Processes (cont.): exec, wait, signal

Computer Operating Systems, Spring 2024

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Poll Everywhere

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- How is penn-parser 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

- Project 0 penn-parser:
  - “due” Tuesday Jan 30
  - Actual due date: submit with penn-shredder, but you need to finish it before penn-shredder will work anyways.
  - Your first C programming assignment

- Project 1 penn-shredder:
  - Due Friday Feb 02nd
  - Release after lecture today
  - You need penn-parser to complete it
  - Is not much more once you have implemented penn-parser
  - You will have everything you need to complete it after
  - Demo at end of lecture

Administrivia

- No check-in due next week
  - I think it makes sense that you are busy with project0 and project 1, no check-in

- First “recitation”
  - Tentatively Monday next week, waiting on room reservation
  - Covers topics that should help with projects, and then have open OH afterwards.

- Pre-semester survey:
  - “due” wed Jan 31
  - Just a short survey

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```
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

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

exec*()

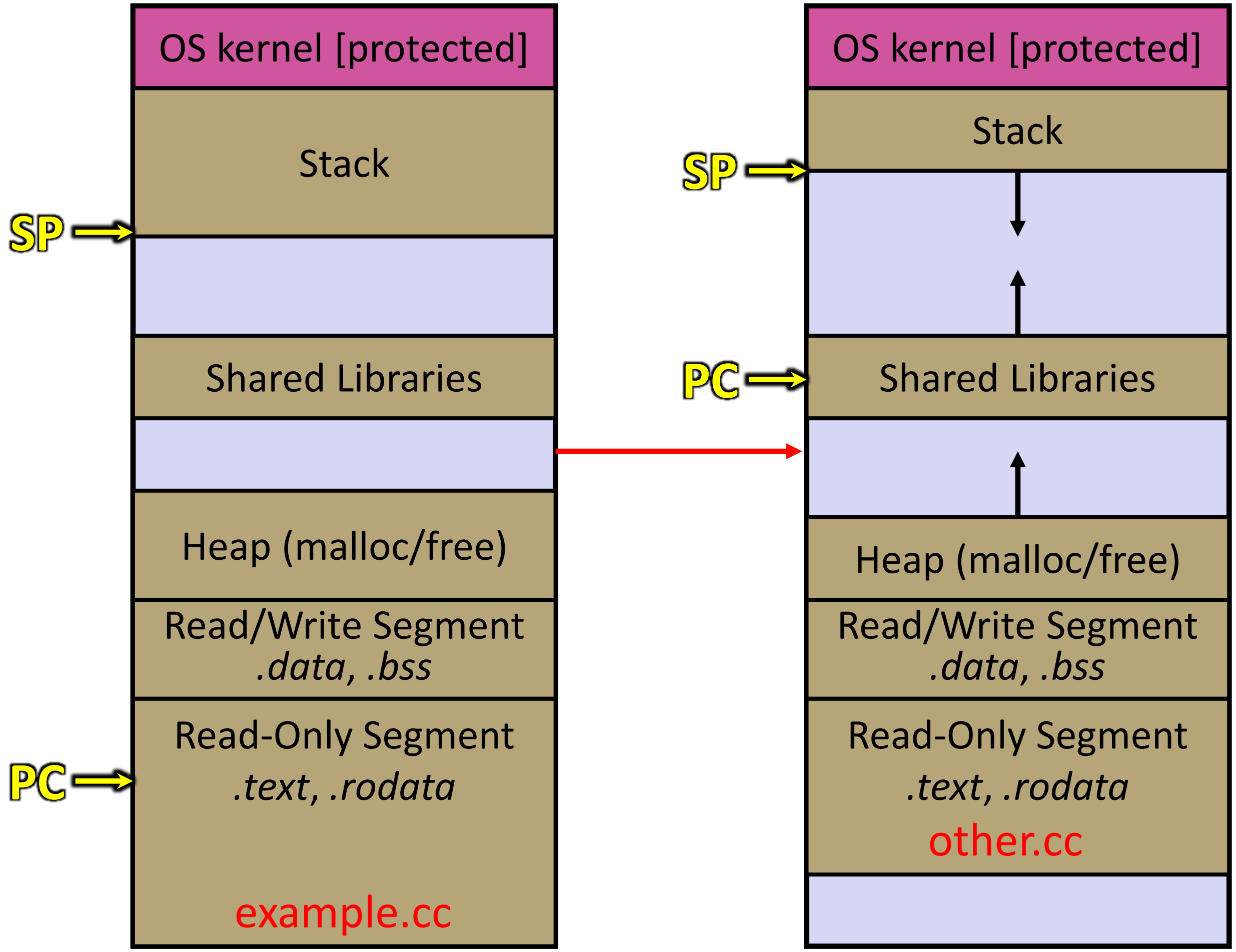
- Loads in a new program for execution
- PC, SP, registers, and memory are all reset so that the specified program can run

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

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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```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 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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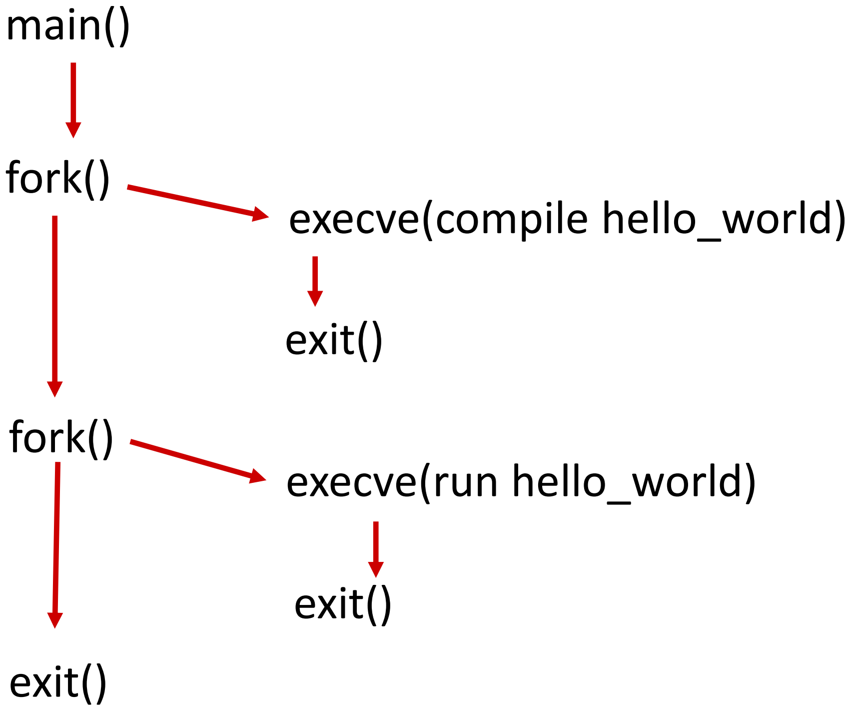

main()

fork()

execve(compile hello_world)

exit()

fork()

execve(run hello_world)

exit()

exit()

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

- 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

- `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

Usual change in status
is to "terminated"

