Processes (cont.): exec, wait, signal

Computer Systems Programming, Fall 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” This Friday 09/05
  - **Extended** to be due the same time as HW01 (Friday the 12th)
  - Mostly a C refresher

- Pre semester Survey
  - Anonymous
  - Short!
  - Due Friday the 5th

- **OH Started Last week, Levine 612! Check out the Course Calendar!**

Administrivia

- Second Assignment (HW01 penn-shredder)
  - Releases after today's lecture sometime tonight
  - Due **Friday Next week** 09/12
  - Intro to system calls, processes, etc.
  - Short Q&A and demo at end of class ☺

- First Check-in
  - Was Due Today! (Extended until the 9th @ 1:45PM…)
  - Don't forget to do them!!!

Administrivia

- Recitation starts this week on Thursday!
  - Look out for an announcement on Ed from the TAs with more information sometime soon.

Lecture Outline

- **Processes & Fork Revisited**
- `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
    - ***There is no way to guarantee the order processes are executed, without*** using some functions we have not talked about (yet),
  - Processes are created by fork() system call
    - Only difference between processes is their process id and the return value from fork() each process gets

Revisting fork()

```
pid_t fork();
```

- Creates a new process (the "child") that is an *exact clone** of the current process (the "parent")
- Fork returns the ***pid of the child*** in the parent, but ***0 in the child.***
- The new process has a separate ***virtual address space*** from the parent

```c
int main(){

    int x = 10;
    pid_t child = fork();
    if(child == 0) 10--;
    printf("This is the pid: %d\n", child);
}
```

*almost everything

Parent vs Child: Separate Address Space

```c
int main(){

    int x = 10;
    pid_t child = fork();
    if(child == 0) 10--;
    printf("This is the pid: %d\n", child);
}
```

pid = 1160

Stack

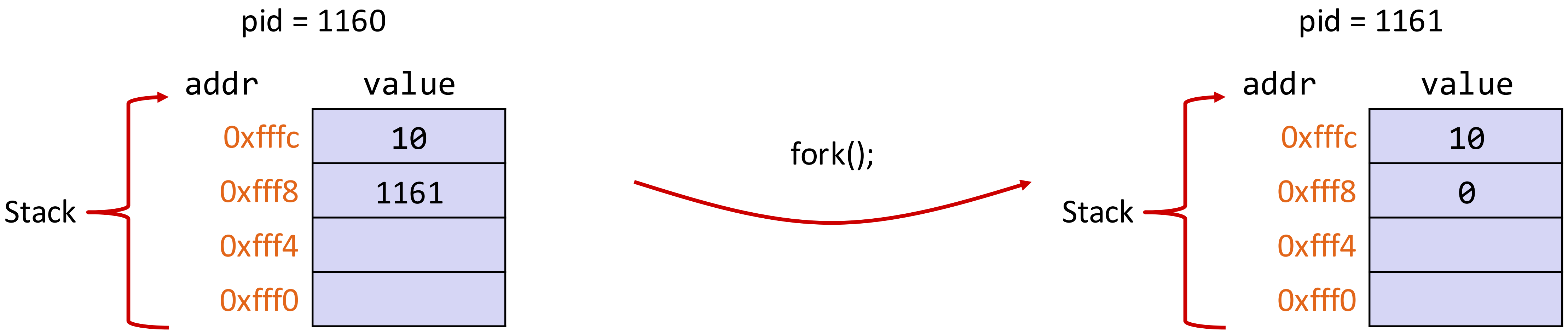
addr	value
0xfffc	10
0xfff8	
0xfff4	
0xfff0	

*almost everything

Parent vs Child: Separate Address Space

```
int main(){

    int x = 10;
    pid_t child = fork();
    if(child == 0) 10--;
    printf("This is the pid: %d\n", child);
}
```



*almost everything

Parent vs Child: Separate Address Space

```
int main(){

        int x = 10;
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        if(child == 0) 10--;
  ───►  printf("This is the pid: %d\n", child);
}
```

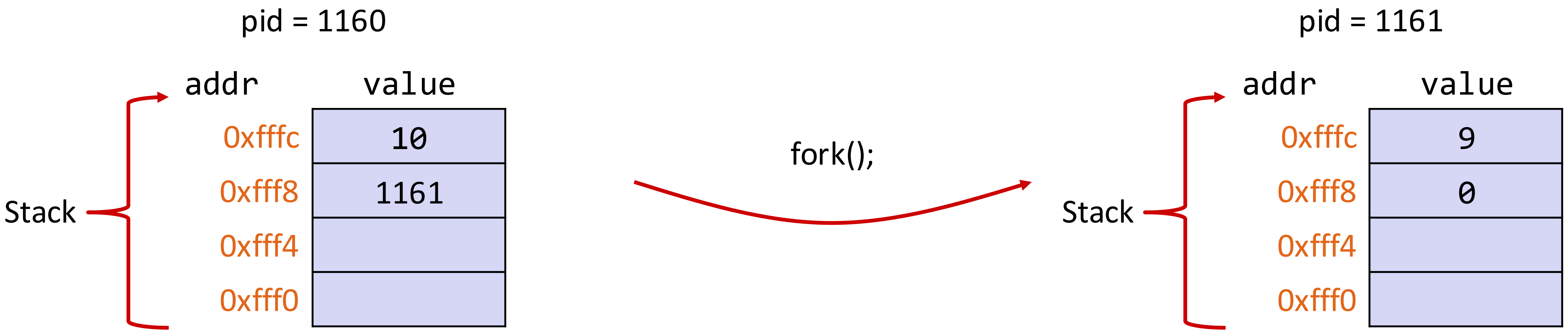


```
root@eb681338c92b:~/workspace/codeplayground/lecture2# ./simple_fork
This is the pid: 1198
This is the pid: 0
```

*almost everything

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- How many times is ":)" printed?

```
int main(int argc, char* argv[]) {
  for (int i = 0; i < 3; i++) {
    pid_t pid = fork();
    if(pid == 0) {
        printf(":)\n");
    }
  }

  return EXIT_SUCCESS;
}
```

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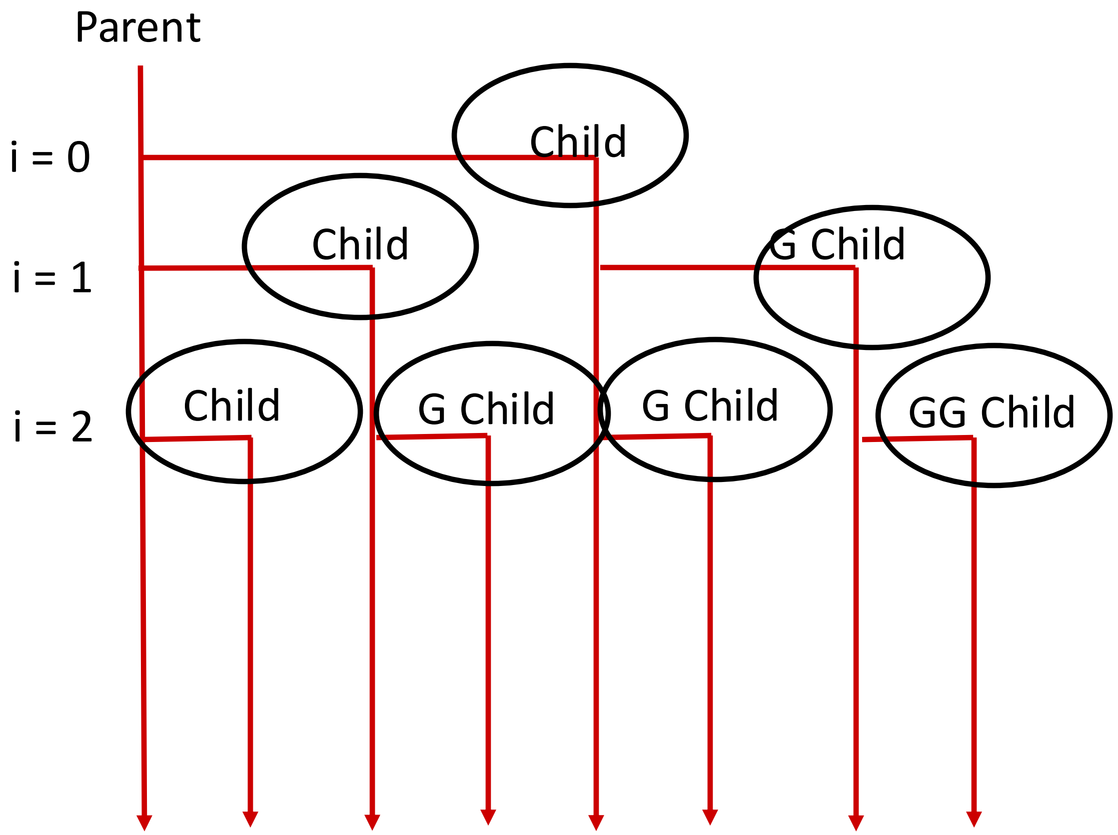
- How many times is ":)" printed?

```c
int main(int argc, char* argv[]) {
  for (int i = 0; i < 3; i++) {
    pid_t pid = fork();
    if(pid == 0) {
       printf(":)\n");
    }
  }

  return EXIT_SUCCESS;
}
```



When will pid be equal to 0?
Each time a new process is created!

Lecture Outline

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

exec*()

- A family of functions that load in a ***new program*** for execution.
  - Replaces the currently running program while using the ***same process***.

