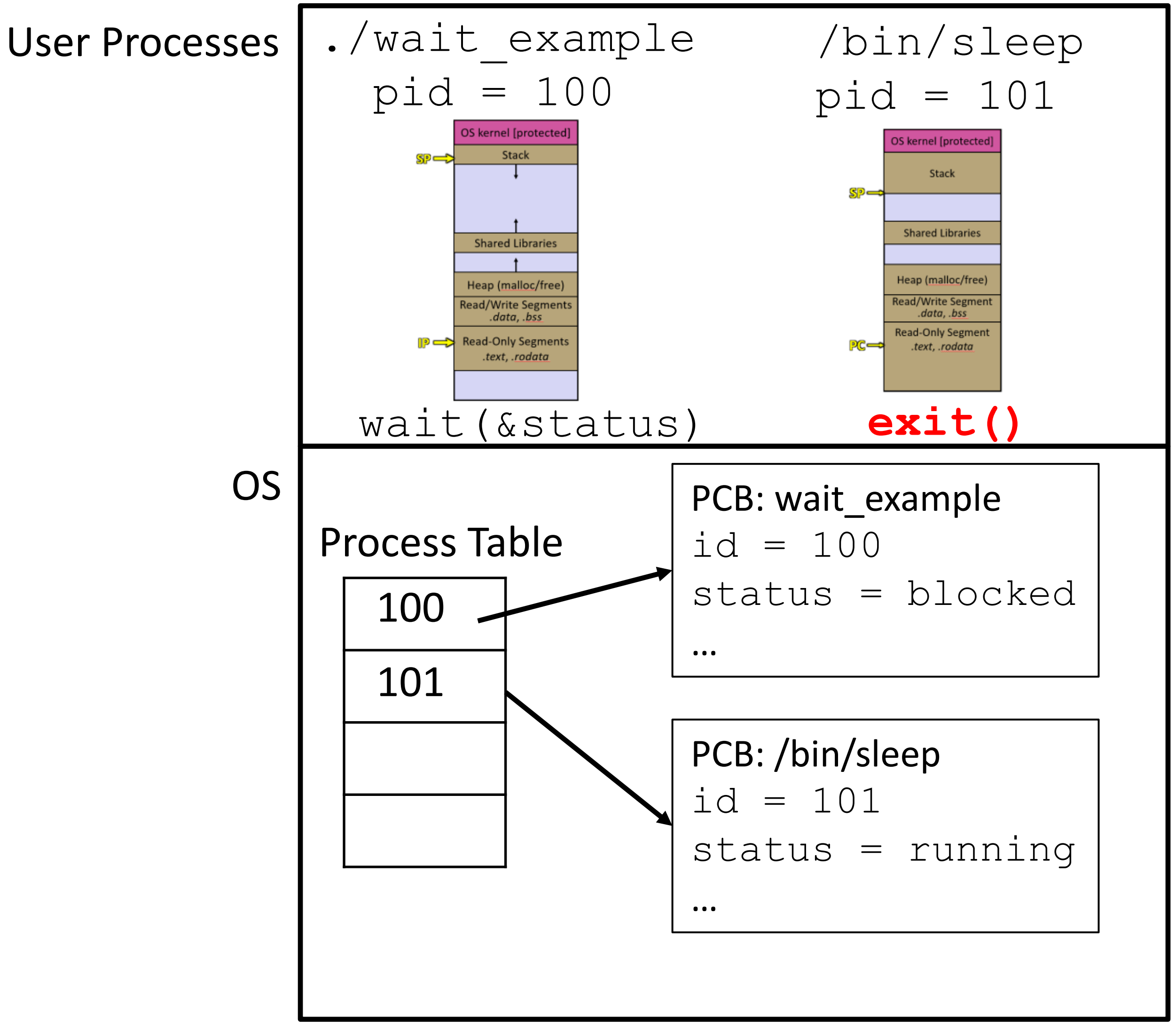


Diagram: wait_example.c