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

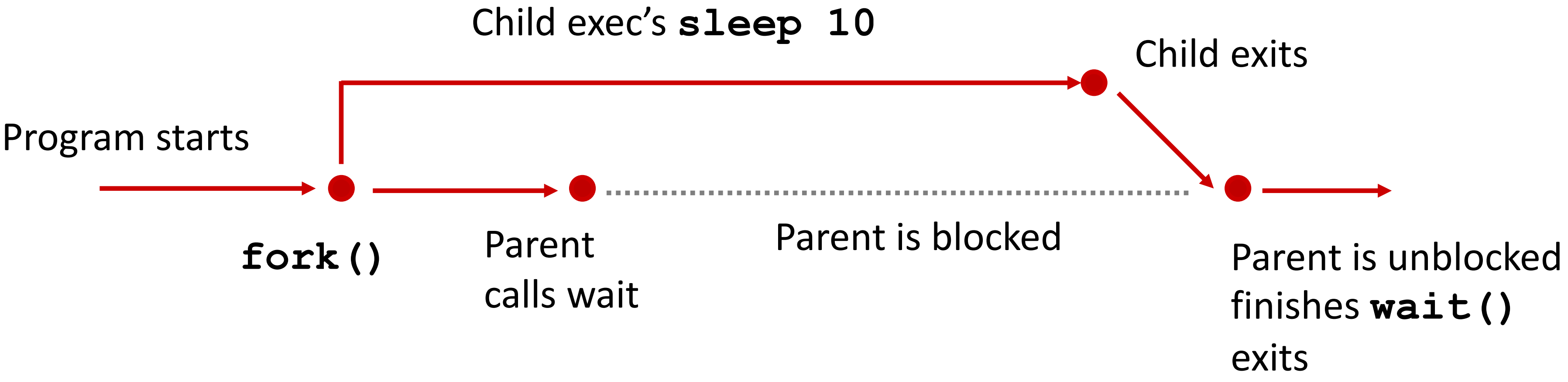
```
int main(int argc, char* argv[]) {
  char* envp[] = { NULL };
  // fork a process to exec clang
  pid_t clang_pid = fork();
  if (clang_pid == 0) {
    // we are the child
    char* clang_argv[] = {"/bin/clang", "-o",
                          "hello","hello_world.c", NULL};
    execve(clang_argv[0],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

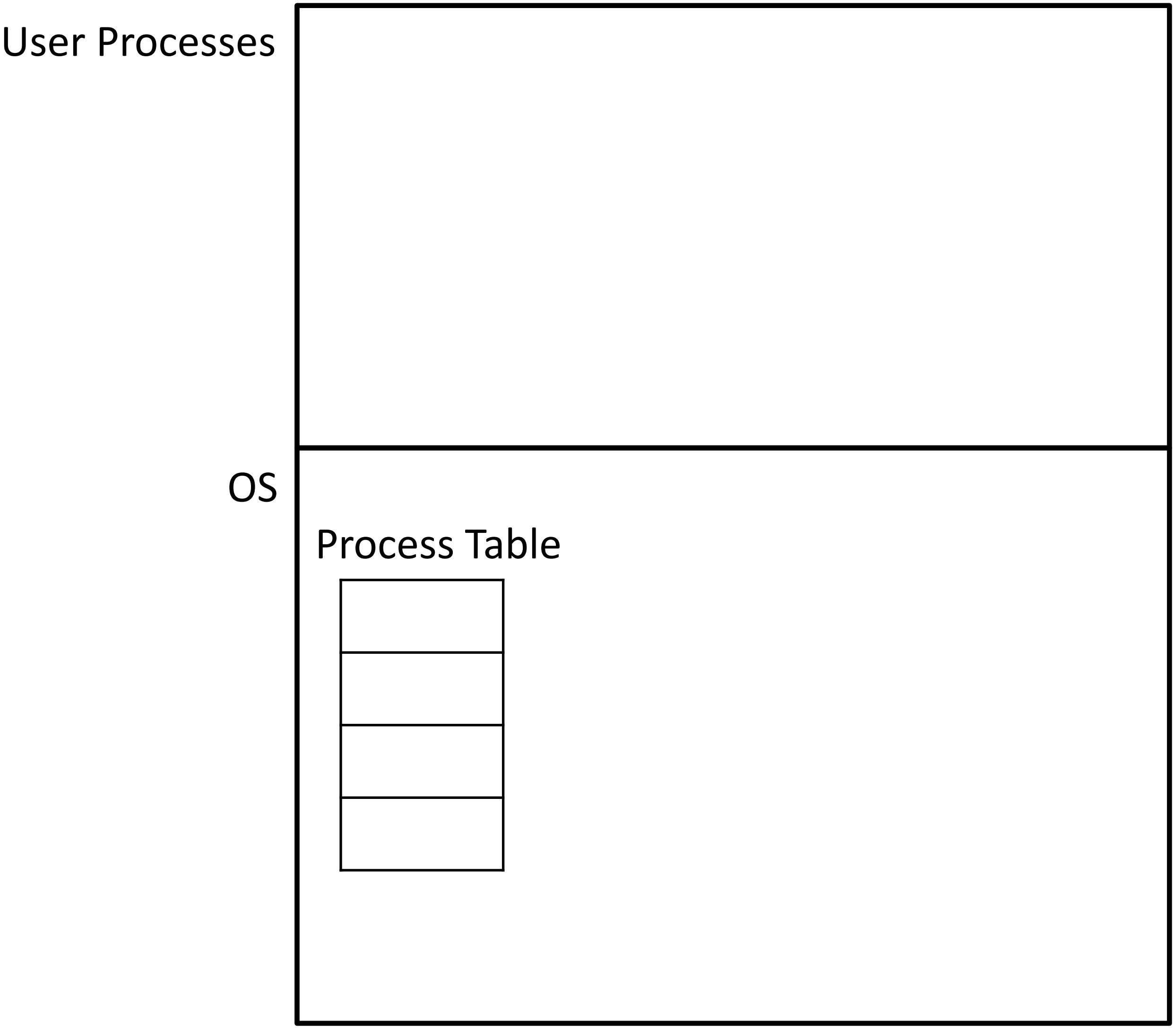
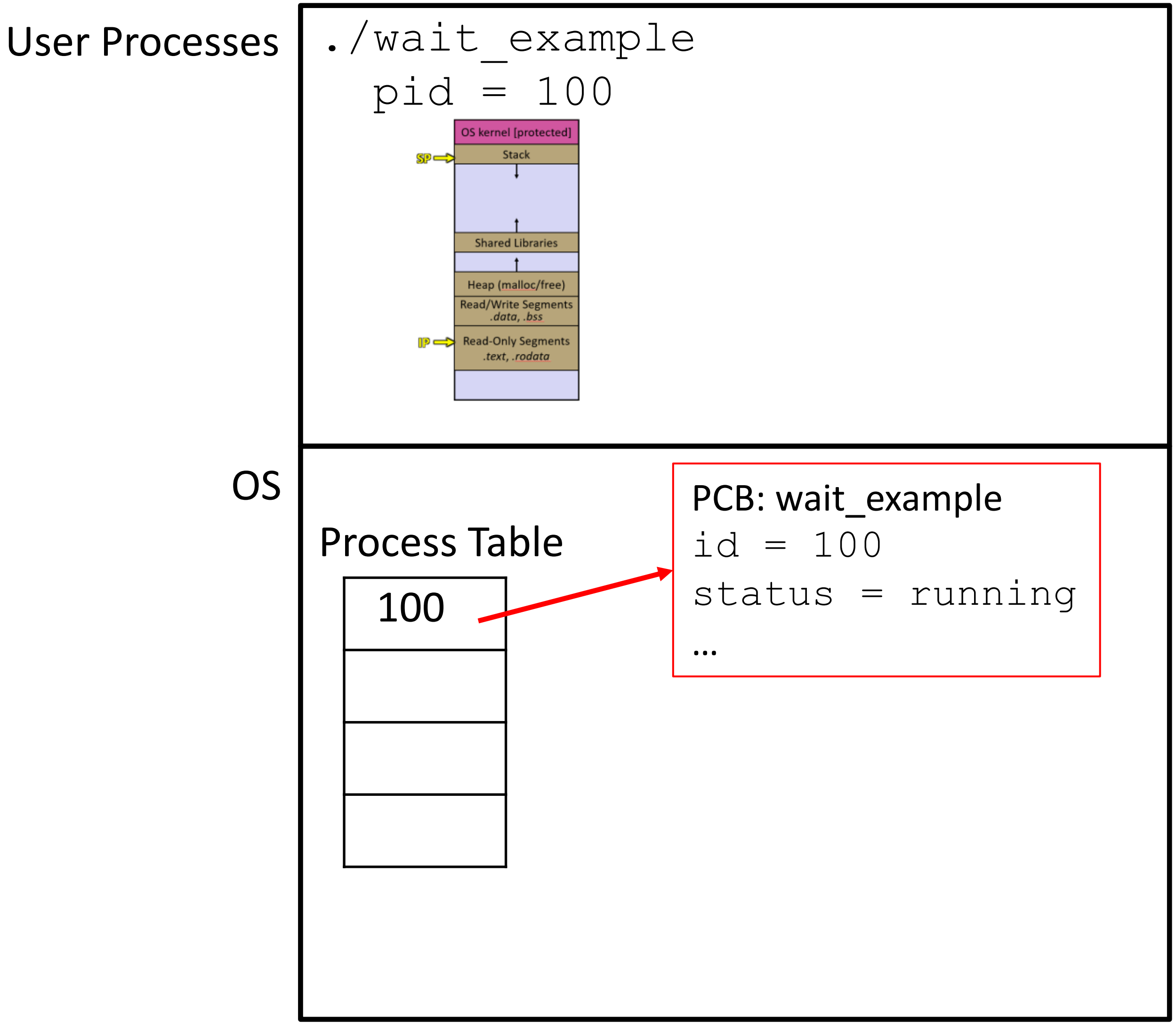


Diagram: wait_example.c