- Things that are newly initialized include
  - Stack
  - Heap
  - Data segments (i.e. globals)
  - Registers (Stack Pointer, Program Counter, Argument-Registers…)
  - Text Segment (This one should make sense!)
  - And more….

execve()

```
int execve(const char *file,
           char* const argv[],
           char* const envp[]);
```

executes the program referred to by **file**.

- `const char *file`
  - The file(path) of the executable to well, execute
- `char* const argv[]` (An array of char *s)
  - **`argv[0]`** MUST have the same contents as the file parameter
  - **`argv`** must have NULL as the last entry of the array
  - `int main(int argc, char *argv[])`

execve()

```
int execve(const char *file,
           char* const argv[],
           char* const envp[]);
```

- `char* const envp[]`
  - list of environment vars that become the environment of the exec'd program.
  - Not important for this course, learn more by doing `man environ`
  - Use this: `char* const envp[] = {NULL};`

- Return Value
  - If successful, there is no return value!
  - On failure, execve returns -1

Aside: The Exit Status

```
void exit(int status);
```

- Initiates the 'tear-down' of a process. "Graceful" exit.
- Generally called by `main()` when control falls off main or when main returns
- `int status`
  - EXIT_SUCCESS or EXIT_FAILURE
  - The exit status of a child is accessible by its parent process via `wait()` or `waitpid()`…

Typically used as follows:

```
execve(…);
exit(…); //shouldn't have reached this…
```

don't confuse exit() with _exit()

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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- 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[]) {

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

   printf(":) \n");

  return EXIT_SUCCESS;
}
```

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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;
}
```

This code compiles, but doesn't do what we want. The program attempts 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)
- Assume we gave the correct args to exec in both cases

broken_autograder.c

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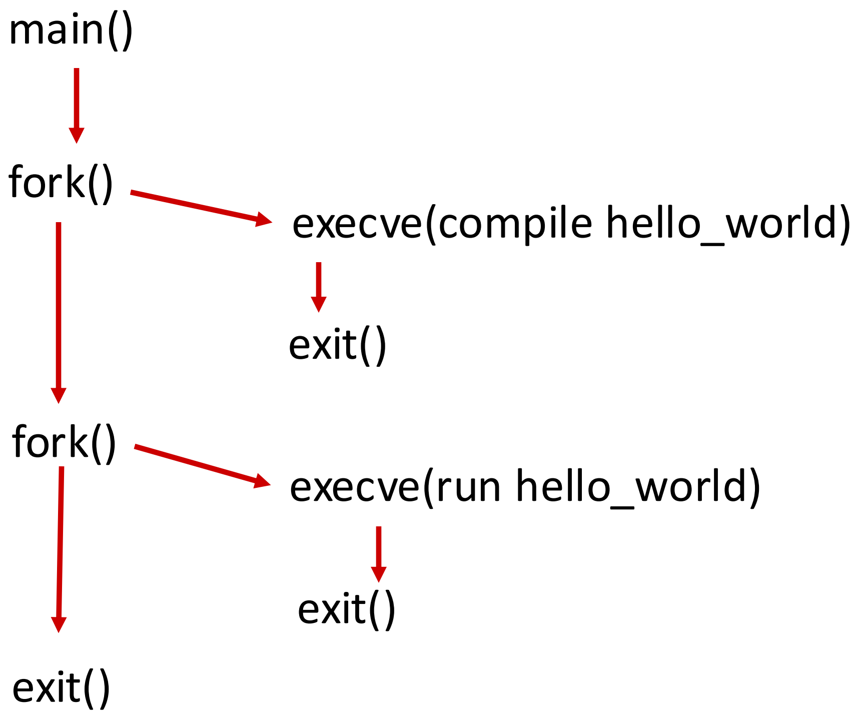


This code is broken. It compiles, but it doesn't do what we want. Why?

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

Lecture Outline

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

From the previous example:

```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

What do we need to happen for this to work correctly?

Waiting for Processes to Finish

- `pid_t wait(int *wstatus);`
  - int *wstatus
    - Output parameter containing the status of the terminated child.
  - Returns process ID of child who changed states for or -1 on error (e.g. no children to wait for)

Calling process waits for any child process to change status to terminated.

```
int main(){
  pid_t pid = fork();
  if(pid == 0){
   //....
   return EXIT_SUCCESS;
  }
  int status;
  pid_t wpid = wait(&status);
  // do something with status
}
```

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

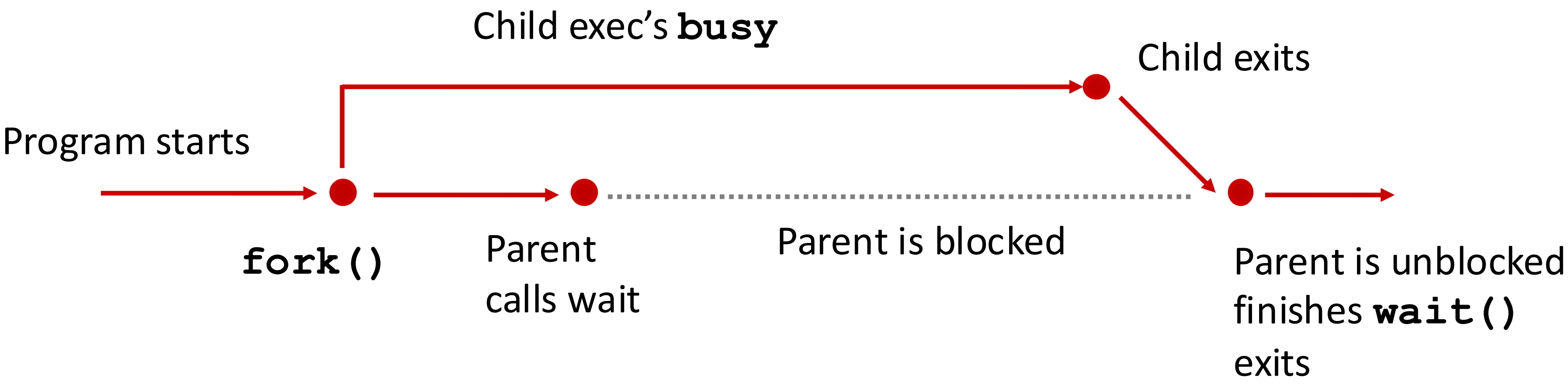
```
int main(int argc, char* argv[]) {
  char* envp[] = { NULL };
  // fork a process to exec clang
  pid_t clang_pid = fork();
  if (clang_pid == 0) {
    // we are the child
    char* clang_argv[] = {"/bin/clang", "-o",
                "hello","hello_world.c", NULL};
    execve(clang_argv[0], clang_argv,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



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 our example, it is extremely likely this happens if the child is calling **`sleep 10`**, **`./busy`**, **`etc.`**
  - 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 OS maintains a table of all processes that aren't "completely done"
- Each process in this table has a process control block (**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