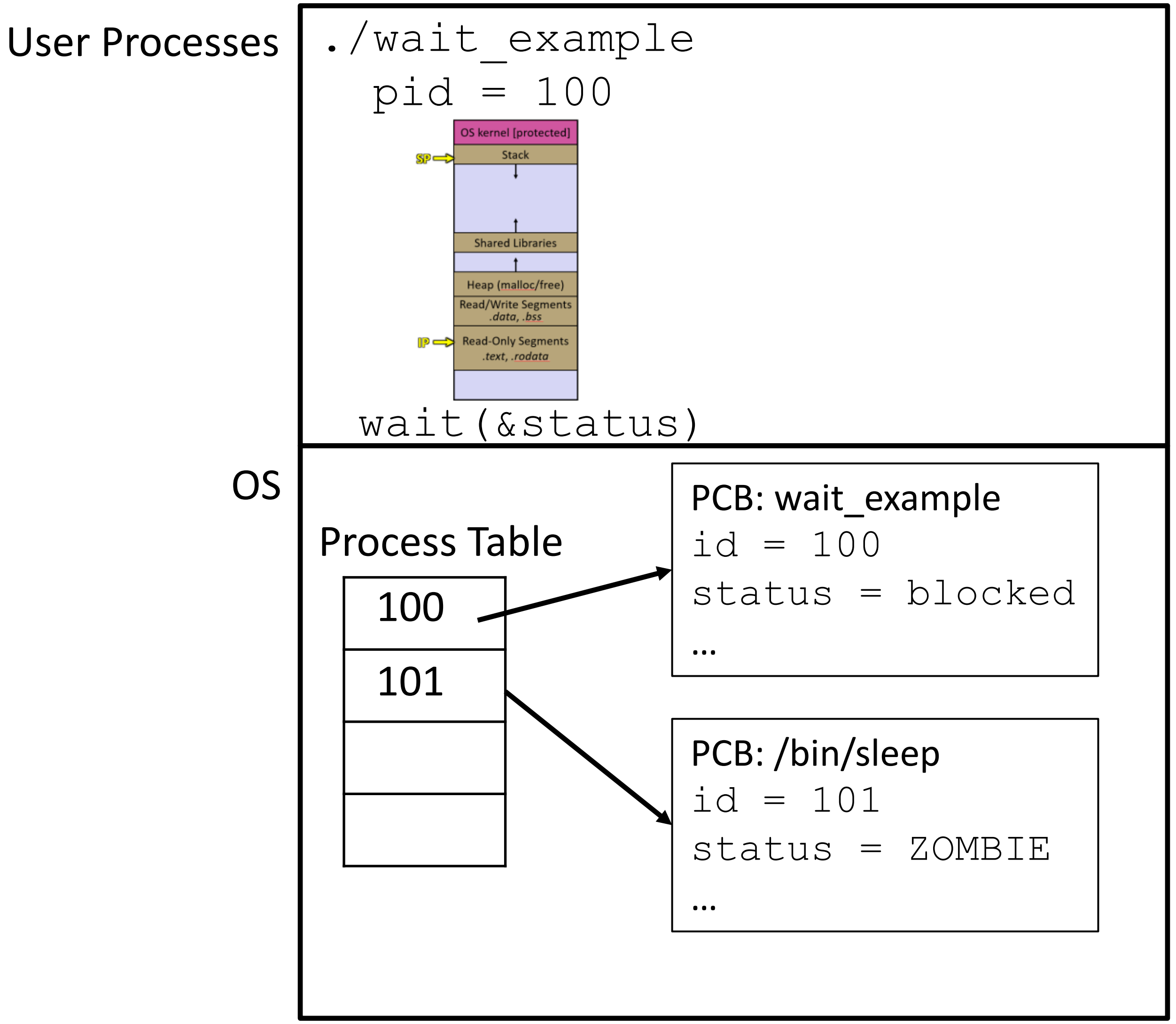


Diagram: wait_example.c