User Processes

`./wait_example`

`pid = 100`

OS

Process Table

100

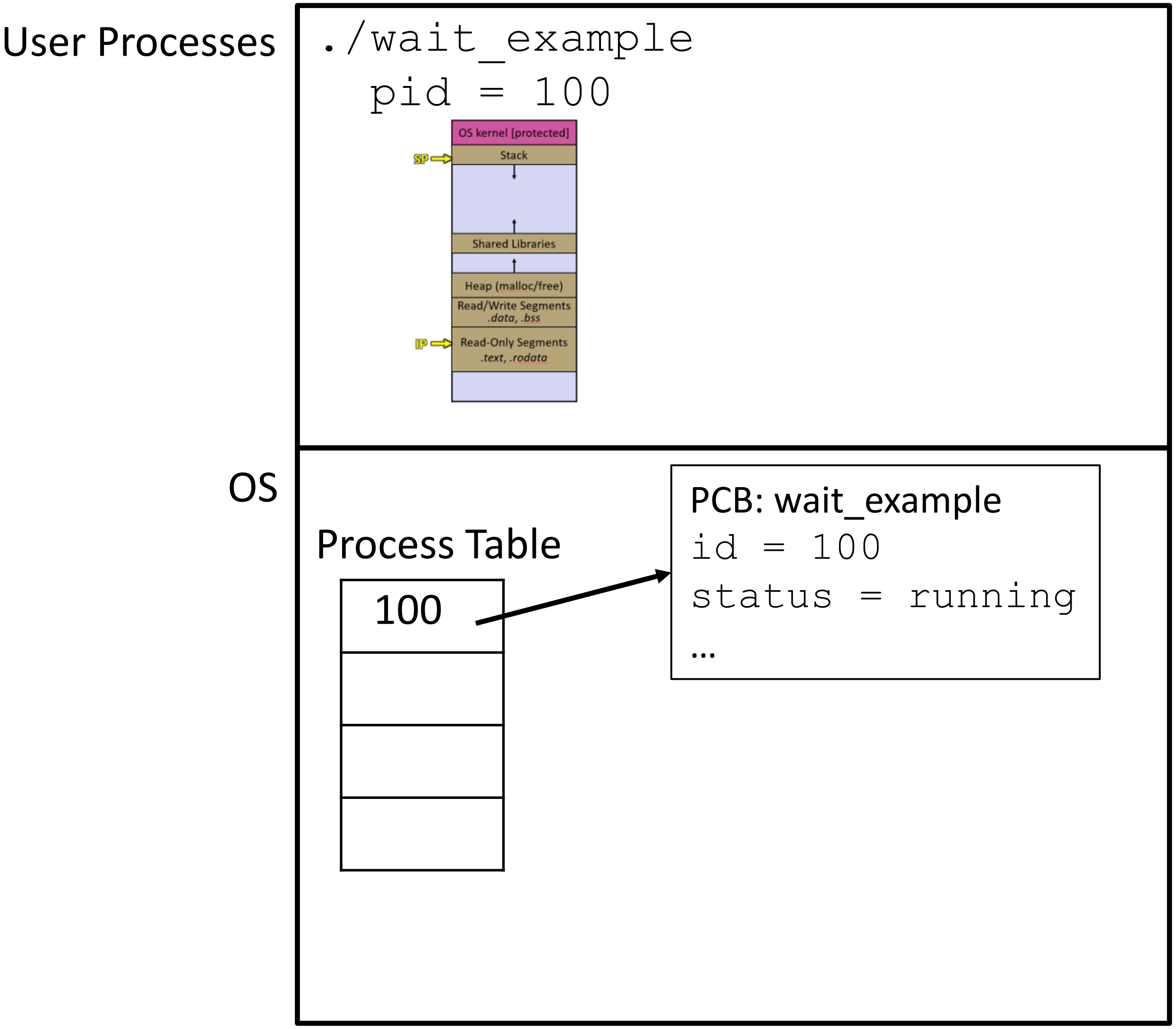
PCB: wait_example

`id = 100`

`status = running`

…

Diagram: wait_example.c



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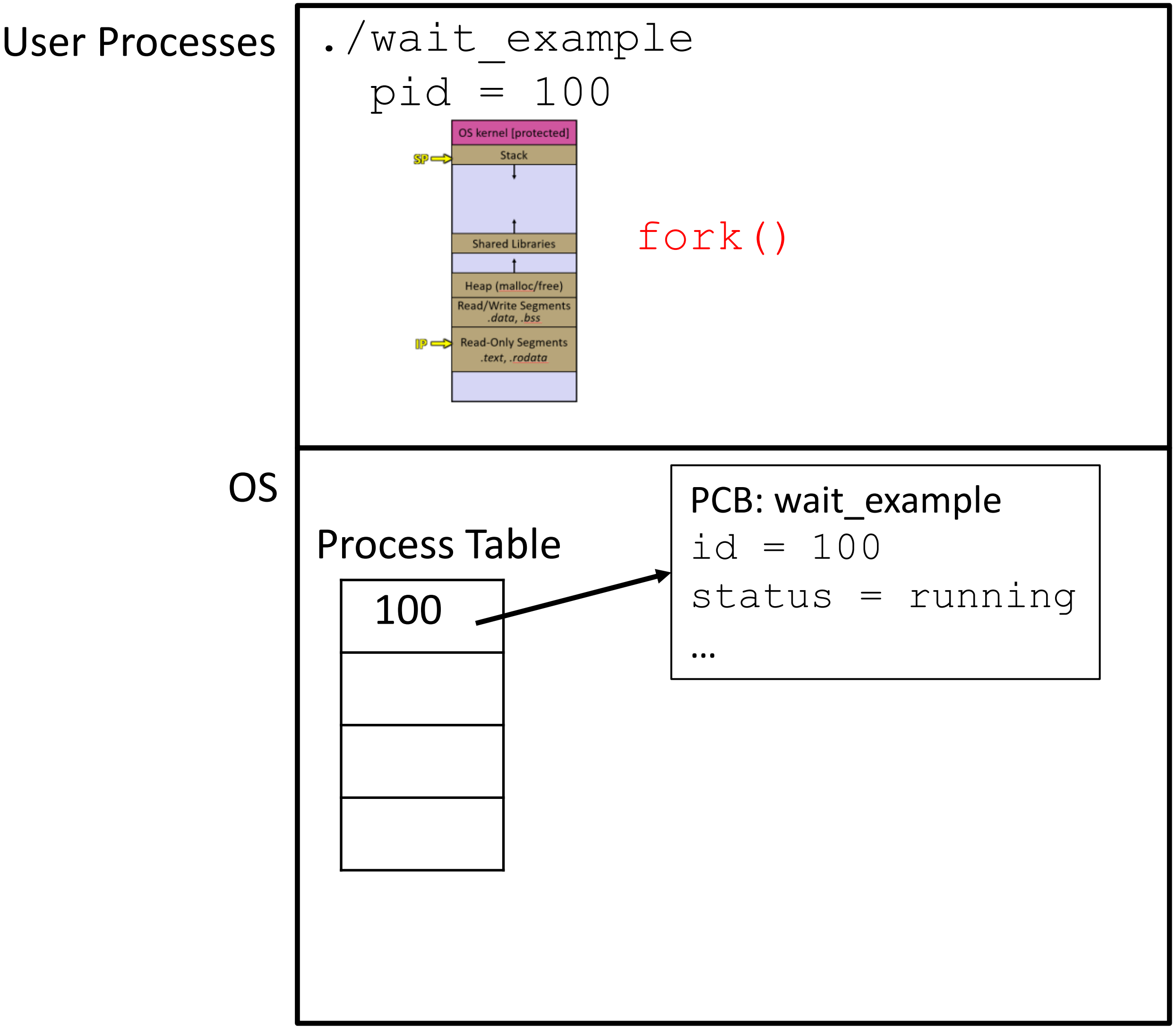


User Processes

`./wait_example`

`pid = 100`

`fork()`

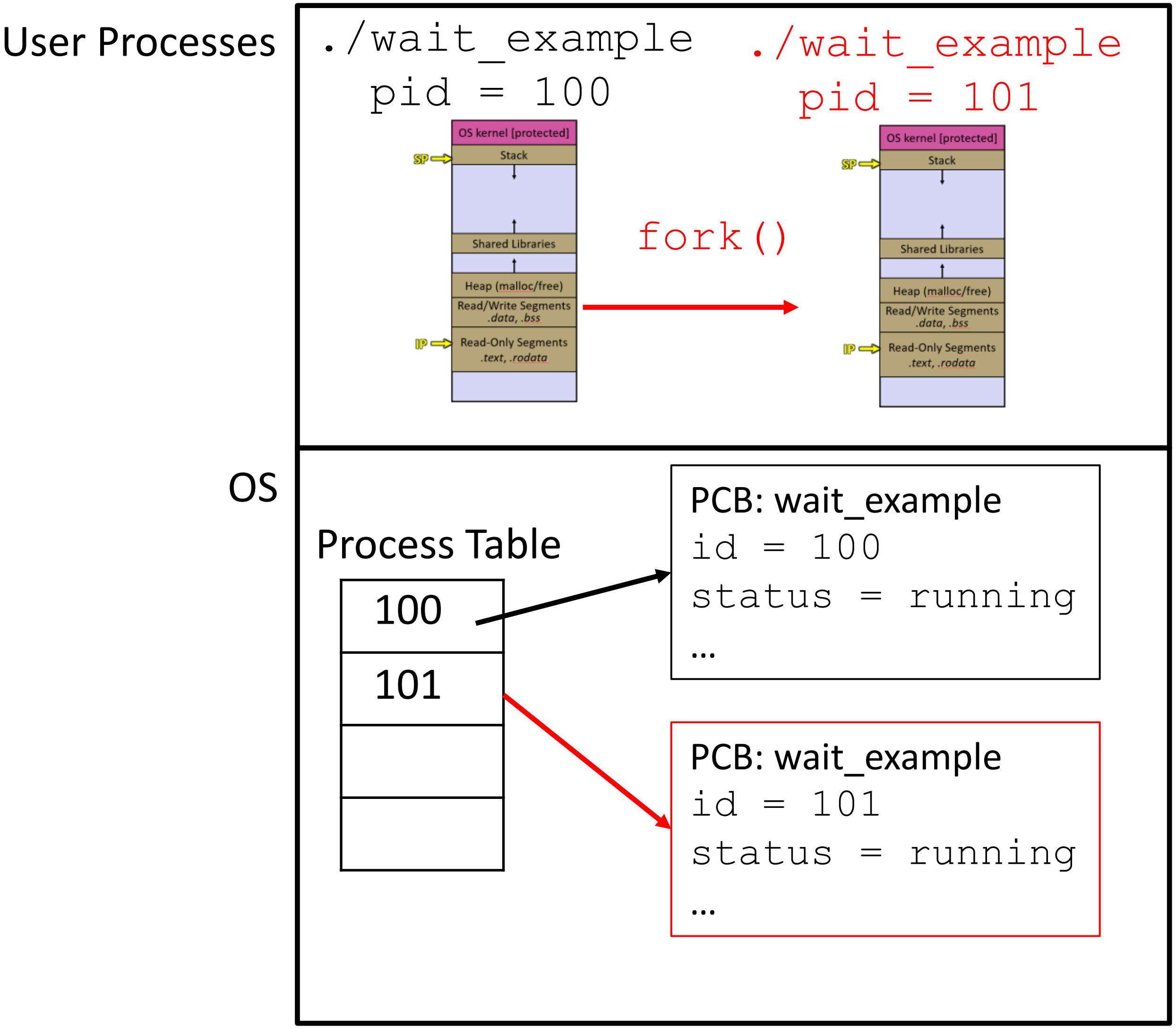
OS

Process Table

100

PCB: wait_example
`id = 100`
`status = running`
…

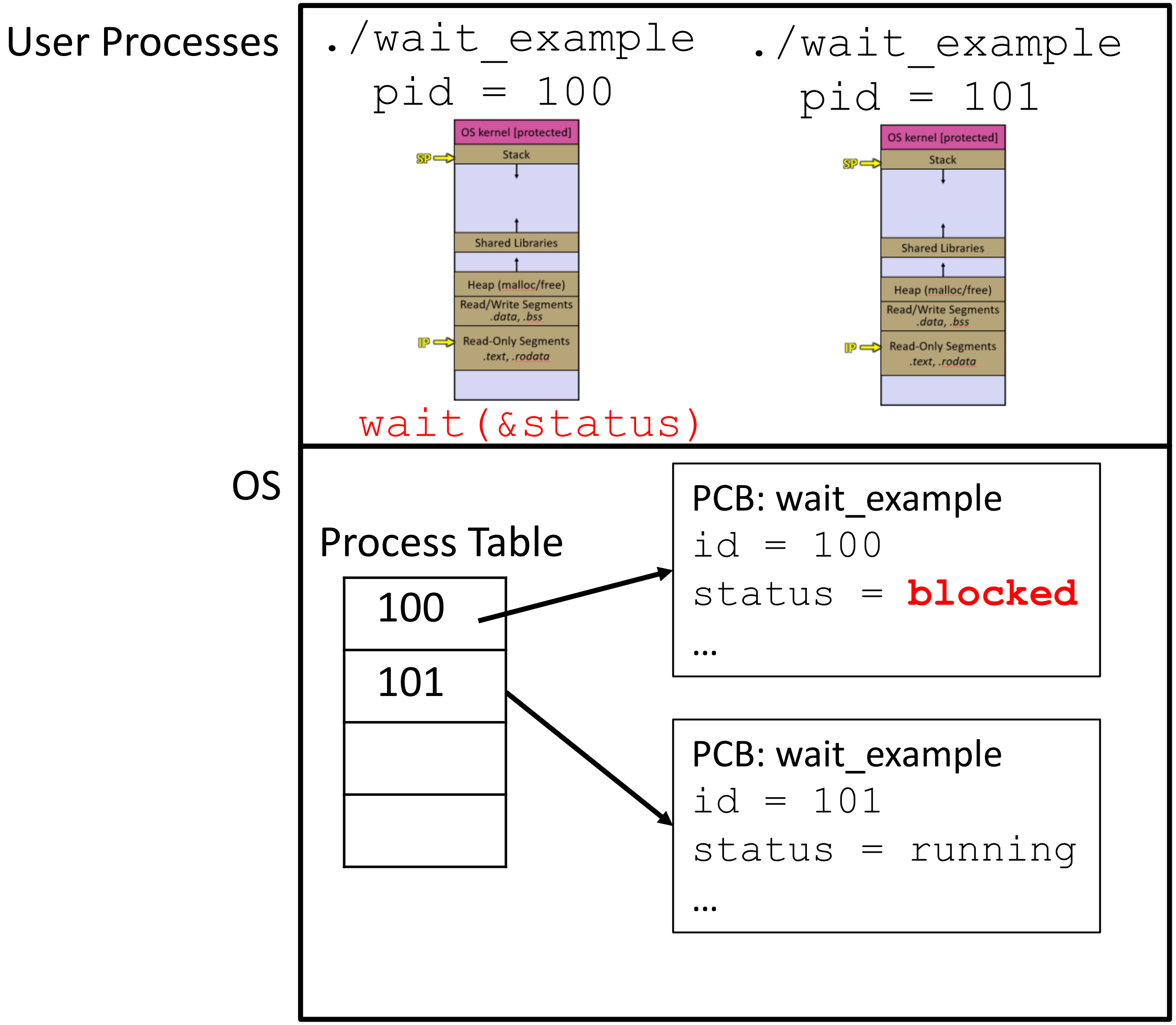
Diagram: wait_example.c



PCB: wait_example
id = 100
status = running
…