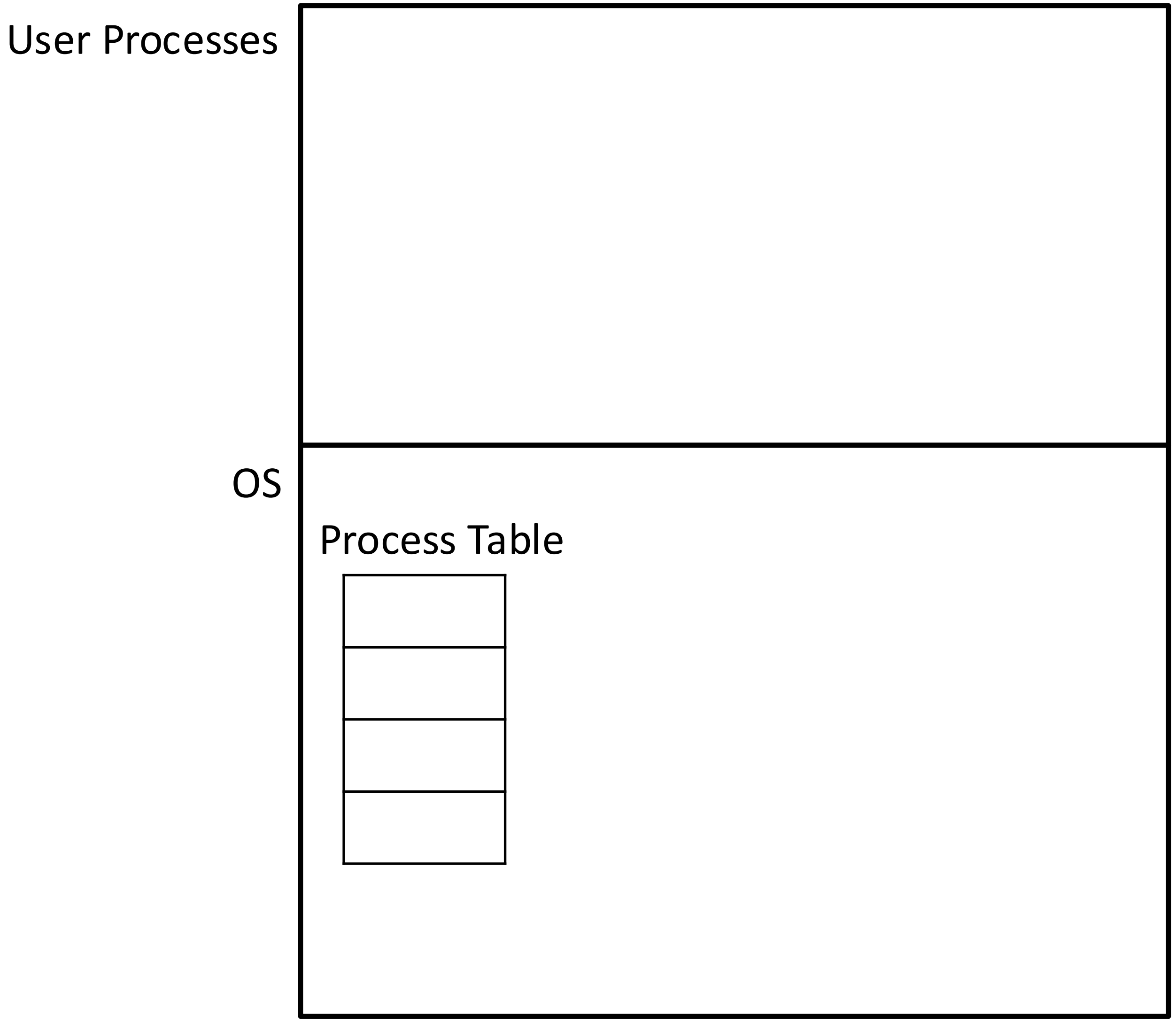


Diagram: wait_example.c

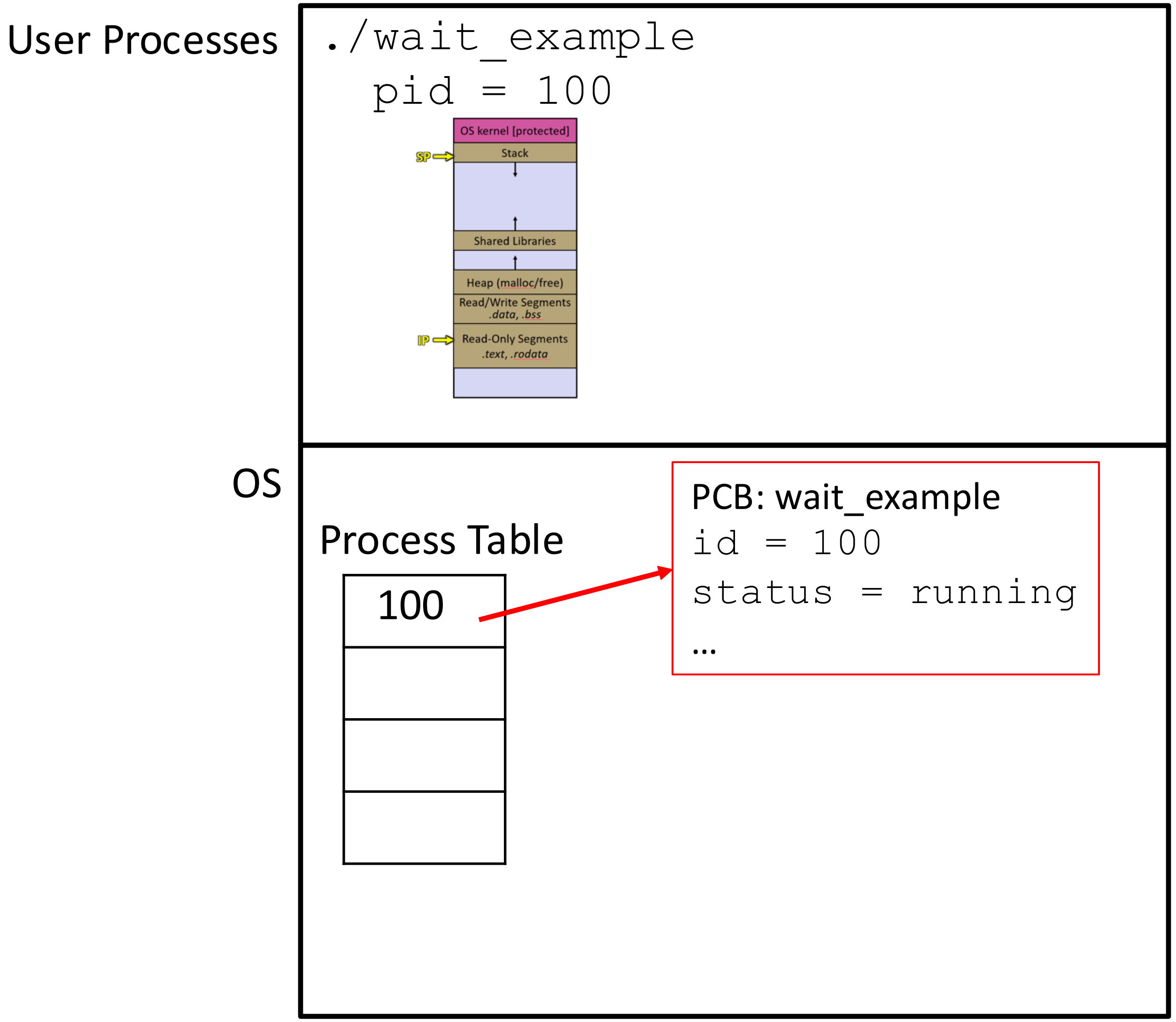


Diagram: wait_example.c

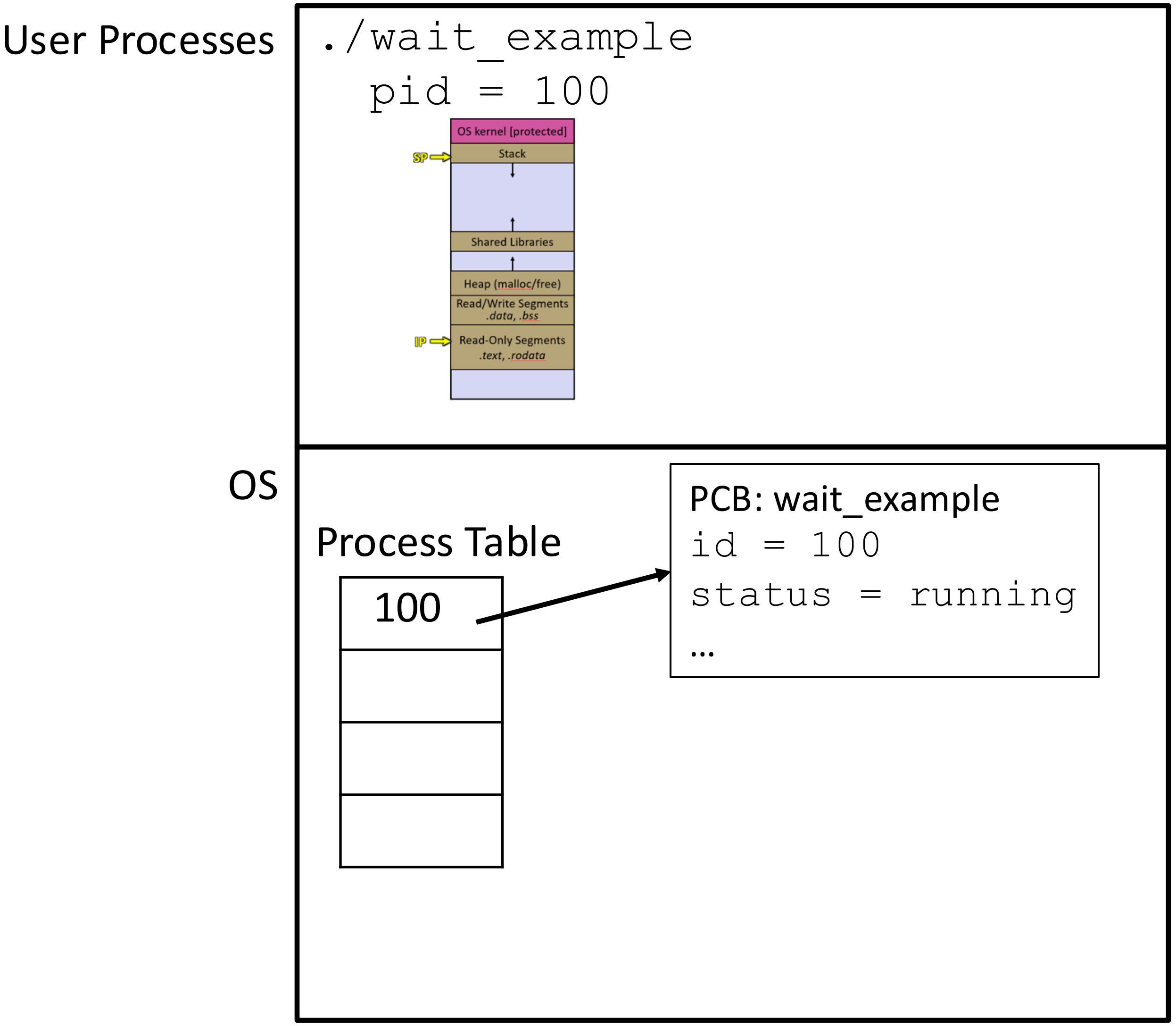
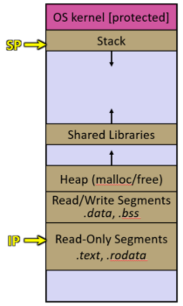


Diagram: wait_example.c

User Processes

./wait_example

pid = 100



fork()