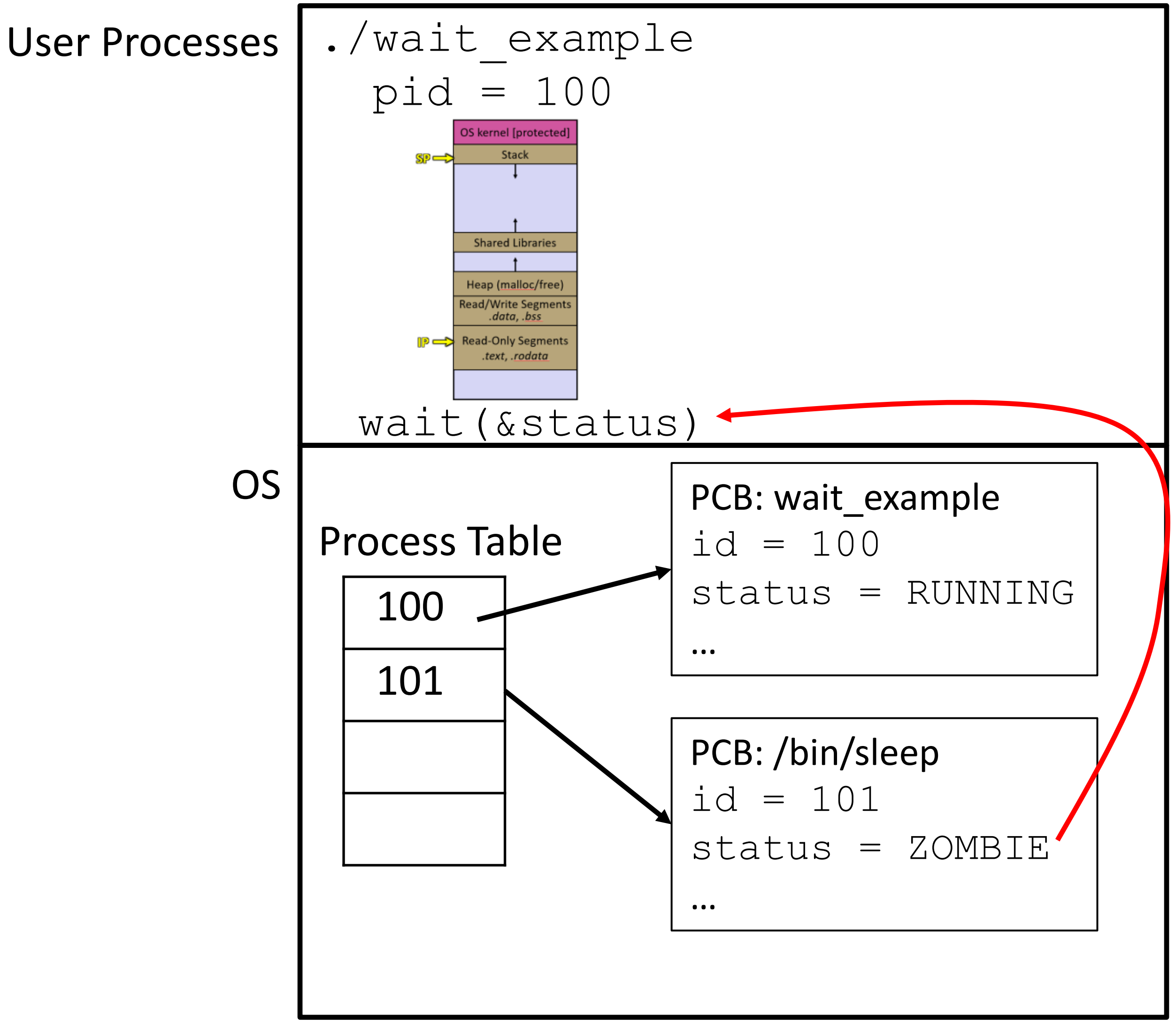
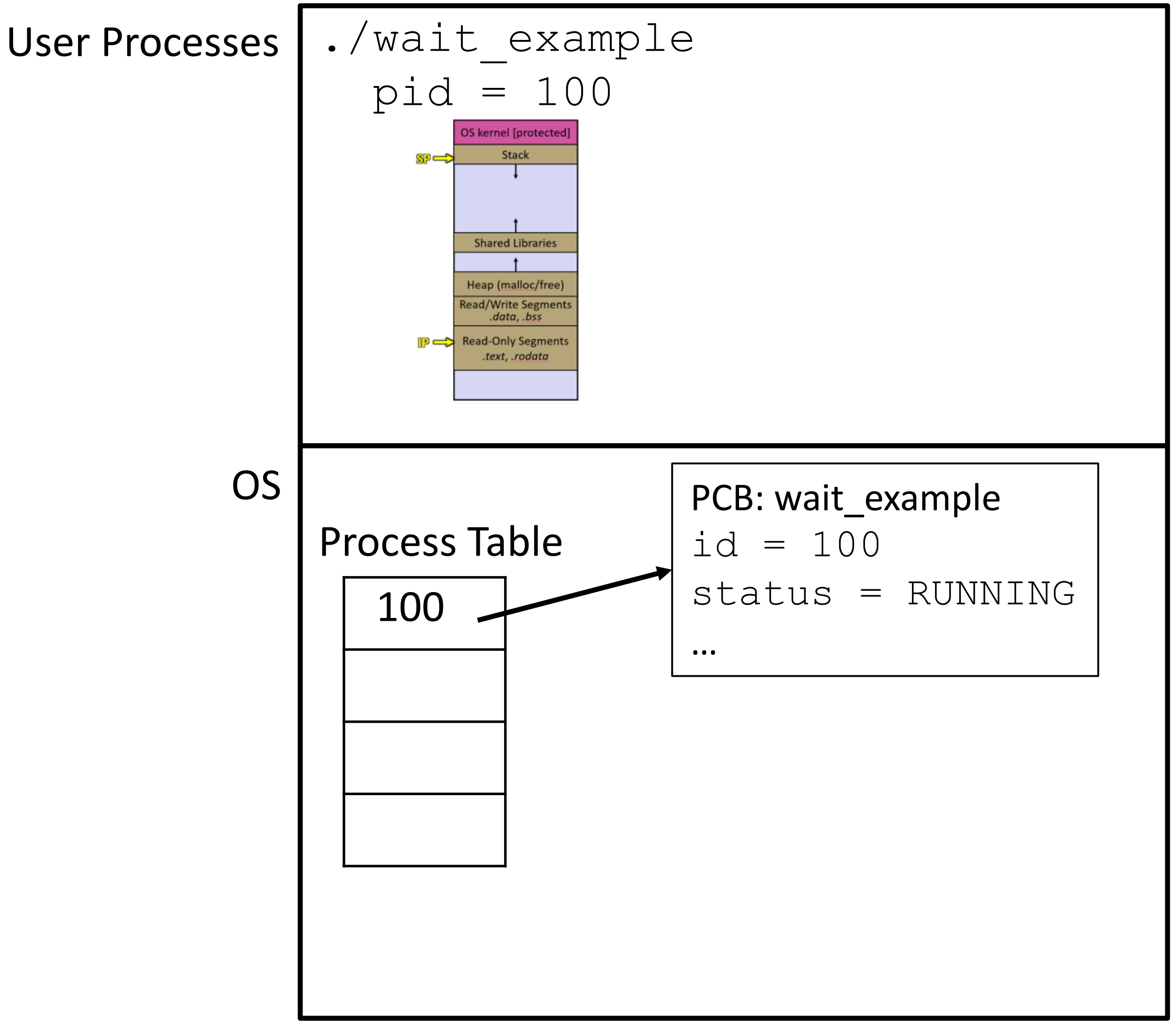


