CS110 Lecture 06: Pipes, Signals, and Concurrency

Principles of Computer Systems

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Stanford University

Computer Science Department

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PDF of this presentation

Revisiting mysystem: fork, execvp, and waitpid

- Here's the implementation, with minimal error checking (the full version is right here, and a working version is on the next slide):

```c
static int mysystem(const char *command) {
  pid_t pid = fork();
  if (pid == 0) {
    char *arguments[] = {"/bin/sh", "-c", (char *) command, NULL};
    execvp(arguments[0], arguments);
    printf("Failed to invoke /bin/sh to execute the supplied command.");
    exit(0);
  }
  int status;
  waitpid(pid, &status, 0);
  return WIFEXITED(status) ? WEXITSTATUS(status) : -WTERMSIG(status);
}
```

- Instead of calling a subroutine to perform some task and waiting for it to complete, **`mysystem`** spawns a **child process** to perform some task and waits for it to complete.
- We don't bother checking the return value of **`execvp`**, because we know that if it returns at all, it returns a -1. If that happens, we need to handle the error and make sure the child process terminates, via an exposed **`exit(0)`** call.
- Why not call **`execvp`** inside parent and forgo the child process altogether? Because **`execvp`** would consume the calling process, and that's not what we want.

Next step: Assignment 4 (stsh)

- The `mysystem` function is the first example of `fork`, `execvp`, and `waitpid` all work together to do something genuinely useful.
  - The test harness we used to exercise `mysystem` is operationally a miniature terminal.
  - We need to continue implementing a few additional mini-terminals to fully demonstrate how `fork`, `waitpid`, and `execvp` work in practice.
  - All of this is paying it forward to your fourth assignment, where you'll implement your own shell—we call it `stsh` for Stanford shell—to imitate the functionality of the shell (`csh`, `bash`, `zsh`, `tcsh`, etc.) you've been using since you started using Unix.
- We'll introduce the notion of a pipe, the `pipe` system call, and how it creates a communication channels between two processes.
- We'll introduce `dup2` system call, and how it allows a process to manipulate its file descriptor table.

Shells do much more

- **`mysystem`** is just a simple read-eval loop: it relies on a real shell (sh) to parse arguments and do all of the other things shells do
  - emacs & - create an emacs process and return control to the shell (backgrounding)
  - cat file.txt | uniq | sort - pipe the output of one command to the input of another
  - uniq < file.txt | sort > list.txt - make file.txt the input of uniq and output sort to list.txt
- Let's walk through the mechanisms of how shells do this so you can implement it for **`stsh`**

pipe(2)

- The **`pipe`** system call takes an uninitialized array of two integers and populates it with two file descriptors such that everything *written* to **`fds[1]`** can be *read* from **`fds[0]`**.
  - Here's the prototype: `int pipe(int fds[]);`
- **`pipe`** is particularly useful for allowing parent processes to communicate with spawned child processes.
  - Because they're file descriptors, there's no global name for the pipe (another process can't "connect" to the pipe)
  - The parent's table is replicated in the child, so the child automatically gets access to the pipe
- Example:cat file.txt | uniq | sort
  - Shell creates three child processes: cat, uniq and sort
  - Shell creates two pipes: one between cat and uniq, one between uniq and sort

pipe(2) example

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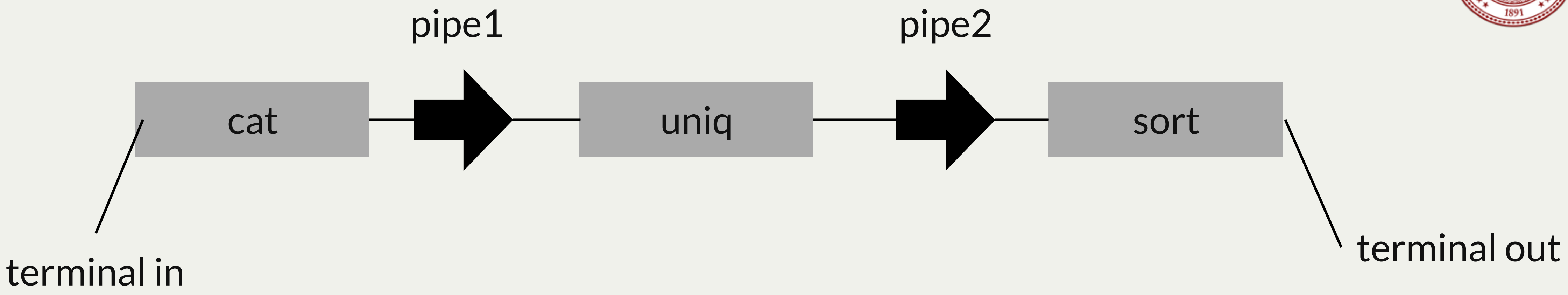



```
int pipe1[2];
int pipe2[2];
pipe(pipe1);
pipe(pipe2);
```