OS

Process Table

100

PCB: wait_example

id = 100

status = running

…

Diagram: wait_example.c

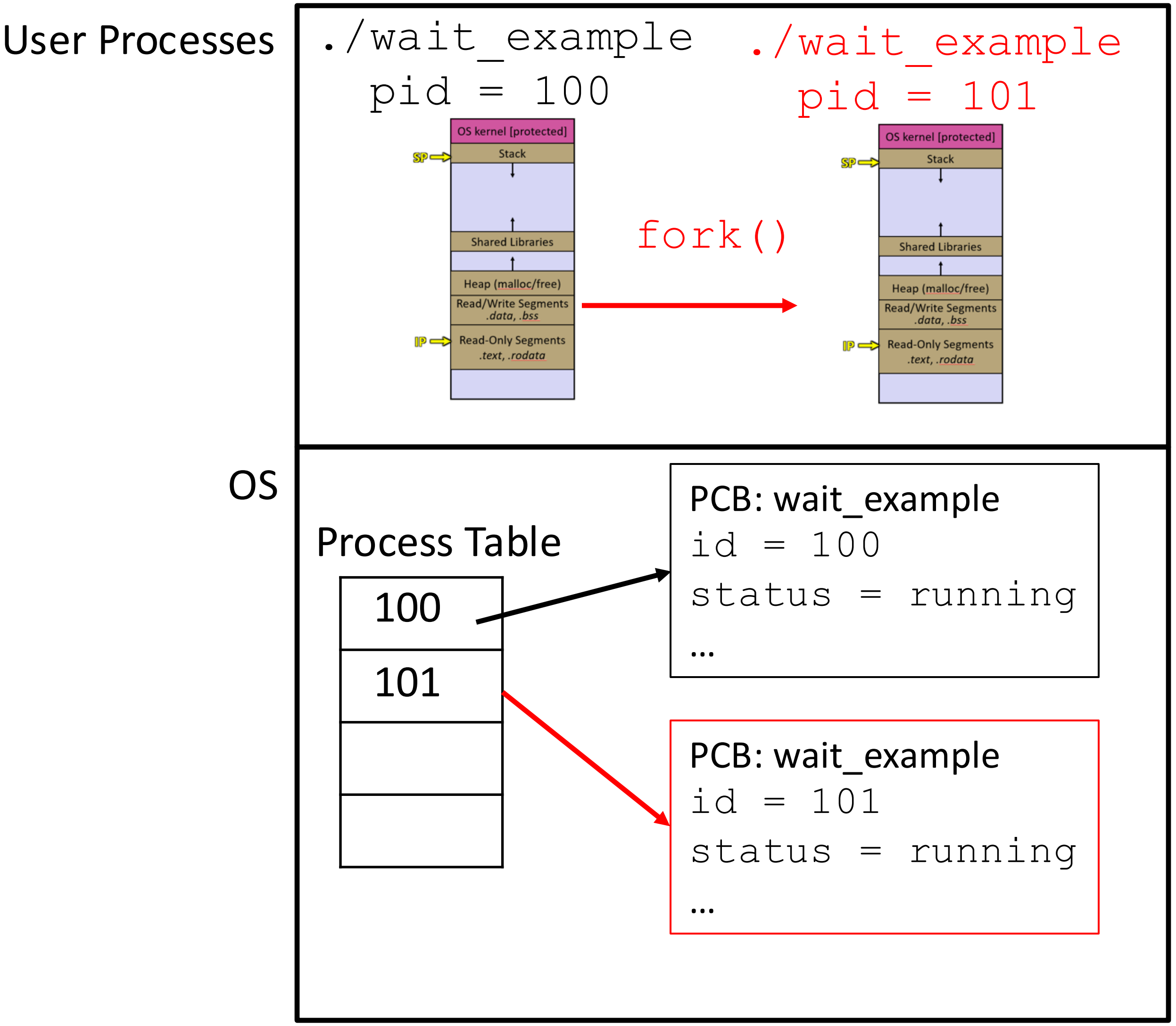


Diagram: wait_example.c

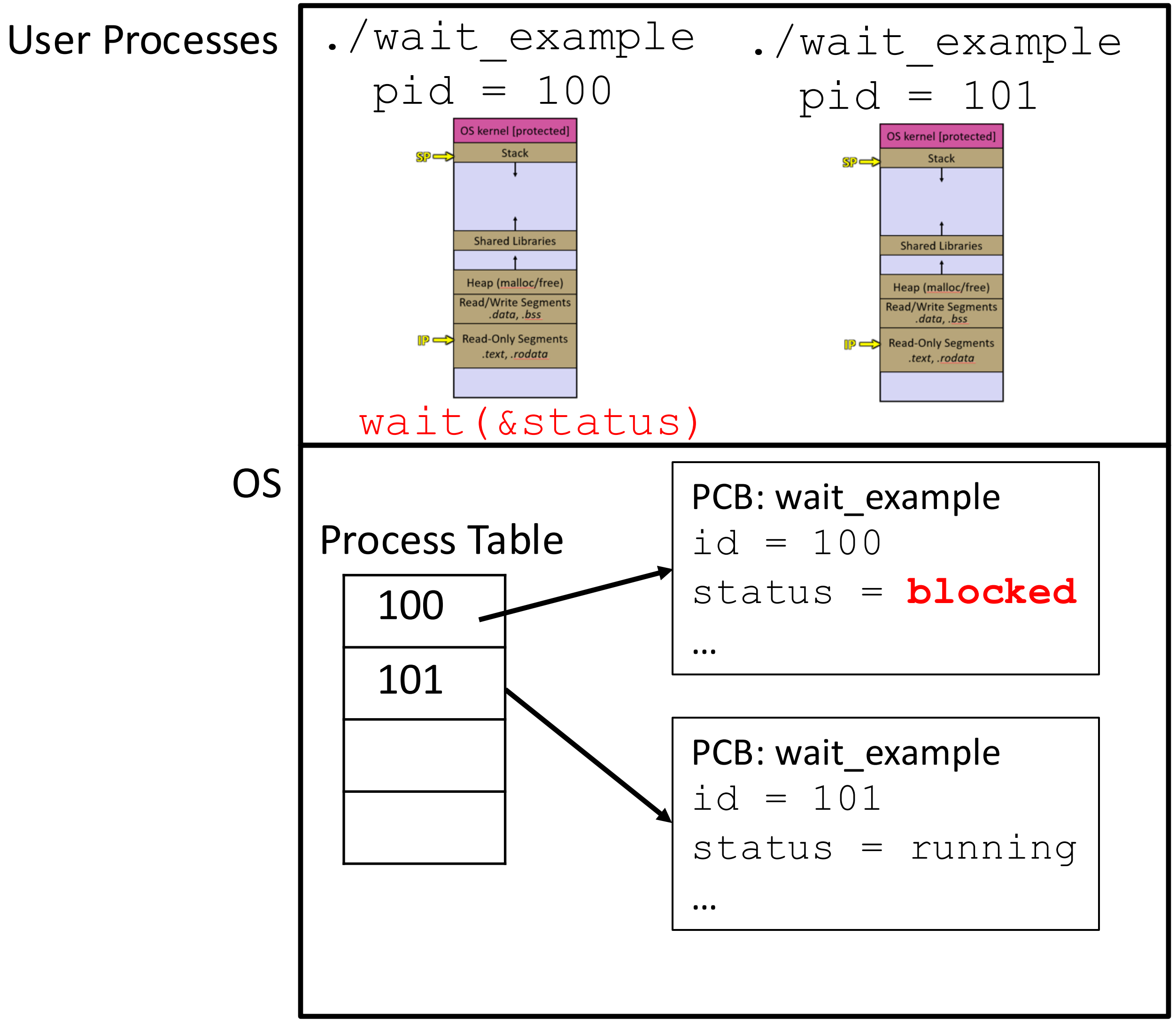


Diagram: wait_example.c