Diagram: wait_example.c



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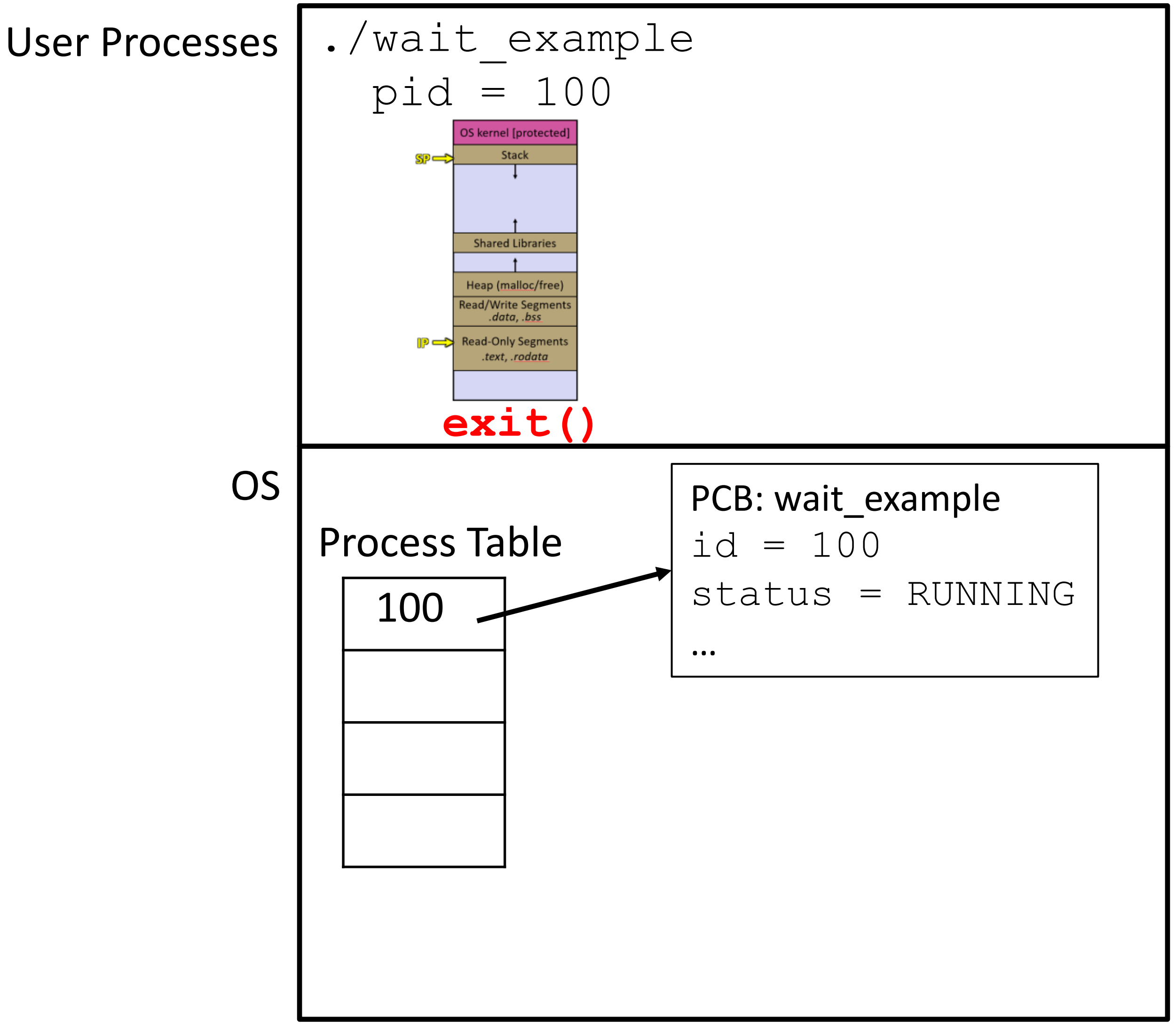
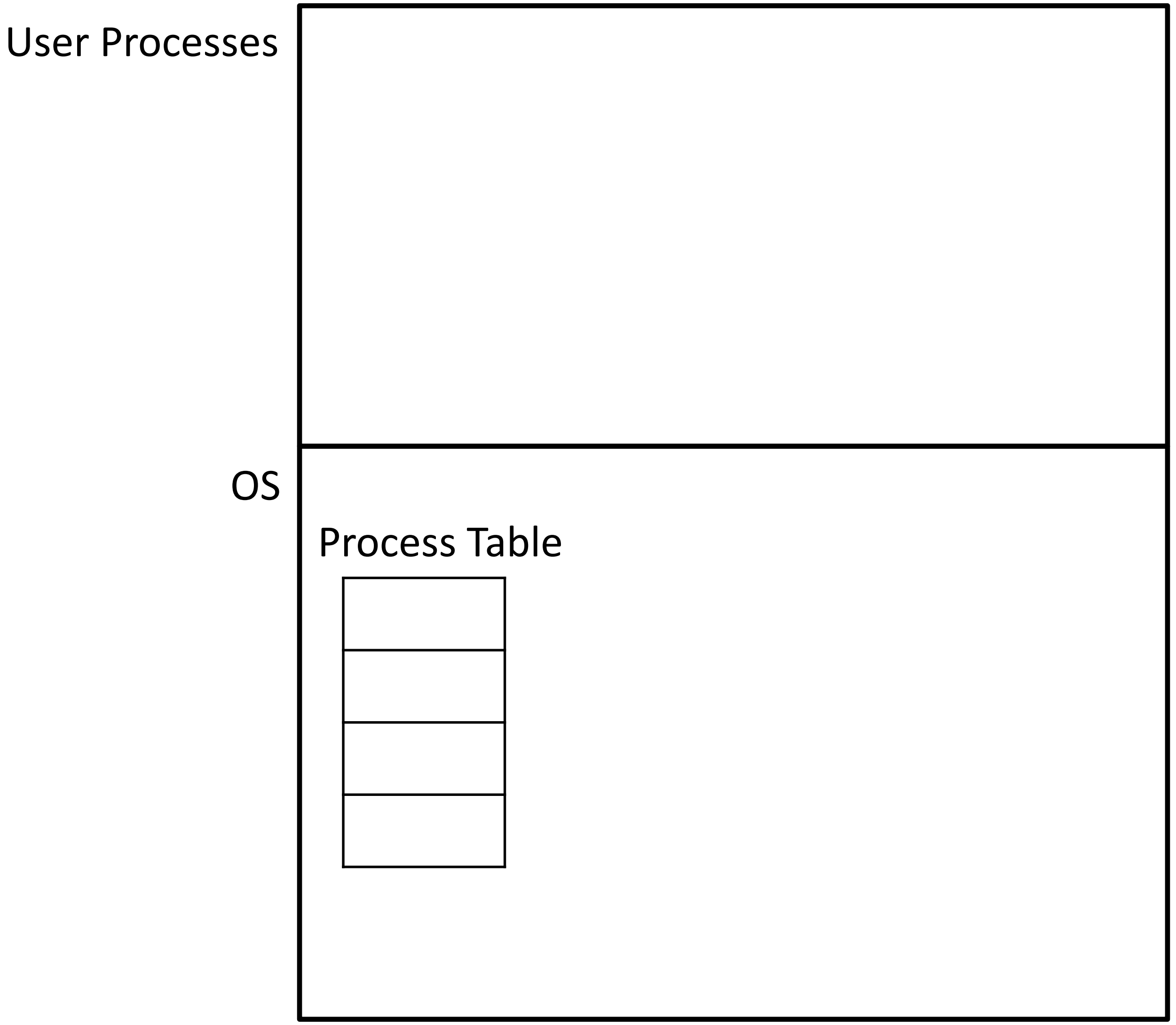