Process	**stdin**	**stdout**
cat	terminal	pipe1[1]
uniq	pipe1[0]	pipe2[1]
sort	pipe2[0]	terminal

Using pipe(2)

- How does **`pipe`** work?
  - To illustrate how **`pipe`** works and how arbitrary data can be passed over from one process to a second, let's consider the following program (which you can find here, or run on the next slide):

```
int main(int argc, char *argv[]) {
  int fds[2];
  pipe(fds);
  pid_t pid = fork();
  if (pid == 0) {
    close(fds[1]);
    char buffer[6];
    read(fds[0], buffer, sizeof(buffer));
    printf("Read from pipe bridging processes: %s.\n", buffer);
    close(fds[0]);
    return 0;
  }
  close(fds[0]);
  write(fds[1], "hello", 6);
  waitpid(pid, NULL, 0);
  close(fds[1]);
  return 0;
}
```

pipe(2) code example

https://cplayground.com/?p=okapi-grasshopper-bear

Pipe file descriptors and file table entries

- How do **`pipe`** and **`fork`** work together in this example?
  - **`pipe`** allocates two descriptors, one for reading and one for writing
  - The **`fork`** call creates a child process, which has a shallow copy of the parent's **`fds`** array.
    - The reference counts in each of the two file table entries of the pipe are incremented from 1 to 2 to reflect the fact that two descriptors—one in the parent, and a second in the child—reference each of them.
    - Immediately after the **`fork`** call, anything printed to **`fds[1]`** is readable from the parent's **`fds[0]`** *and* the child's **`fds[0]`**.
    - Similarly, both the parent and child are capable of publishing text to the same resource via their copies of **`fds[1]`**.

Be clean and careful in your systems code

- The parent closes **`fds[0]`** before it writes to anything to **`fds[1]`** because it will never use it; close it doesn't linger around as long as the parent does
  - Similarly, the child closes **`fds[1]`** before it reads from **`fds[0]`**
- Further benefit: clearly shows someone reading the code that parent never uses **`fds[0]`** and child never uses **`fds[1]`**
- Explicitly clean up resources: close a file descriptor as soon as its use is over
  - Ensures that if the process runs for a long time it doesn't hold references to lots of dead files
  - In this code you could say "hey, I know the process will exit and clean up", but what if you start extending and building out this code, and put this logic in a loop?

Example: forking with fd manipulation

- Using **`pipe`**, **`fork`**, **`dup2`**, **`execvp`**, **`close`**, and **`waitpid`**, we can implement the **`subprocess`** function, which relies on the following record definition and is implemented to the following prototype (full implementation of everything is right here):

```c
typedef struct {
  pid_t pid;
  int supplyfd;
} subprocess_t;
subprocess_t subprocess(const char *command);
```

- The child process created by **`subprocess`** executes the provided **`command`** (assumed to be a **`'\0'`**-terminated C string) by calling **`"/bin/sh -c <command>"`** as we did in our **`mysystem`** implementation.
  - **`subprocess`** returns a **`subprocess_t`** with the process's **`pid`** and a descriptor called **`supplyfd`**.
- The child process reads writes to **`supplyfd`** from its standard input
  - We can pass arbitrary input to the child process