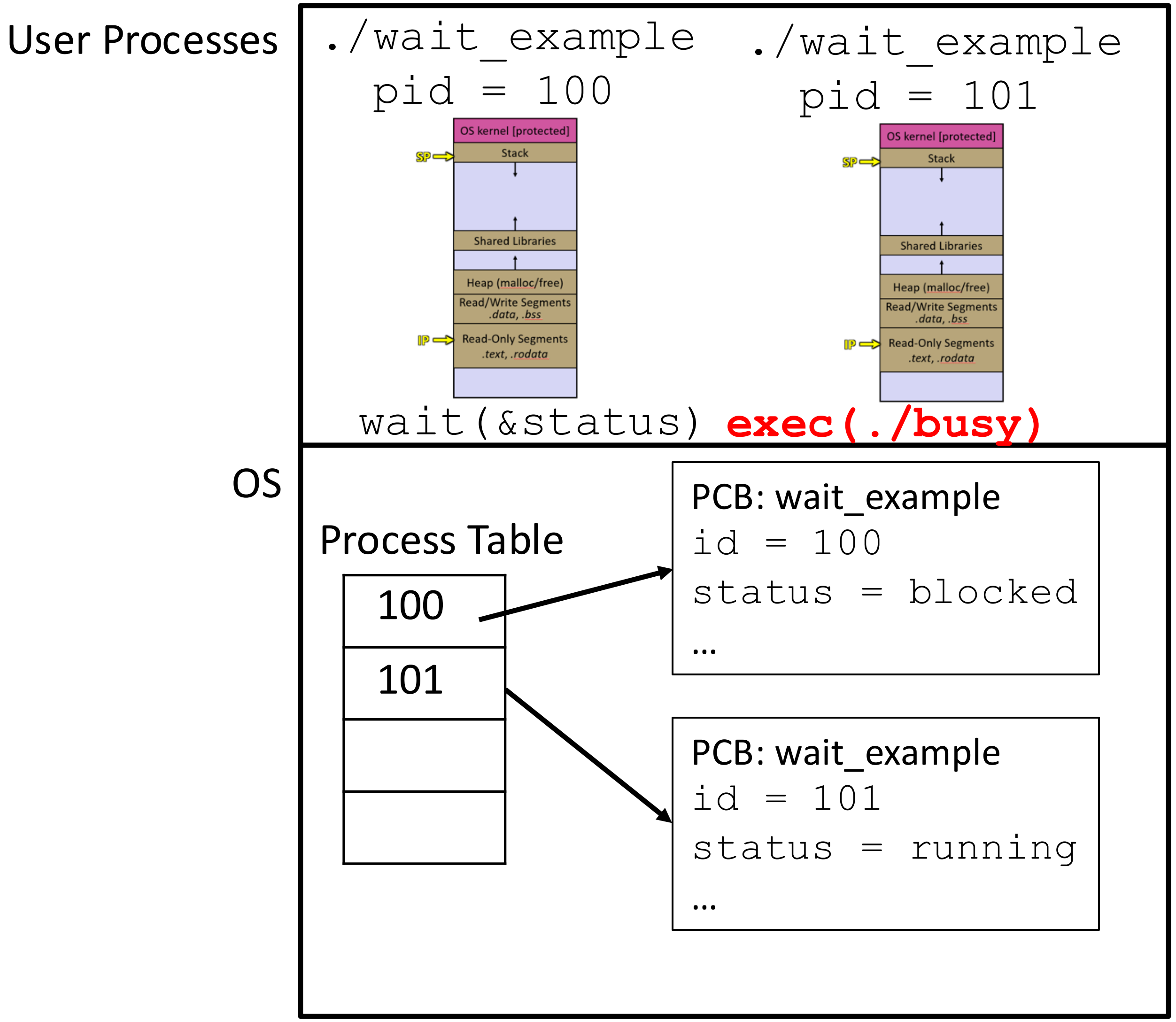


Diagram: wait_example.c

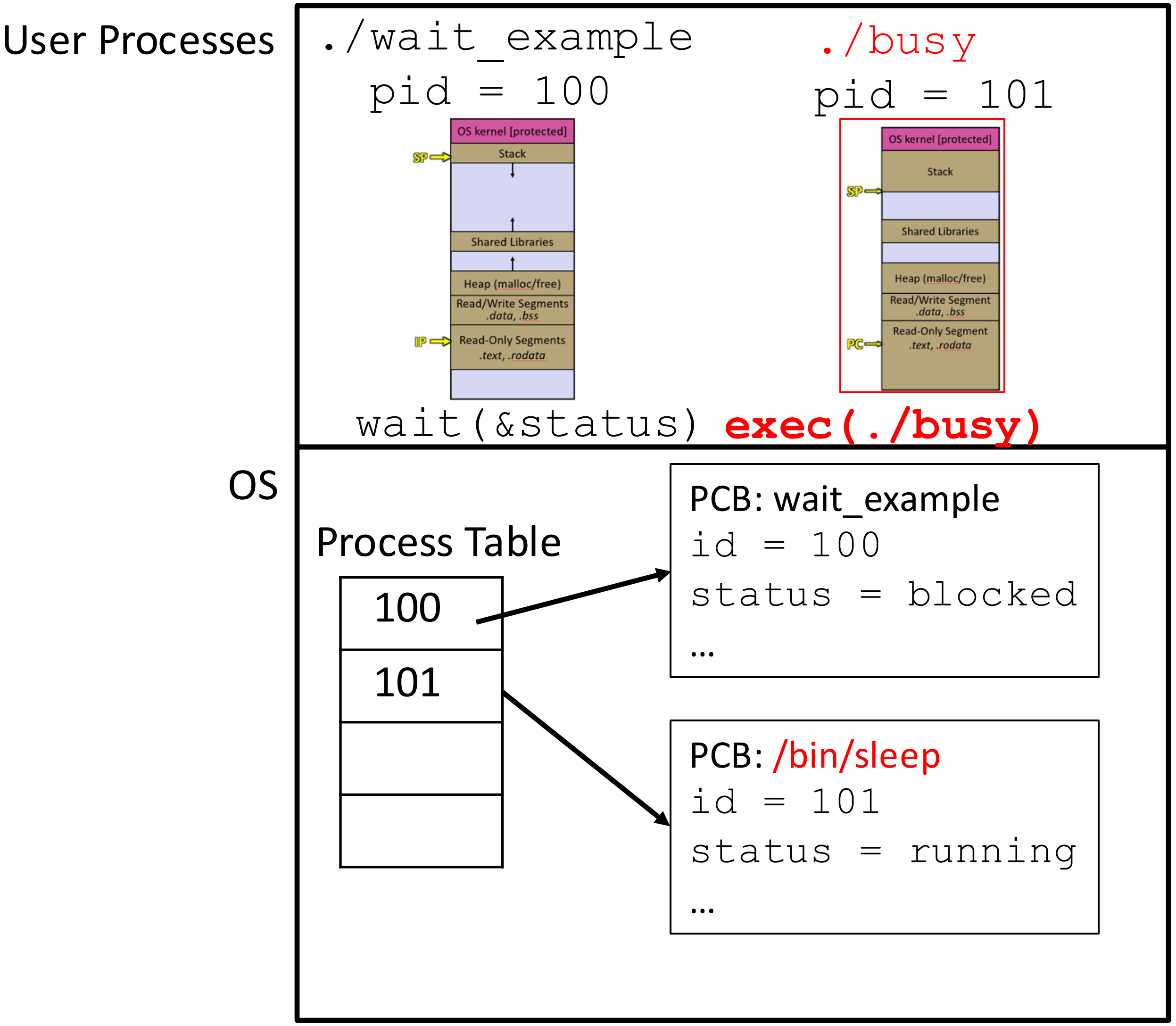


Diagram: wait_example.c

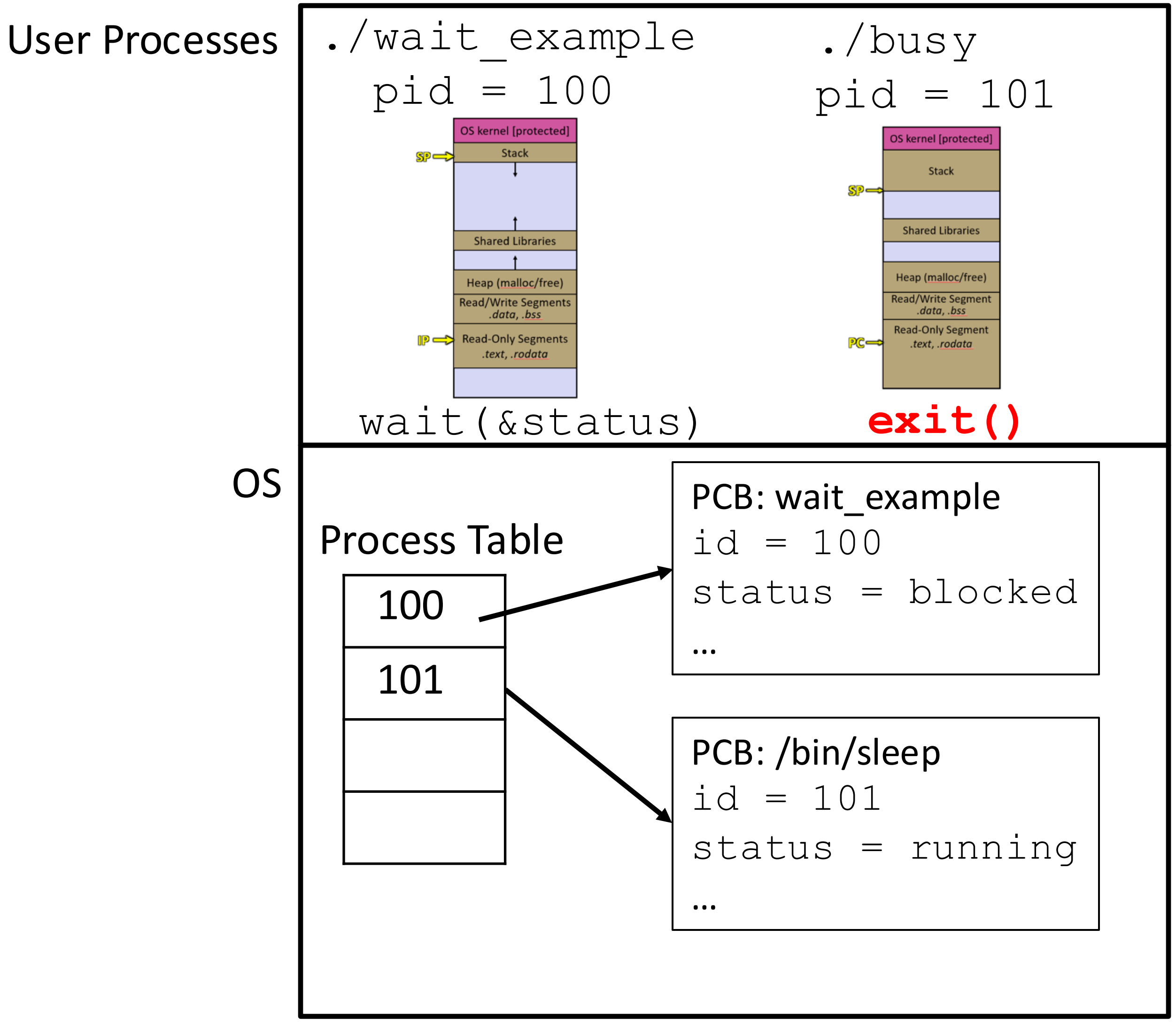
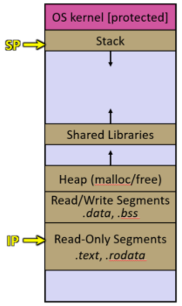