Diagram: wait_example.c



`./wait_example`
Is reaped by its parent. In our example, that is the terminal shell

Demo: `state_example`

- See `state_example.c`
  - Brief code demo to see the various states of a process
    - Running
    - Zombie
    - Terminated
  - Makes use of `sleep()`, `waitpid()` and `exit()`!
  - Aside: `sleep()` takes in an integer number of seconds and blocks till those seconds have passed

More: `waitpid()`

-
  ```
  pid_t waitpid(pid_t pid, int *wstatus,
                          int options);
  ```
  - Calling process waits for a child process (specified by **`pid`**) to exit
    - Also cleans up the child process
  - Gets the exit status of child process through output parameter **`wstatus`**
  - **`options`** are optional, pass in `0` for default options in *most* cases
  - Returns process ID of child who was waited for or `-1` on error

wait() status

- `status` output from `wait()` can be passed to a macro to see what changed
- `WIFEXITED()` true iff the child exited nomrally
- `WIFSIGNALED()` true iff the child was signaled to exit
- `WIFSTOPPED()` true iff the child stopped
- `WIFCONTINUED()` true iff child continued
- See example in `state_check.c`

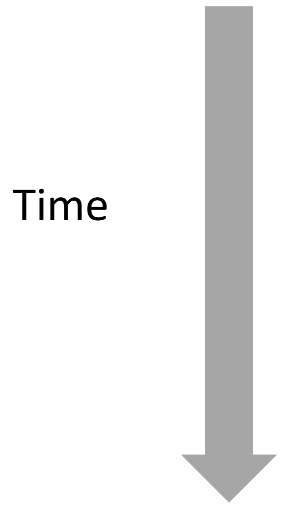
Lecture Outline

- exec
- wait & process states
- **Hardware interrupts**
- Software signals
- Process States updated
- penn-shredder demo

Control Flow

- Processors do only one thing:
  - From startup to shutdown, a CPU simply reads and executes (interprets) a sequence of instructions, one at a time
  - This sequence is the CPU's *control flow* (or *flow of control*)

Physical control flow



<startup>
inst_1
inst_2
inst_3
…
inst_n
<shutdown>

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The bge instruction is being executed for the first time, which instruction is executed next?

- **A.** bge
- **B.** add
- **C.** sub
- **D.** j
- **E.** I'm not sure

```
        li     t0, 5   # load immediate 5 into t0
        li     t1, 2   # load immediate 2 into t1
        li     t2, 0   # load immediate 0 into t2

.LOOP
        add t2, t2, 1       # t2 = t2 + 1
        sub t0, t0, t1      # t0 = t0 - t1
        bge t0, x0, .LOOP # GOTO .loop if t0 > 0

.END
        j .END              # GOTO .END
                            # (infinite loop)
```

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"