PCB: wait_example
id = 101
status = running
…

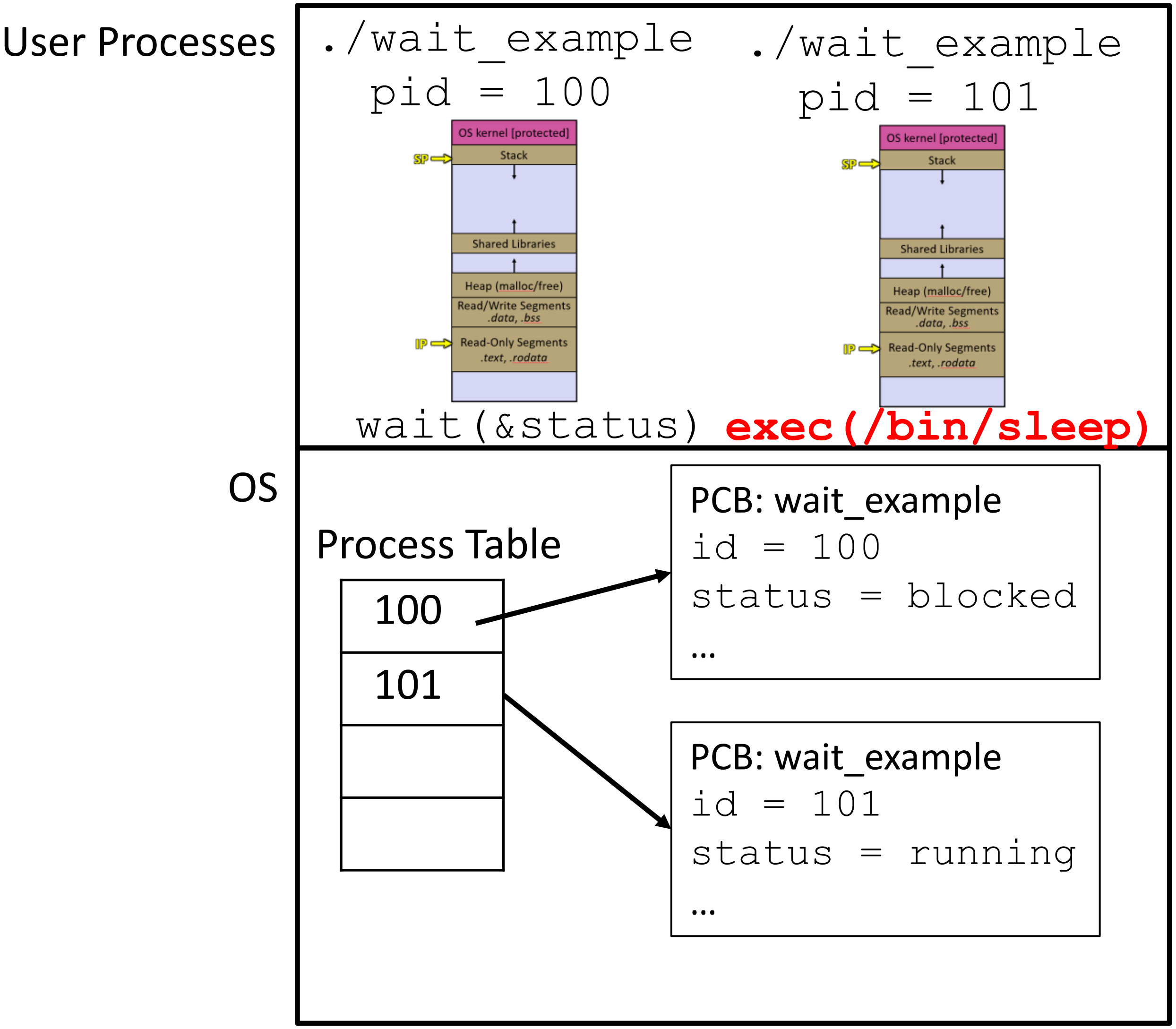
Diagram: wait_example.c



PCB: wait_example
`id = 100`
`status =` **`blocked`**
…

PCB: wait_example
`id = 101`
`status = running`
…

Diagram: wait_example.c



User Processes

`./wait_example`
`pid = 100`

`./wait_example`
`pid = 101`

`wait(&status)` **`exec(/bin/sleep)`**

OS

Process Table

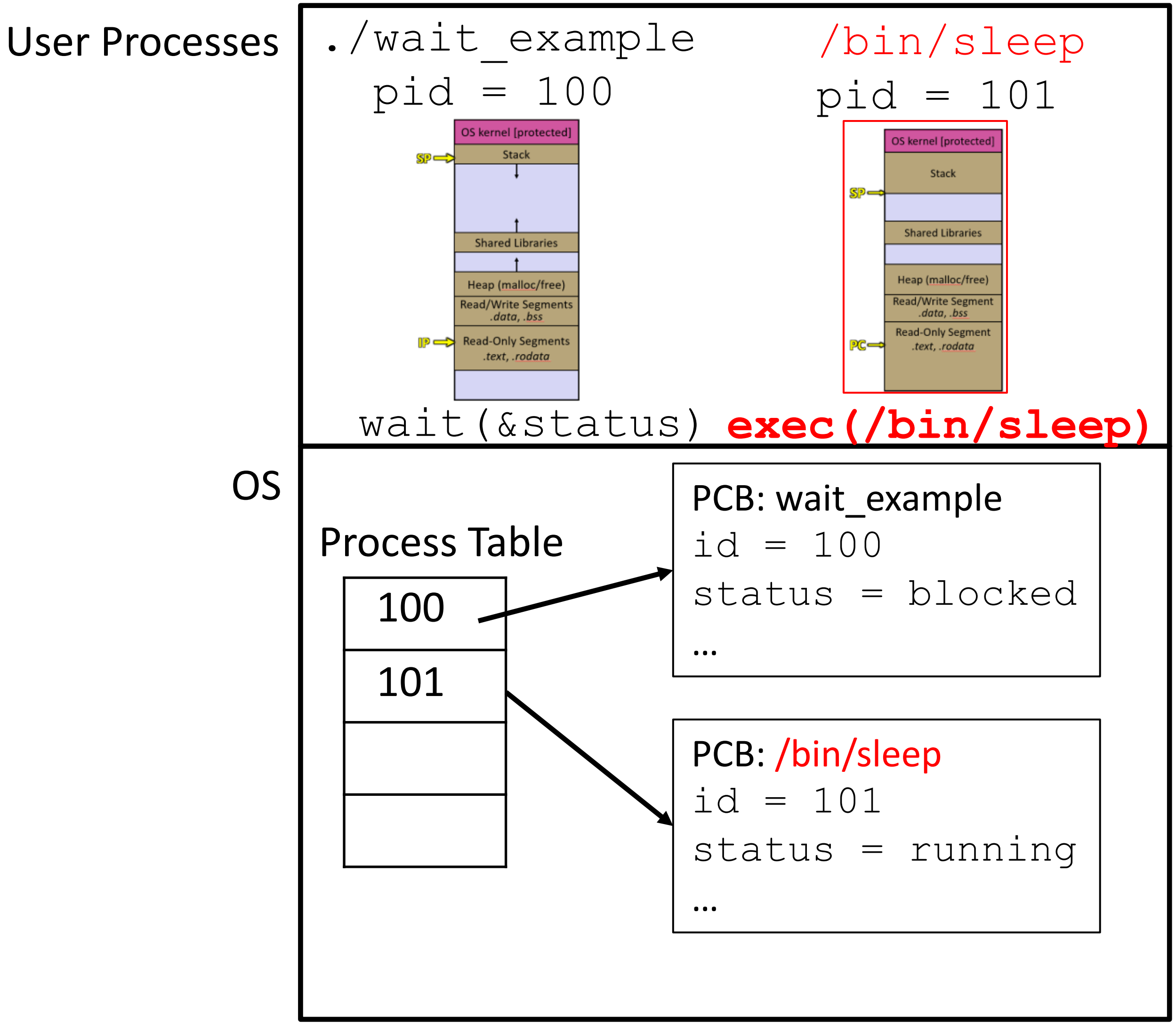
100

101

PCB: wait_example
`id = 100`
`status = blocked`
…

PCB: wait_example
`id = 101`
`status = running`
…

Diagram: wait_example.c



User Processes