Diagram: wait_example.c

User Processes

```
./wait_example
  pid = 100
```




```
wait(&status)
```

OS

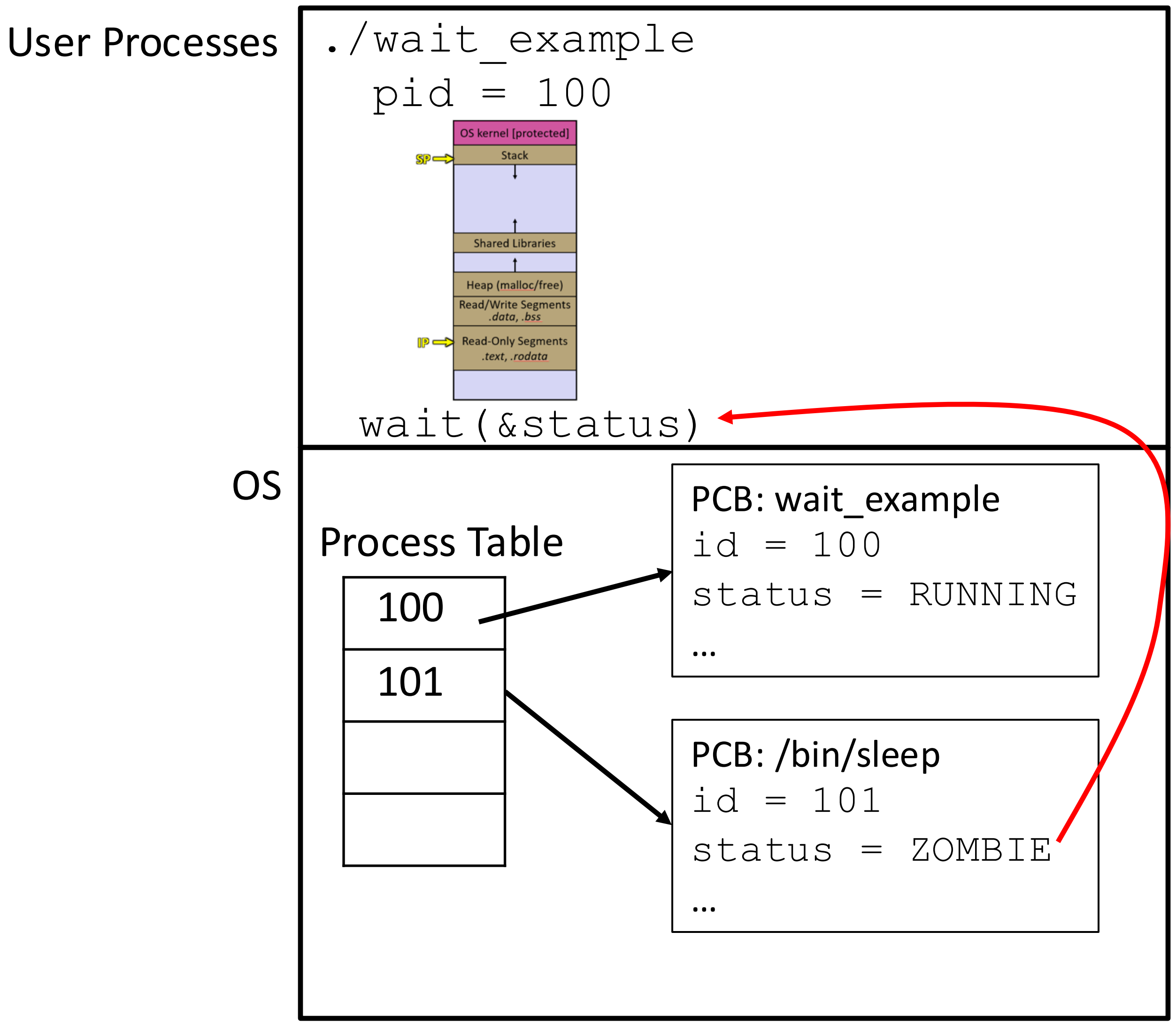
Process Table

100
101

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

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

Diagram: wait_example.c



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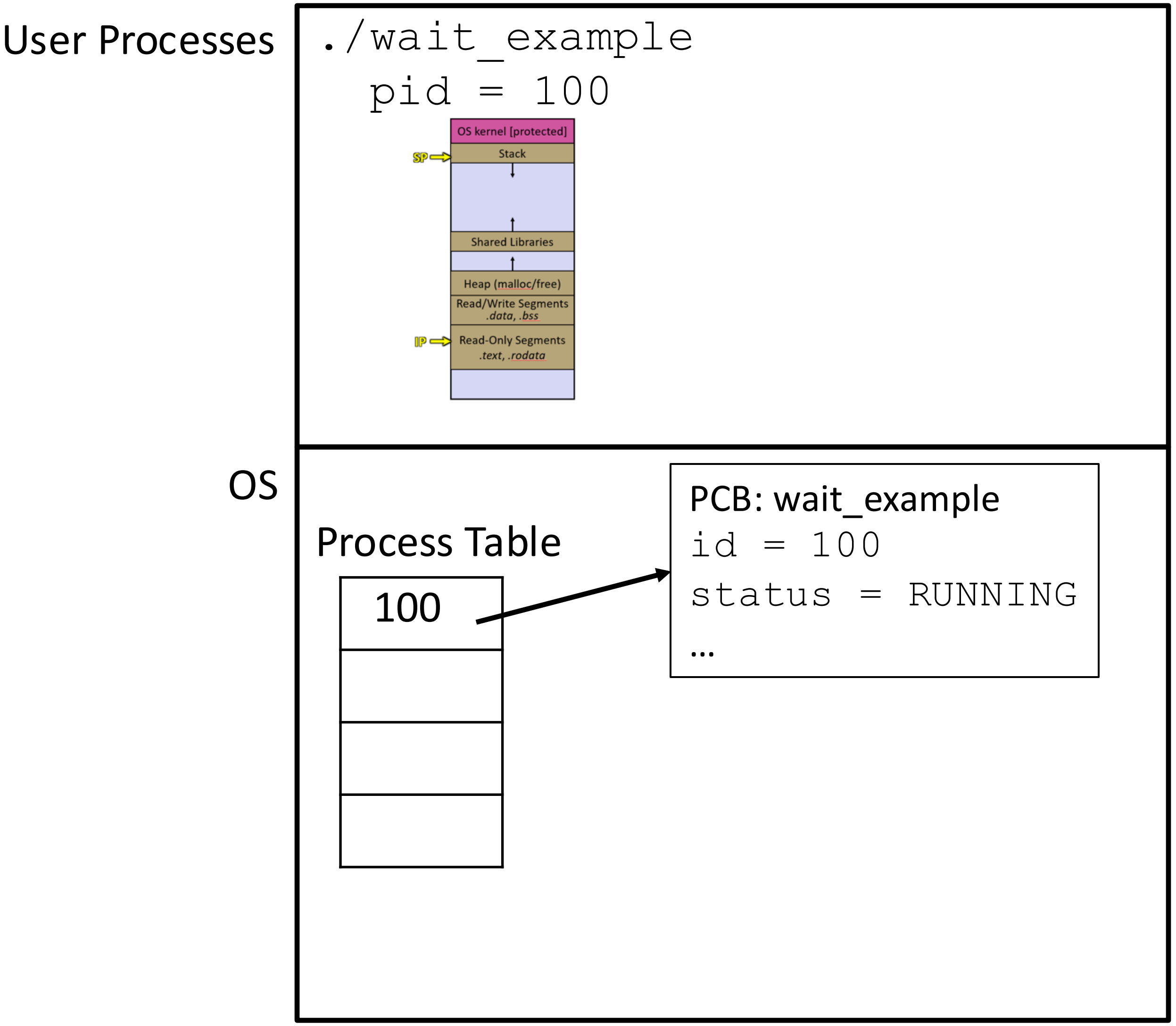