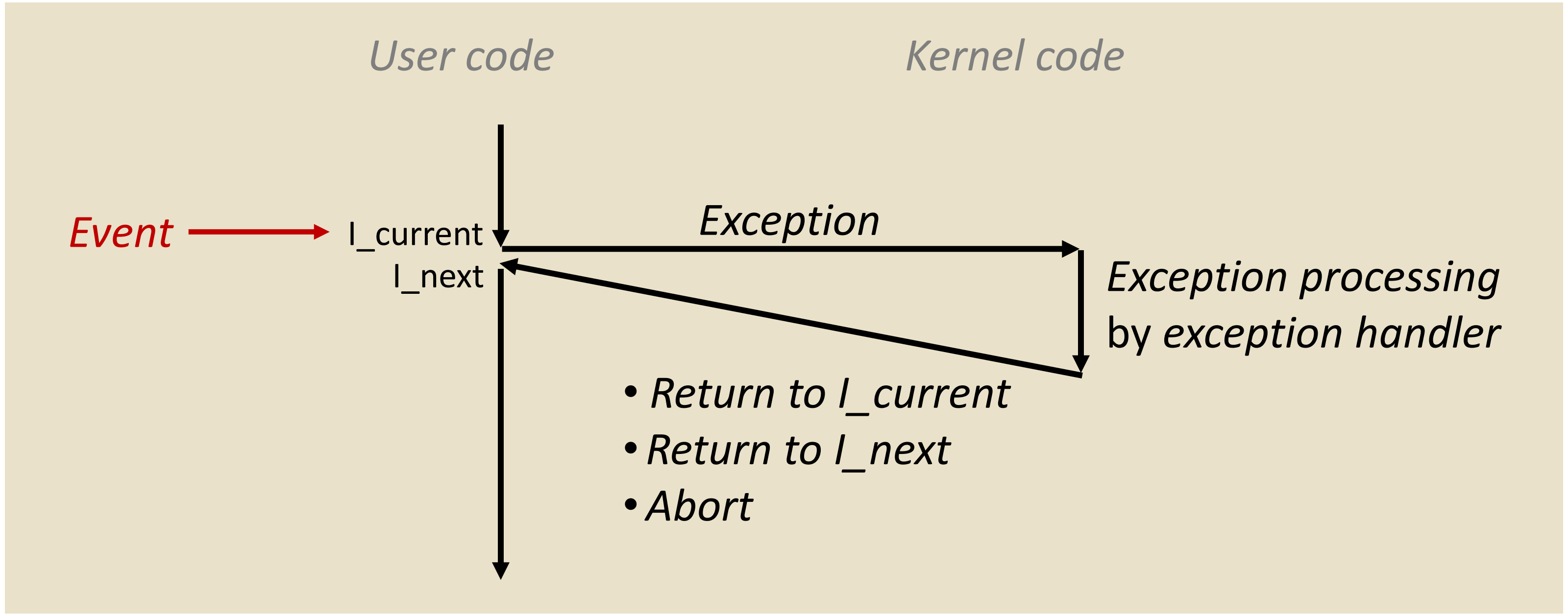
Exceptional Control Flow

- Exists at all levels of a computer system
- Low level mechanisms

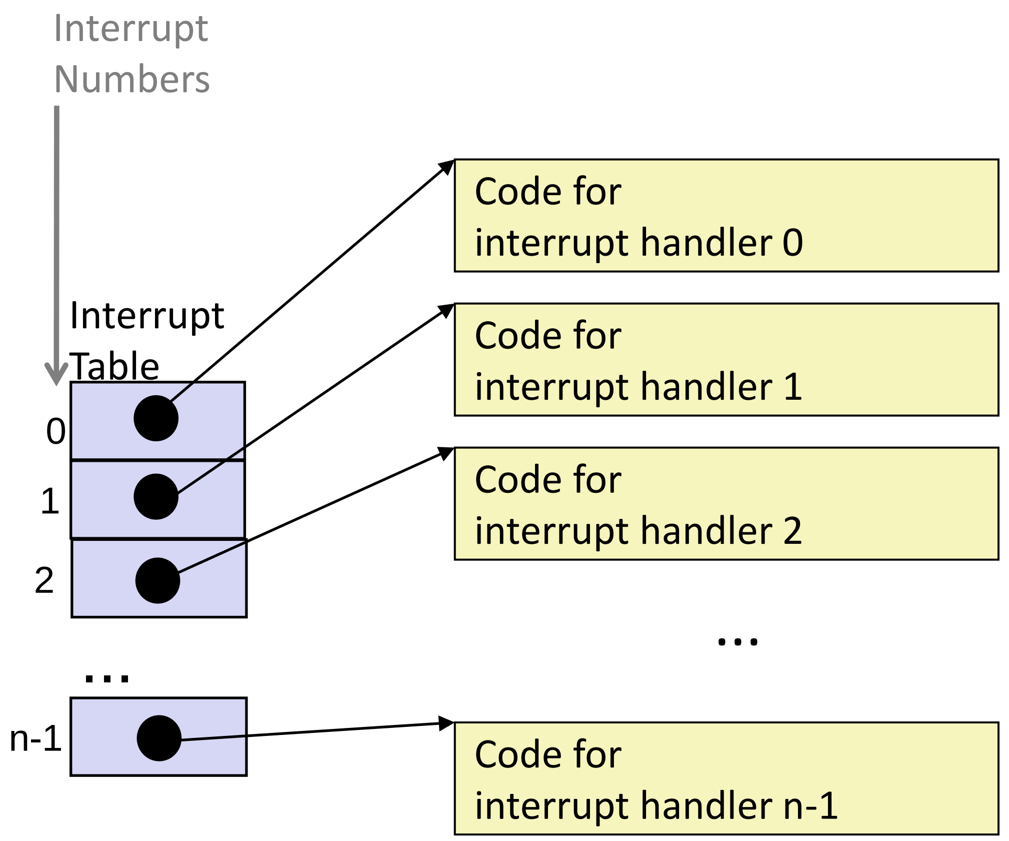
  What we will be looking at today
  - 1. **Hardware Interrupts**
    - Change in control flow in response to a system event (i.e., change in system state)
    - Implemented using combination of hardware and OS software
- Higher level mechanisms
  - 2. **Process context switch**
    - Implemented by OS software and hardware timer
  - 3. **Signals**
    - Implemented by OS software