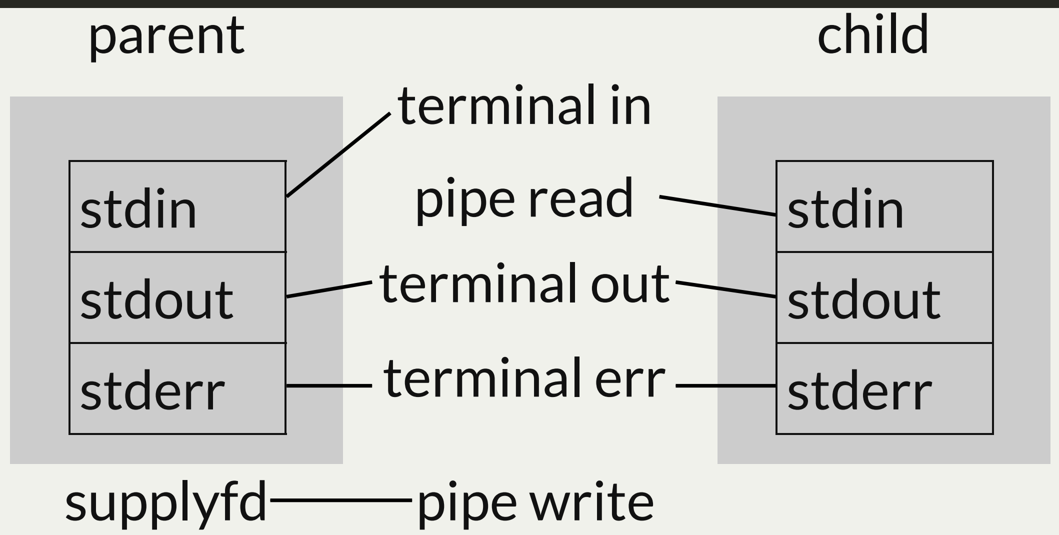
subprocess Test Harness

- This program spawns a child process that reads eight fancy words from **`stdin`**, sorts them, and writes the output to standard out:

```c
int main(int argc, char *argv[]) {
  subprocess_t sp = subprocess("/usr/bin/sort");
  const char *words[] = {
    "felicity", "umbrage", "susurration", "halcyon",
    "pulchritude", "ablution", "somnolent", "indefatigable"
  };
  for (size_t i = 0; i < sizeof(words)/sizeof(words[0]); i++) {
    dprintf(sp.supplyfd, "%s\n", words[i]);
  }
  close(sp.supplyfd);
  int status;
  pid_t pid = waitpid(sp.pid, &status, 0);
  return pid == sp.pid && WIFEXITED(status) ? WEXITSTATUS(status) : -127;
}
```

subprocess Test Harness File Descriptors

```c
int main(int argc, char *argv[]) {
  subprocess_t sp = subprocess("/usr/bin/sort");
  const char *words[] = {
    "felicity", "umbrage", "susurration", "halcyon",
    "pulchritude", "ablution", "somnolent", "indefatigable"
  };
  for (size_t i = 0; i < sizeof(words)/sizeof(words[0]); i++) {
    dprintf(sp.supplyfd, "%s\n", words[i]);
  }
  close(sp.supplyfd);
  int status;
  pid_t pid = waitpid(sp.pid, &status, 0);
  return pid == sp.pid && WIFEXITED(status) ? WEXITSTATUS(status) : -127;
}
```



Subtle requirement of semantics

- We need to produce a file descriptor that allows the caller to write data to the child's stdin
  - We know how to create such a file descriptor: a pipe
  - But how do we set up the read side of the pipe as the child's standard in?
- **`dup2(2)`**: copy a file descriptor into another file descriptor, closing the replaced file descriptor's entry if needed
  - **`dup2(int oldfd, int newfd)`**
  - Use **`dup2`** to copy the pipe read file descriptor into child's standard input

subprocess implementation

- Implementation of **`subprocess`** (error checking intentionally omitted for brevity):

```
subprocess_t subprocess(const char *command) {
  int fds[2];
  pipe(fds);
  subprocess_t process = { fork(), fds[1] };
  if (process.pid == 0) {
    close(fds[1]);
    dup2(fds[0], STDIN_FILENO);
    close(fds[0]);
    char *argv[] = {"/bin/sh", "-c", (char *) command, NULL};
    execvp(argv[0], argv);
  }
  close(fds[0]);
  return process;
}
```

  - The write end of the pipe is embedded into the **`subprocess_t`**. That way, the parent knows where to publish text so it flows to the read end of the pipe, across the parent process/child process boundary. This is bonafide interprocess communication.
  - The child process uses **`dup2`** to bind the read end of the pipe to its own standard input. Once the reassociation is complete, **`fds[0]`** can be closed.