Diagram: wait_example.c

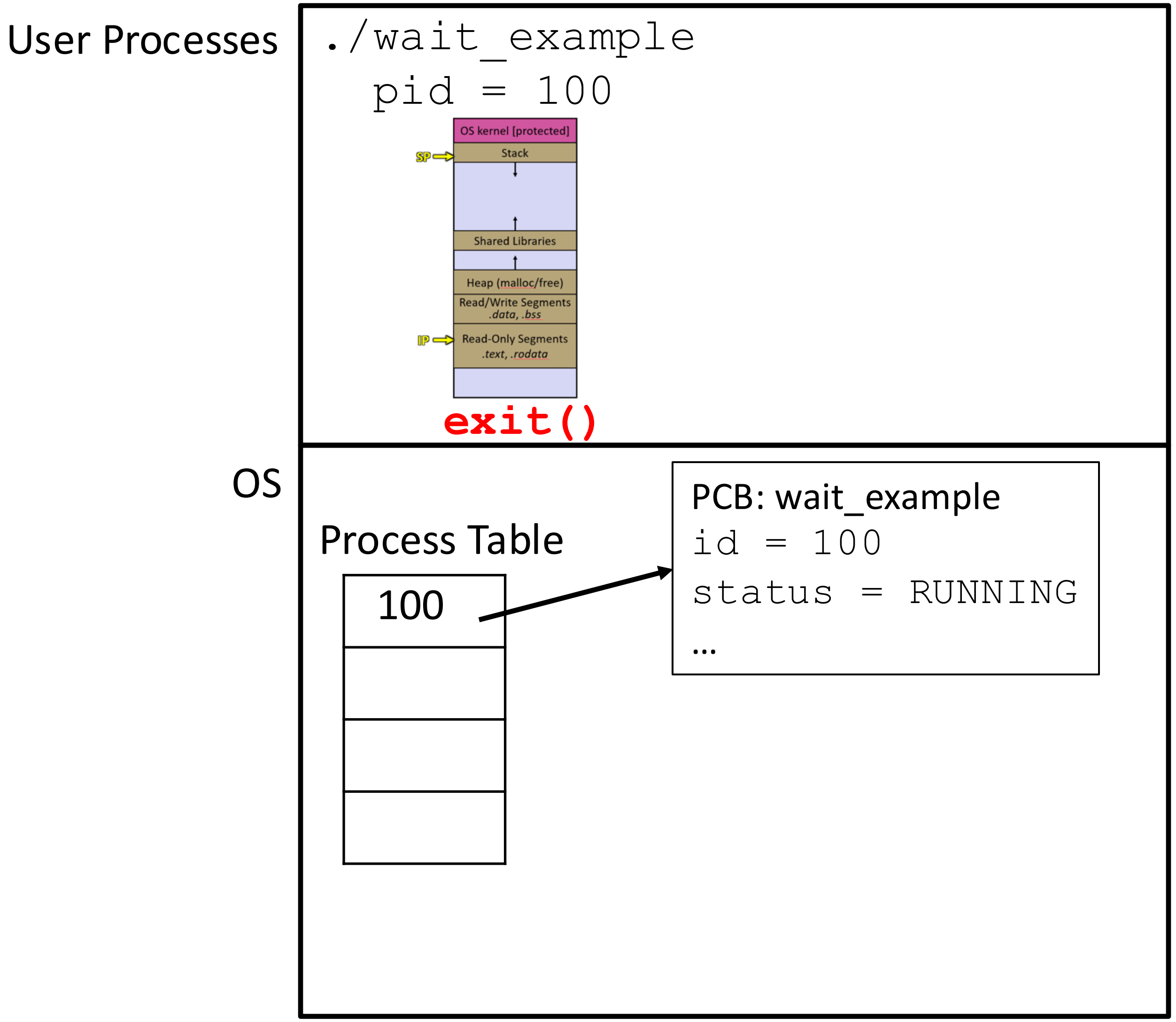
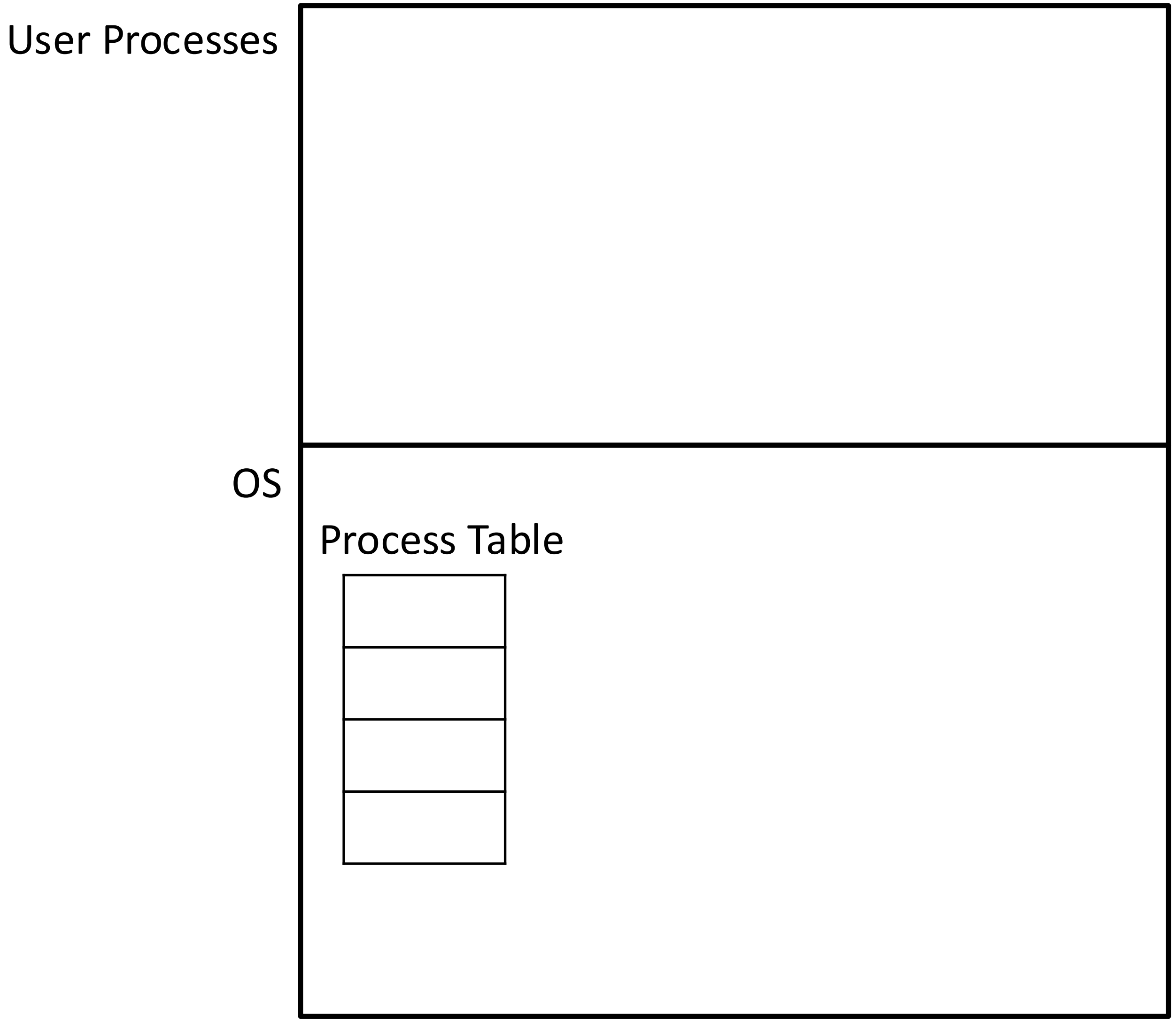


Diagram: wait_example.c



./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()`, `wait()` and `exit()`!
  - Aside: `sleep()` takes in an integer number of seconds and blocks till those seconds have passed

But wait(), it gets better.

```
pid_t waitpid(pid_t pid, int *wstatus, int options);
```

- **`pid_t pid`**
  - The pid of the child we are waiting for.
  - If pid is -1, then we wait for *any child process!*
- **`int *wstatus`**
  - Same as `wait()`
- **`int options`**
  - A set of bitwise-or'd flags to indicate behavior of waitpid!
  - Setting options to 0 makes waitpid return when a child has terminated.
- 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

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

Time

<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

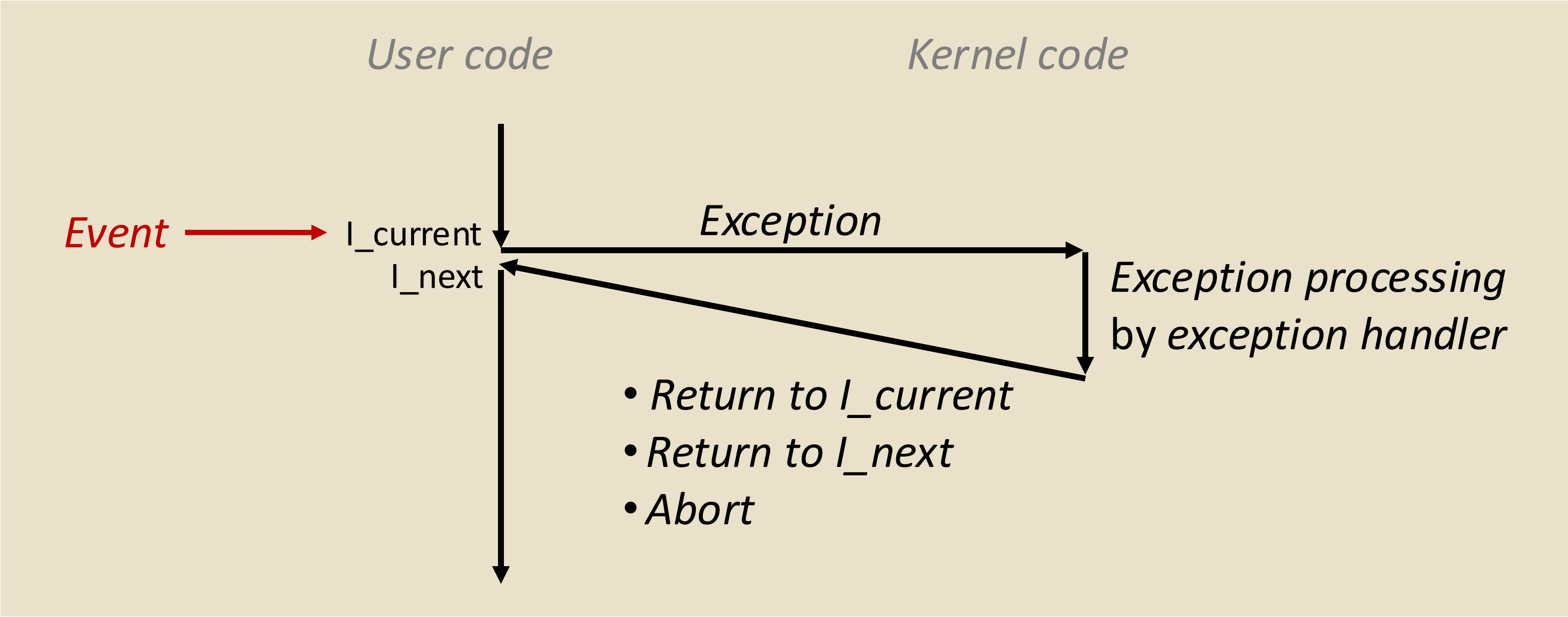
- Exists at all levels of a computer system
- Low level mechanisms
  - 1. **Hardware Interrupts**
    - Change in control flow in response to a system event (i.e., change in system state)
    - Implemented using combination of hardware and OS software