Interrupts

- An *Interrupt* 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 completes, typing Ctrl-C



Interrupt Tables


Interrupt Numbers
Interrupt Table
0
1
2
...
n-1
Code for interrupt handler 0
Code for interrupt handler 1
Code for interrupt handler 2
...
Code for interrupt handler n-1

- Each type of event has a unique number k
- k = index into table (a.k.a. interrupt vector)
- Handler k is called each time interrupt k occurs

Asynchronous 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 timer chip triggers 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 Interrupts

- Caused by events that occur as a result of executing an instruction:
  - ***Traps***
    - Intentional
    - Examples: ***system calls***, breakpoint traps, special instructions
    - Returns control to "next" instruction
  - ***Faults***
    - Unintentional but theoretically recoverable
    - Examples: page faults (recoverable), protection faults (recoverable sometimes), 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

FUN FACT: the terminology and definitions aren't fully agreed upon. Many people may use these interchangeably

Lecture Outline

- Processes & Fork Refresher
- exec
- wait & process states
- Hardware interrupts
- **Software signals**
- Process States updated
- penn-shredder demo

Signals

- A Process can be interrupted with various types of signals
  - This interruption can occur in the middle of most code

- Each signal type has a different meaning, number associated with it, and a way it is handled

- These are different from an interrupt, but similar idea
  - signals are “higher level” and apply to a process. The kernel / some process will deliver the signal.
  - Interrupts are lower level mechanisms that cause the hardware to poke the kernel and respond
  - Some interrupts lead to a signal being sent (CTRL + C on keyboard -> SIGINT)

Signals

- A Process can be interrupted with various types of signals
  - This interruption can occur in the middle of most code
- Each signal type has a different meaning, number associated with it, and a way it is handled
- Examples:

`SIGCHLD`	Default: ignore

`SIGINT`
`SIGKILL`
`SIGALRM`
	Default: terminate the process

`SIGSEGV`	Default: terminate & core dump

sigaction()

- You can change how a certain signal is handled

-
  ```
  int sigaction(int signum,   struct sigaction* act,
                      struct sigaction* old);
  ```
- Signum specifies a signal
- Uses the **`struct sigaction`** type to specify which signal handler to run and other options for how the signal should be handled
- Returns previous handler & behaviour for that signal through the **`old`** output parameter
- Some signals like **`SIG_KILL`** and **`SIG_STOP`** can't be handled differently

Signal handlers

-
  ```c
  typedef void (*sighandler_t)(int);
  ```
- A function that takes in as parameter, the signal number that raised this handler. Return type is void
- Is **automatically** called when your process is interrupted by a signal
- Can manipulate global state
- If you change signal behaviour within the handler, it will be undone when you return
- Signal handlers set by a process will be retained in any children that are created

`struct sigaction`

- Has 5 different fields to specify the behaviour of how a signal should be handled. For our case, we only care about **`sa_handler`** and **`sa_flags`**
  - (for now)

```
struct sigaction {
  void       (*sa_handler)(int);
  void       (*sa_sigaction)(int, siginfo_t *, void *);
  sigset_t     sa_mask;
  int          sa_flags;
  void       (*sa_restorer)(void);
};
```

struct sigaction

-
  ```
  struct sigaction {
    void       (*sa_handler)(int);
    int          sa_flags;
    ...
  };
  ```
- Set sa_handler equal to the signal handler we want to use
  - Set **sa_handler** to **SIG_IGN** to ignore the signal
  - Set **sa_handler** to **SIG_DFL** for default behaviour
- In this class: set **sa_flags** to **SA_RESTART**
  - This makes it so that system calls are automatically restart/continue if they are interrupted by a signal.

Demo ctrlc.c

- See `ctrlc.c`
  - Brief code demo to see how to use a signal handler
  - Blocks the ctrl + c signal: SIGINT
  - Note: will have to terminate the process with the `kill` command in the terminal, use `ps –u` to fine the process id

alarm()

- Alarm

```
unsigned int alarm(unsigned int seconds);
```

- Delivers the **SIGALRM** signal to the calling process after the specified number of seconds

- Default **SIGALRM** behaviour: terminate the process

- How to cancel alarms?
  - I leave this as an exercise for you: try reading the man pages

- HINT FOR EXTRA CREDIT: What is the default behaviour of SIGALRM? Can you take advantadge of the default behaviour?

discuss

- Finish this program
- After 15 seconds, print a message and then exit
- Can't use the **`sleep()`** function, must use **`alarm()`**

```
int main(int argc, char* argv[]) {

  alarm(15U);

  return EXIT_SUCCESS;
}
```

- Currently: program calls alarm then immediately exits

Demo no_sleep.c

- See `no_sleep.c`
  - “Sleeps” for 10 seconds without sleeping, using alarm
  - Brief code demo to see how to use a signal handler & alarm
  - Signal handler manipulates global state

kill()

- Can send specific signals to a specific process manually

-
  ```
  int kill(pid_t pid, int sig);
  ```
- pid: specifies the process
- sig: specifies the signal

-
  ```
  kill(child, SIGKILL);
  ```

- If for some reason **kill()** is not recognized and you #include everything you need: Put this at the top of your penn-shredder.c file (before #includes) to use **kill()**

```
#define _POSIX_C_SOURCE 1
```