`./wait_example`
`pid = 100`

`/bin/sleep`
`pid = 101`

`wait(&status)` **`exec(/bin/sleep)`**

OS

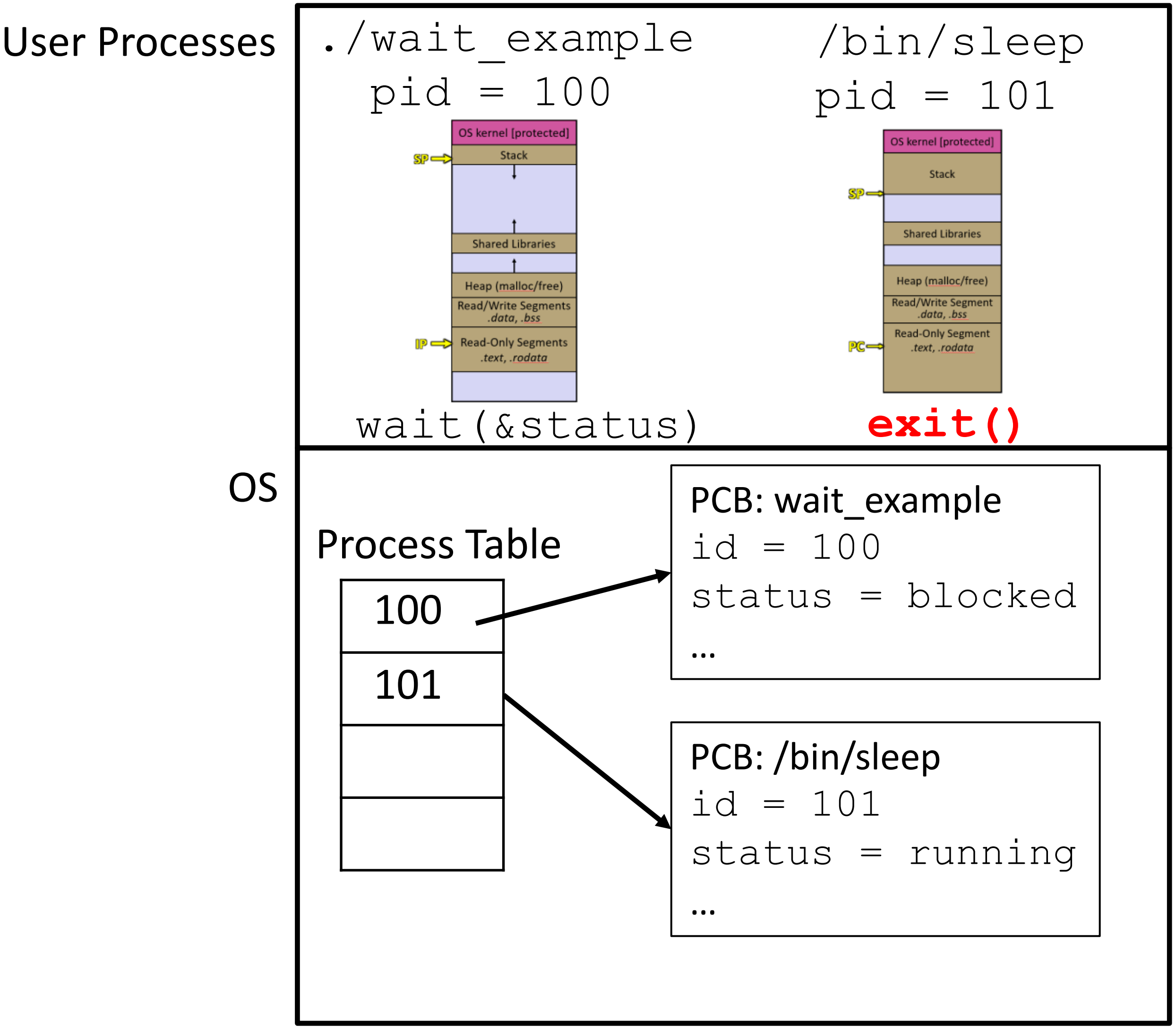
Process Table

100
101

PCB: wait_example
`id = 100`
`status = blocked`
…

PCB: /bin/sleep
`id = 101`
`status = running`
…

Diagram: wait_example.c



User Processes

`./wait_example`

`pid = 100`

`wait(&status)`

`/bin/sleep`

`pid = 101`

`exit()`

OS

Process Table

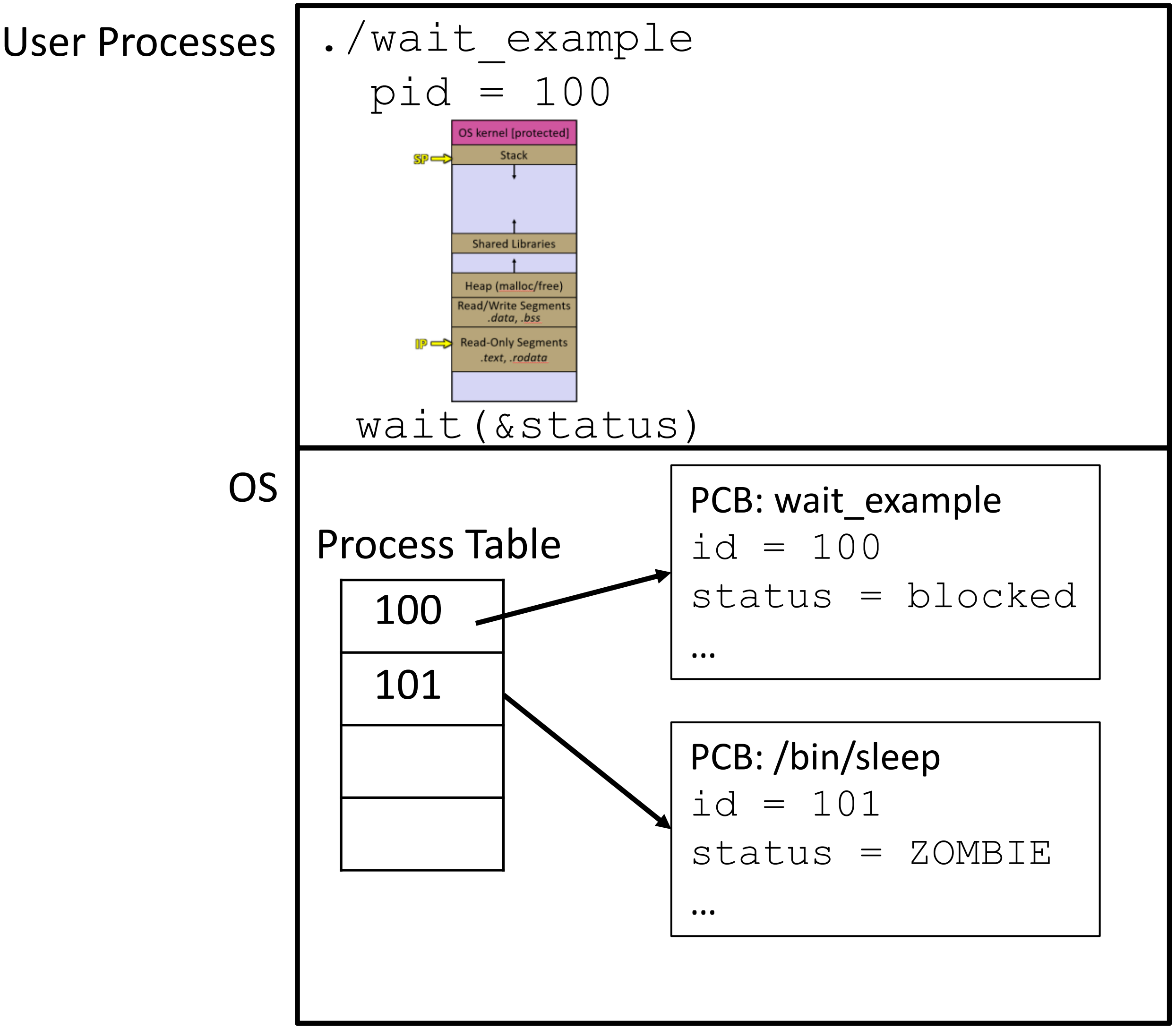
100

101

PCB: wait_example
`id = 100`
`status = blocked`
…

PCB: /bin/sleep
`id = 101`
`status = running`
…