what we will be looking at today

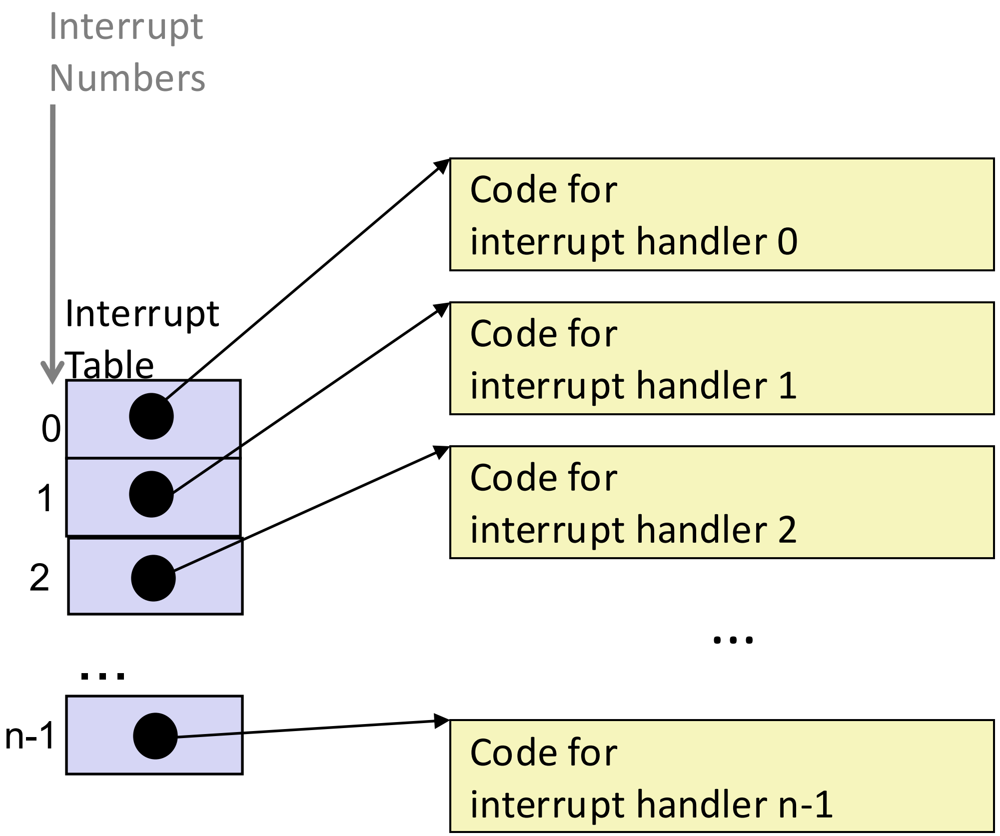
- Higher level mechanisms
  - 2. **Process context switch**
    - Implemented by OS software and hardware timer
  - 3. **Signals**
    - Implemented by OS software

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:

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

  - ***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

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 (disposition)

- Examples:
  - `SIGCHLD`
  - `SIGINT`
  - `SIGKILL`
  - `SIGALRM`
  - `SIGSEGV`

Default Disposition: ignore

Default Disposition: terminate the process

Default Disposition : terminate & core dump

`sigaction()`

- You can change how a certain signal is handled
- ```
  int sigaction(int signum, struct sigaction* act,
                                   struct sigaction* old);
  ```
- `int signum -> is the 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 & behavior for that signal through the **`old`** output parameter
- You can not change the disposition of **`SIG_KILL`** and **`SIG_STOP`**.
  ```

struct sigaction

- Has 5 different fields to specify the behaviour of how a signal should be handled. For today, we only care about **sa_handler** and **sa_flags**

```
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 set disposition to IGNORE
  - Set **`sa_handler`** to **`SIG_DFL`** for default disposition
- In this class: set **`sa_flags`** to **`SA_RESTART`**
  - This makes it so that *certain* system calls are automatically restart/continue if they are interrupted by a signal. (wanna see the list? `man 7 signal` ☺)

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 behavior 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 (think about why?)

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** disposition: ***terminate the process***

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

- HINT FOR OPTIONAL CHALLENGE: What is the default behavior of SIGALRM? Can you take advantage of the default behavior?

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

```c
int kill(pid_t pid, int sig);
```

- System call that sends a signal to a process (has a somewhat dramatic name).
- `pid_t pid`
  - Specifies the process to send the signal to
- `int sig`
  - The signal to forward!

- 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()`

```c
#define _POSIX_C_SOURCE 1
```

Non blocking wait w/ `waitpid()`

- ```
  pid_t waitpid(pid_t pid, int *wstatus, int options);
  ```
  - Our first option! WNOHANG
  - WNOHANG makes `waitpid` immediately return
    - Either: there is no update in a child's state or there was.
  - You must check the return value of `waitpid`
  - **WITH THIS OPTION WAITPID** Returns process ID of child who was waited for or `-1` on error ***or 0 if there are no updates in children processes***
  ```

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

  - In penn-shredder **`waitpid()`** IS NOT ALLOWED so don't copy this. ☺
  - Plus, using **`sleep()`** AND **`alarm()`** together can cause issues because on some systems, sleep uses alarm, go figure.

SIGCHLD handler

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

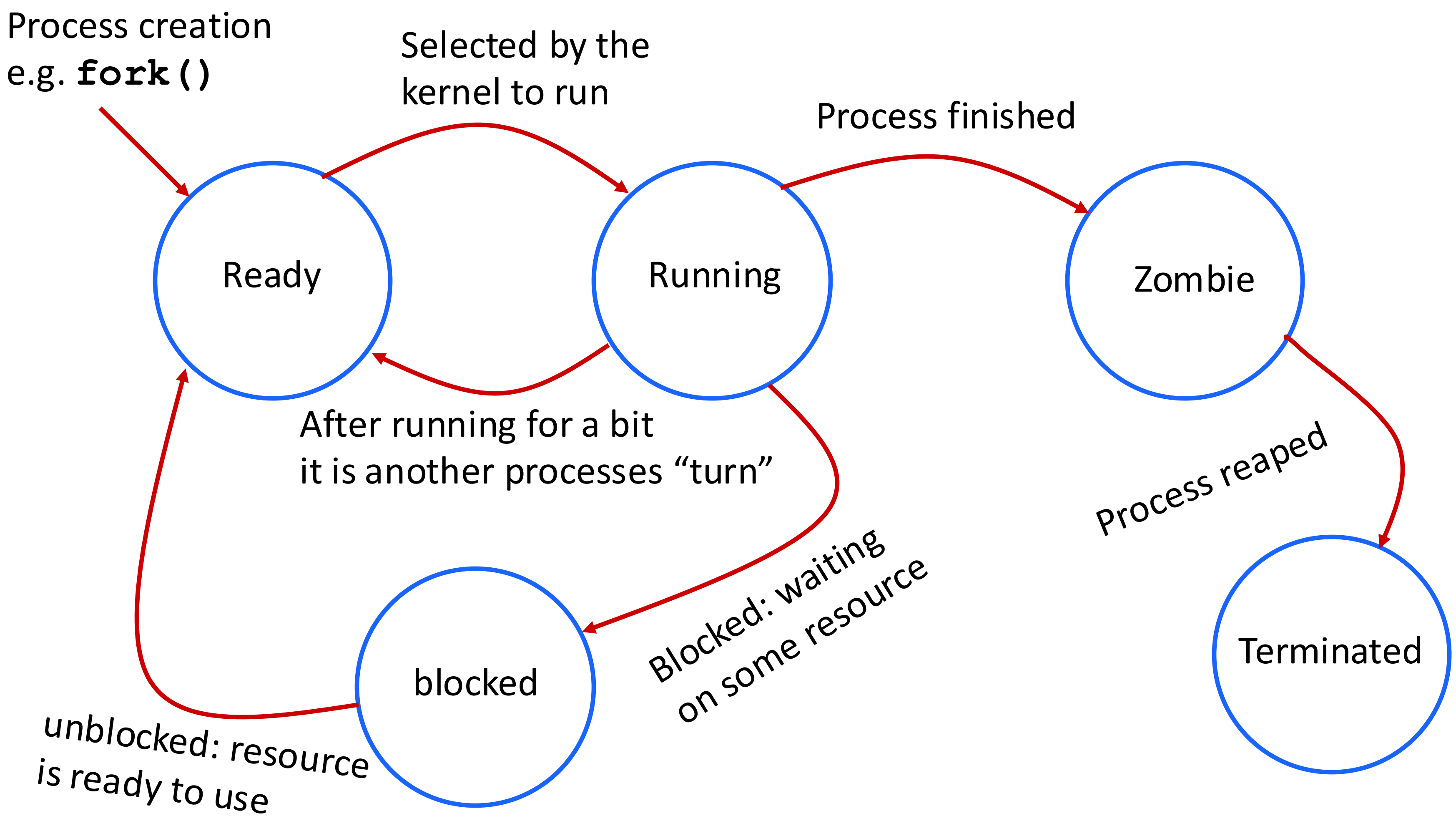
- You can write a signal handler for `SIGCHLD`, and use that to help handle children update statuses: allowing the parent process to do other things instead of calling `wait()` or `waitpid()`

- 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



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