Non blocking wait w/ `waitpid()`

-
  ```
  pid_t waitpid(pid_t pid, int *wstatus,
                           int options);
  ```
  - Can pass in `WNOHANG` for **`options`** to make **`waitpid()`** not block or “hang”.
  - Returns process ID of child who was waited for or `-1` on error or 0 if there are no updates in children processes and WNOHANG was passed in

Demo impatient.c

- See `impatient.c`
  - Parent forks a child, checks if it finishes every second for 5 seconds, if child doesn't finish send SIGKILL

  - LOOKS SIMILAR TO WHAT YOU ARE DIONG IN penn-shredder. DO NOT COPY THIS
    - **`waitpid()`** IS NOT ALLOWED
    - USING **`sleep()`** AND **`alarm()`** TOGETHER CAN CAUSE ISSUES

SIGCHLD handler

- Whenever a child process updates, a **`SIGCHLD`** signal is received, and by default ignored.

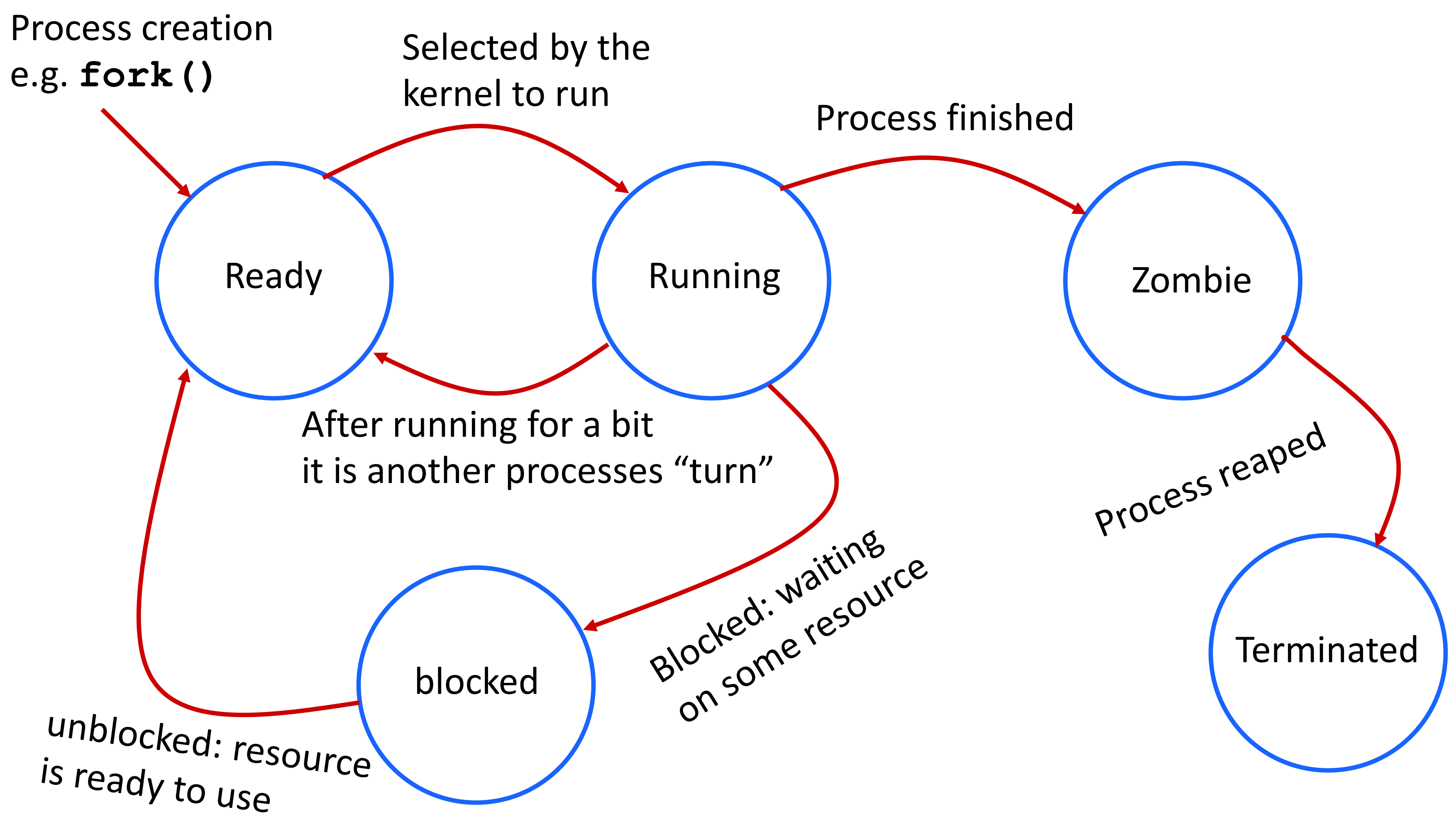
- You can write a signal handler for **`SIGCHLD`**, and use that to help handle children update statuses: allowing the parent process to do other things instead of calling **`wait()`** or **`waitpid()`**

- Relevant for proj2: **`penn-shell`**

Lecture Outline

- Processes & Fork Refresher
- exec
- wait & process states
- Hardware interrupts
- Software signals
- **Process States updated**
- penn-shredder demo

Process State Lifetime



Lecture Outline

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- **penn-shredder demo**