Diagram: wait_example.c



User Processes

`./wait_example`

`pid = 100`

`wait(&status)`

OS

Process Table

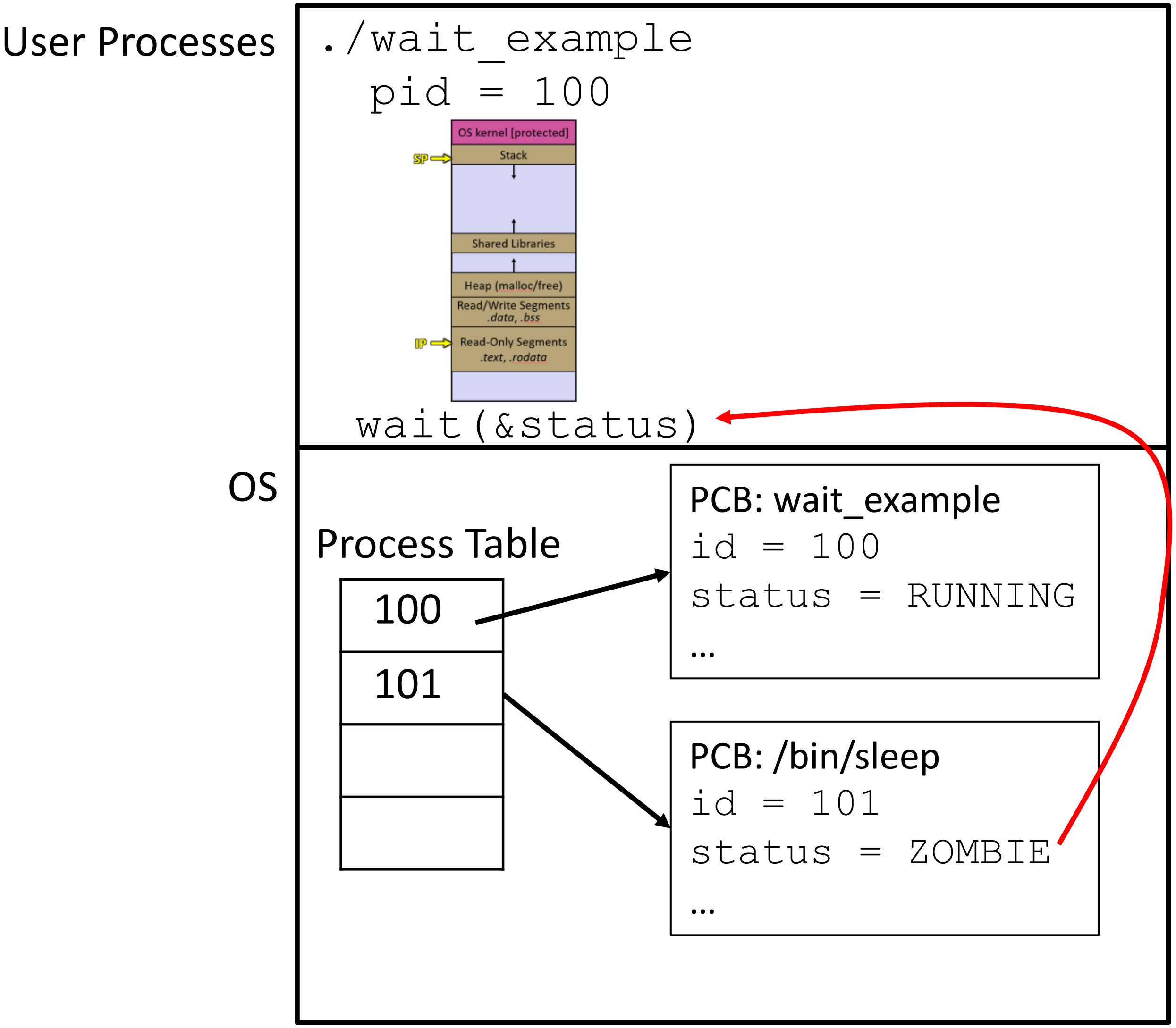
100

101

PCB: wait_example
`id = 100`
`status = blocked`
…

PCB: /bin/sleep
`id = 101`
`status = ZOMBIE`
…

Diagram: wait_example.c



User Processes

`./wait_example`

`pid = 100`

`wait(&status)`

OS

Process Table

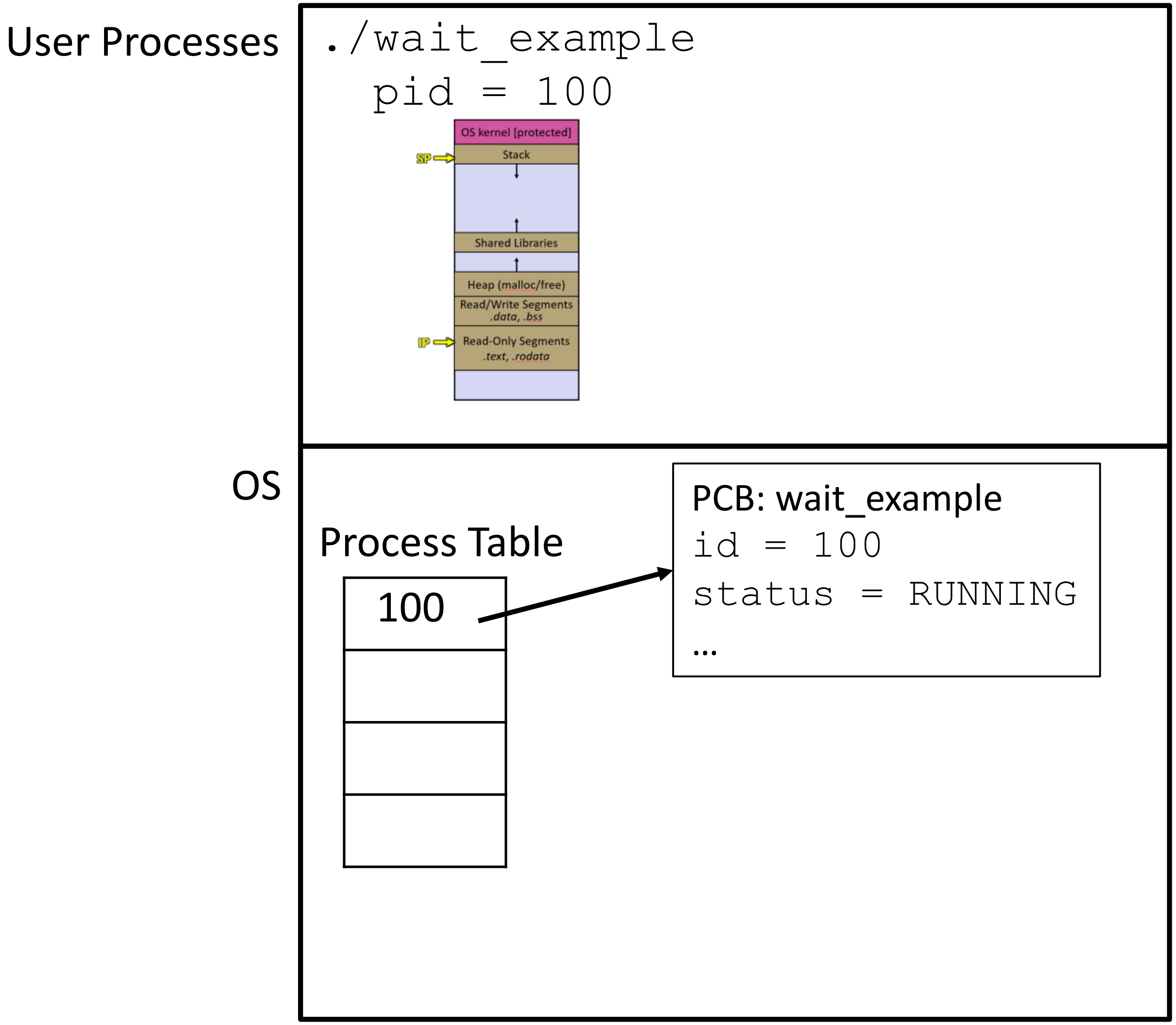
100

101

PCB: wait_example
`id = 100`
`status = RUNNING`
…

PCB: /bin/sleep
`id = 101`
`status = ZOMBIE`
…

Diagram: wait_example.c



User Processes

`./wait_example`

`pid = 100`

OS

Process Table

100

PCB: wait_example

`id = 100`

`status = RUNNING`

…

Diagram: wait_example.c

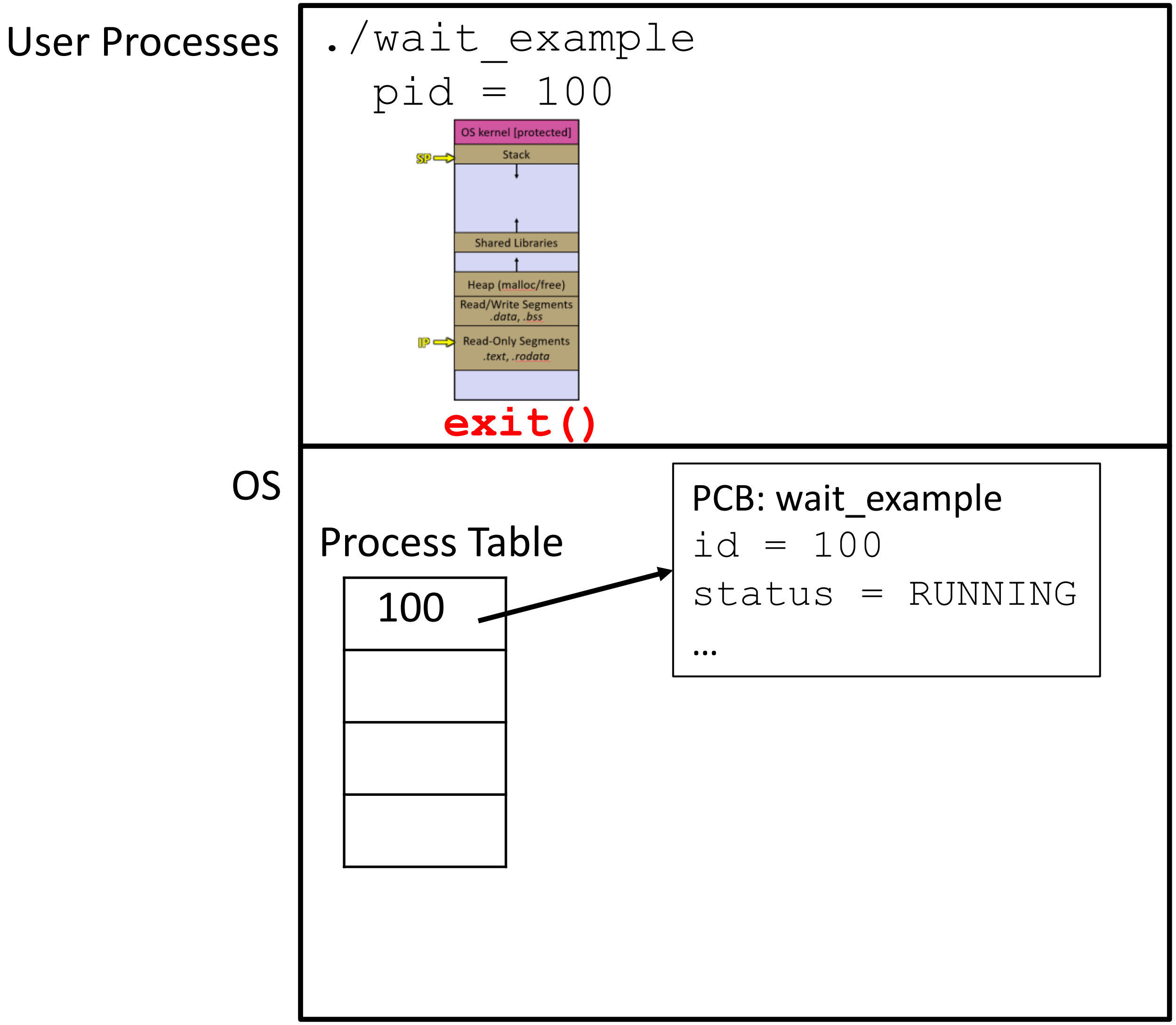
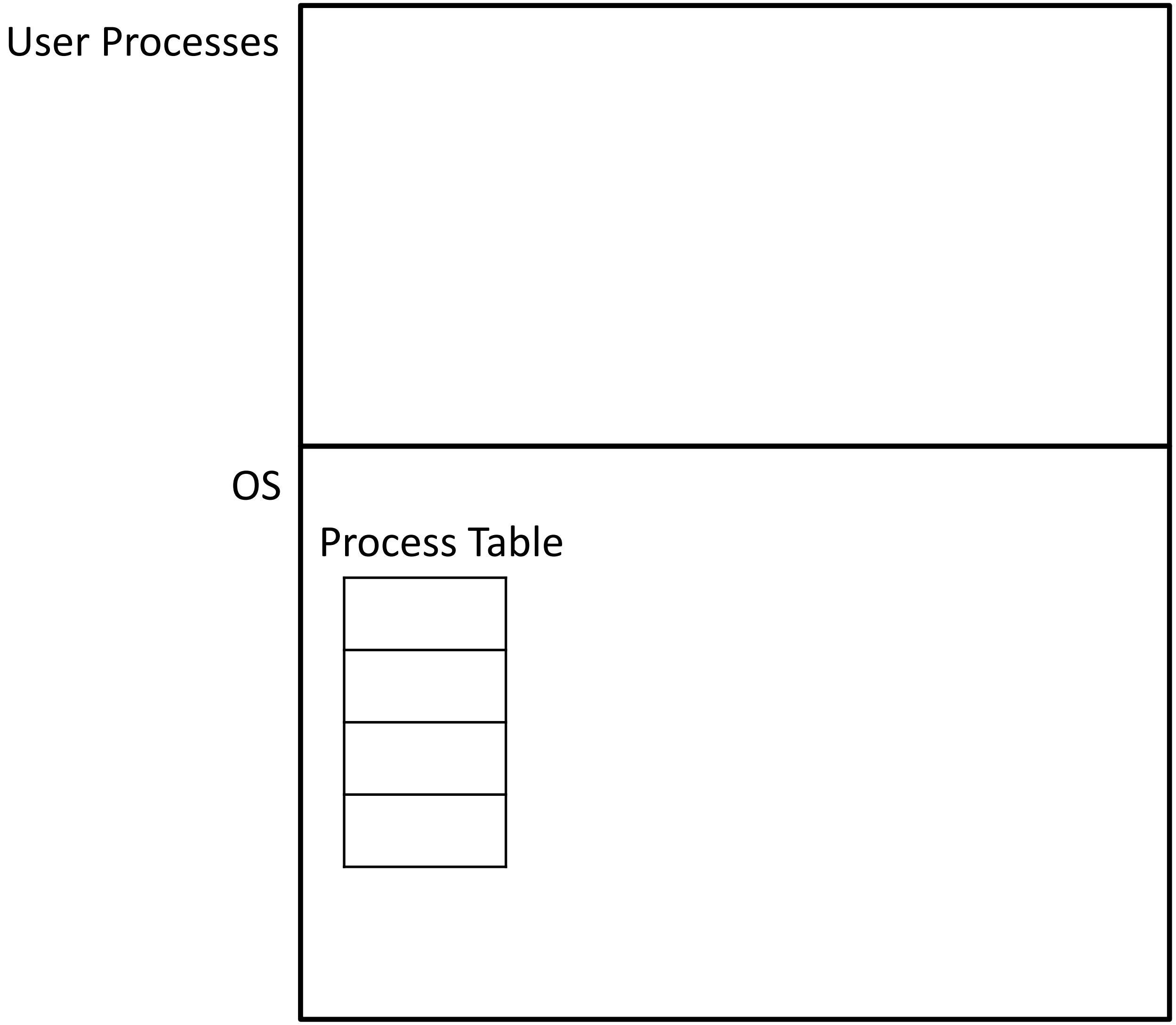


Diagram: wait_example.c



`./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`

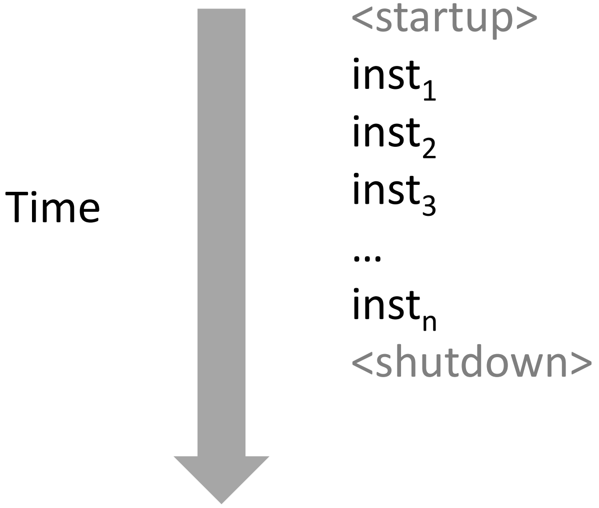
Lecture Outline

- 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 BRp instruction is being executed for the first time, which instruction is executed next?

- **A. BRp**
- **B. ADD**
- **C. SUB**
- **D. JMP**
- **E. I’m not sure**

```
         CONST R0, #5
         CONST R1, #2
         CONST R2, #0

LOOP     ADD R2, R2, #1
         SUB R0, R0, R1
         BRp LOOP
END      JMP #-1
```

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

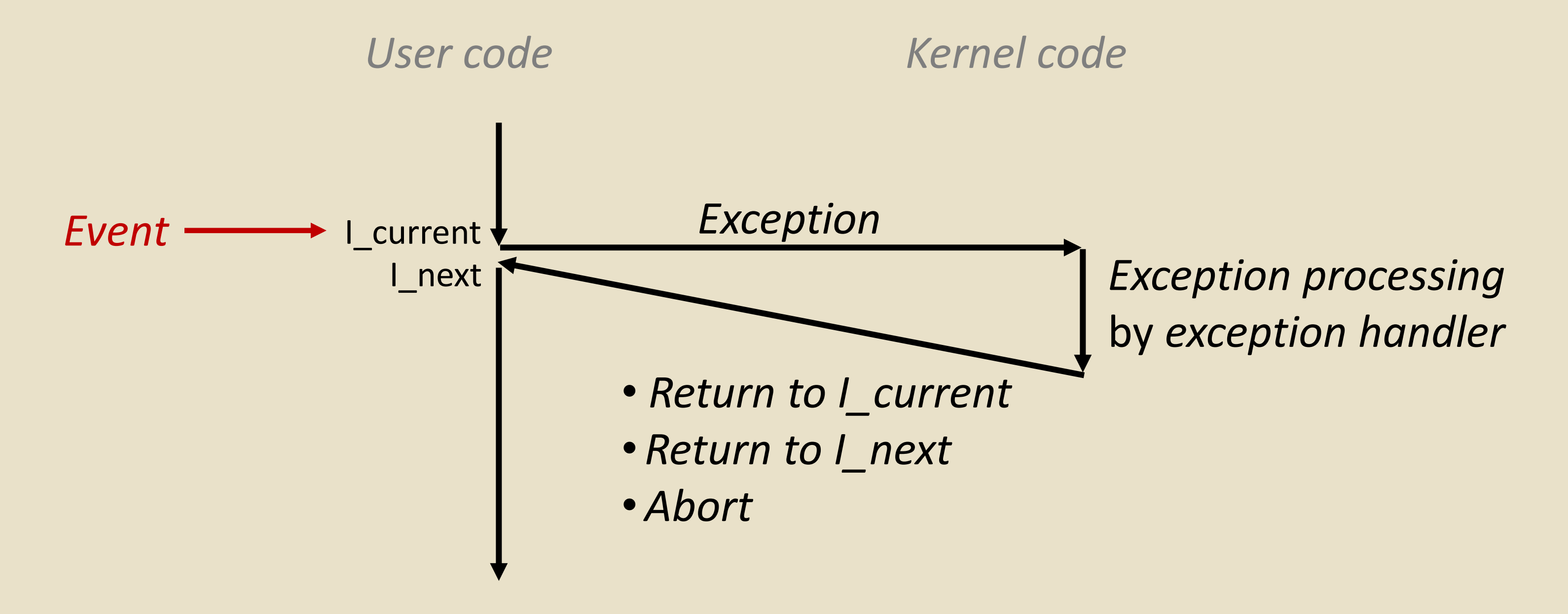
- Exists at all levels of a computer system
- Low level mechanisms
  - 1. **Hardware Interrupts**
    - Change in control flow in response to a system event (i.e., change in system state)
    - Implemented using combination of hardware and OS software

what we will be looking at today

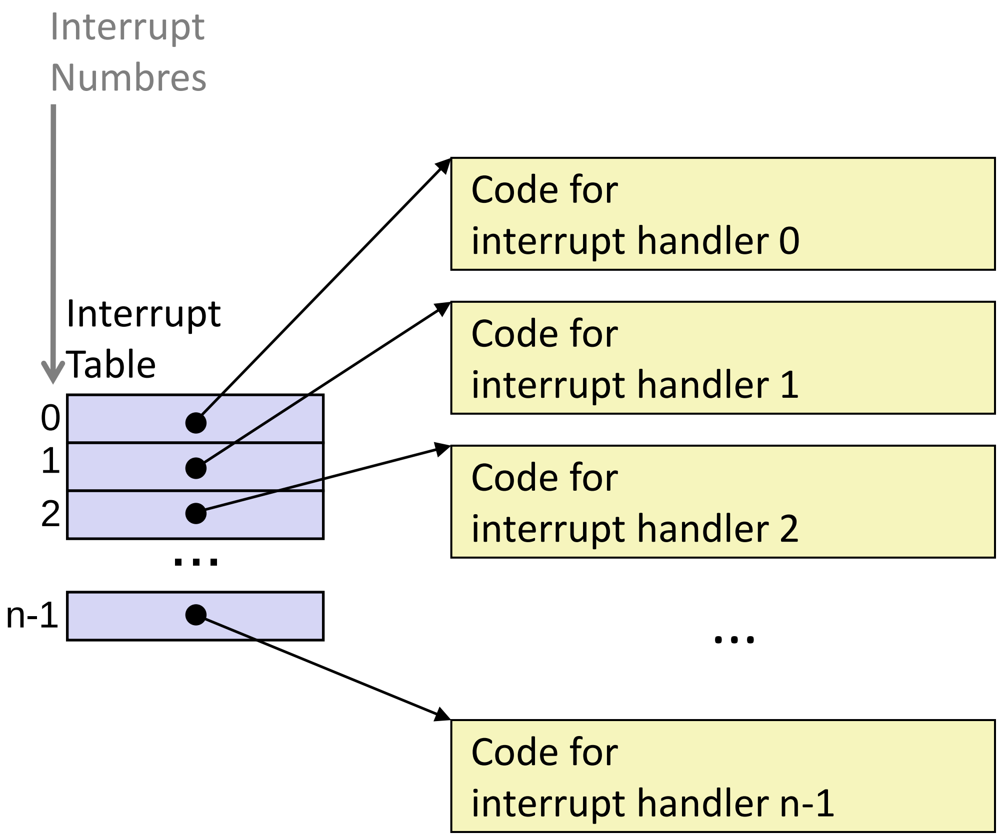
- Higher level mechanisms
  - 2. **Process context switch**
    - Implemented by OS software and hardware timer
  - 3. **Signals**
    - Implemented by OS software

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



- 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

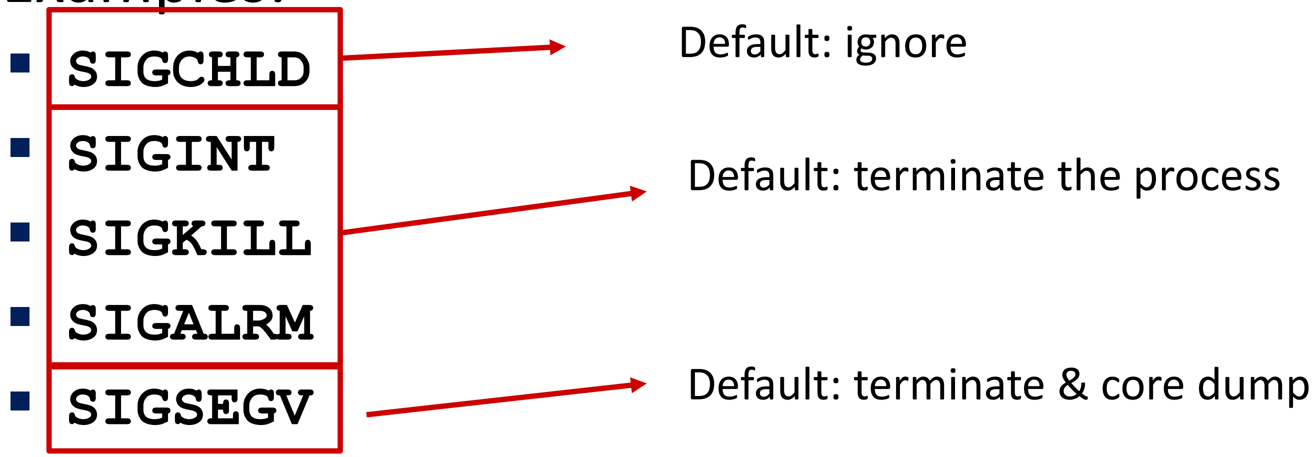
Lecture Outline

- 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

- Examples:



  - `SIGCHLD`
  - `SIGINT`
  - `SIGKILL`
  - `SIGALRM`
  - `SIGSEGV`

Default: ignore

Default: terminate the process

Default: terminate & core dump

`signal()`

- You can change how a certain signal is handled

-
  ```
  sighandler_t signal(int signum,
                      sighandler_t handler);
  ```
- Uses the **`sighandler_t`** type: a function pointer

  -
    ```
    typedef void (*sighandler_t)(int);
    ```
- Returns previous handler for that signal
  - **`SIG_ERR`** when there is an error
- Pass in **`SIG_IGN`** to ignore the signal
- Pass in **`SIG_DFL`** for default behaviour
- Some signals like **`SIG_KILL`** and **`SIG_STOP`** can't be handled differently

Signal handlers

- `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

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()`

- `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 happens if the child process calls alarm? … and default handles it?

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

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

- 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

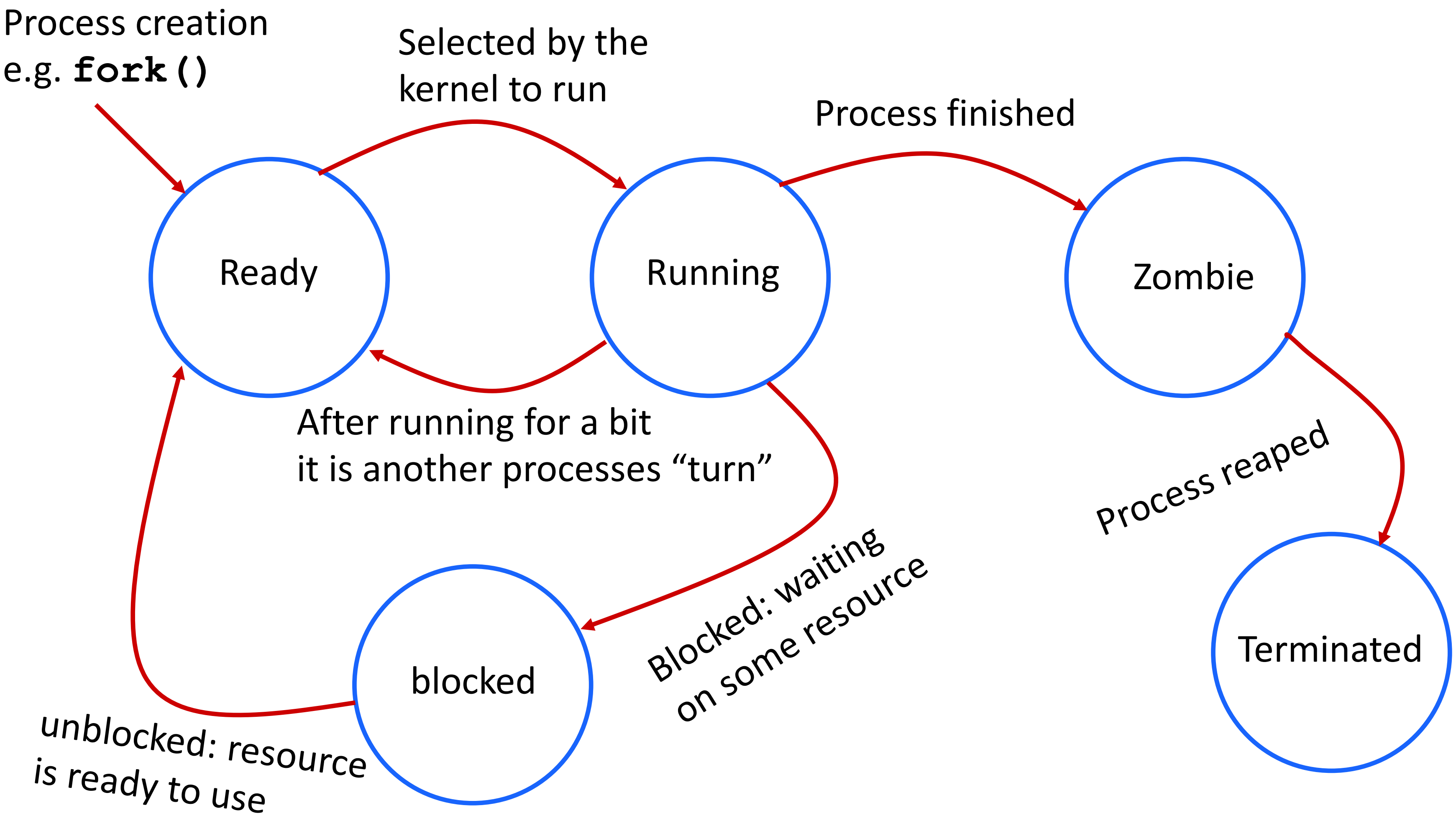
SIGCHLD handler

- 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

- 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**