Questions about pipes?

UNIX Signals

- A **signal** is a way to notify a process that an event occurred.
  - The kernel sends many signals (SIGSEGV, SIGBUS, SIGINT, ...)
    - Everyone who's programmed in C has unintentionally dereferenced a `NULL` pointer.
    - The kernel delivers a `SIGSEGV`, informally known as a segmentation fault (or a **SEG**mentation **V**iolation, or `SIGSEGV`, for short).
    - Unless you install a custom signal handler to manage the signal differently, a `SIGSEGV` terminates the program and generates a core dump.
  - Processes can send each other signals as well (SIGSTOP, SIGKILL)
- A **signal handler** is a function that executes when the signal arrives
  - Some signals have default handler(e.g., SIGSEGV terminates process and dumps core)
  - You can install custom handlers for most signals
- Each signal is represented internally by some number (e.g. `SIGSEGV` is 11).

Some Signals

- **`SIGFPE`**: whenever a process commits an integer-divide-by-zero (and, in some cases, a floating-point divide by zero on older architectures), the kernel hollers and issues a **`SIGFPE`** signal to the offending process. By default, the program handles the **`SIGFPE`** by printing an error message announcing the zero denominator and generating a core dump.
- **`SIGINT`**: when you type ctrl-c, the kernel sends a **`SIGINT`** to the foreground process group. The default handler terminates the process group.
- **`SIGTSTP`**: when you type ctrl-z, the kernel issues a **`SIGTSTP`** to the foreground process group. The foreground process group is halted until a **`SIGCONT`** signal.
- **`SIGPIPE`**: when a process attempts to write data to a pipe after the read end has closed, the kernel delivers a **`SIGPIPE`**. The default **`SIGPIPE`** handler prints a message identifying the pipe error and terminates the program.

A Systems Mystery

```
$ grep error file.txt > errors.txt &
[1] 4287
$
[1]+ Done                 grep error file.txt > errors.txt
```

- How does this work?
  - The shell returns control to the user after forking the child (not calling waitpid on the child)
  - But the shell still knows when the child completes
- There must be a way for the shell to learn about when things have happened to its children

SIGCHLD

- Whenever a child process **changes state**—that is, it exits, crashes, stops, or resumes from a stopped state, the kernel sends a `SIGCHLD` signal to the process's parent.
  - By default, the signal is ignored. We've ignored it until right now and gotten away with it.
- This particular signal type is instrumental to allowing forked child processes to run in the background while keeping the parent immediately aware of when something happens.
- Custom `SIGCHLD` handlers can call `waitpid`, which tells them the pids of child processes that gave changed state. If the child process terminated, either normally or abnormally, the `waitpid` also cleans up/frees the child.

Signals at Disneyland

- Here's an example of when you might want to use a **`SIGCHLD`** handler.
- The premise? Dad takes his five kids out to play. Each of the five children plays for a different length of time. When all five kids are done playing, the six of them all go home.
  - If Dad has stuff to do (rather than nap), this is a very simple analogy to many parallel data processing applications (if Dad only naps just call **`wait`**)
- The parent is dad, and subprocesses are children. (Full program is right here.)

```
static const size_t kNumChildren = 5;
static size_t numDone = 0;

int main(int argc, char *argv[]) {
  printf("Let my five children play while I take a nap.\n");
  signal(SIGCHLD, reapChild);
  for (size_t kid = 1; kid <= 5; kid++) {
    if (fork() == 0) {
      sleep(3 * kid); // sleep emulates "play" time
      printf("Child #%zu tired... returns to dad.\n", kid);
      return 0;
    }
  }
```

Signals at Disneyland

- Our first signal handler example: Disneyland
  - The program is crafted so each child process exits at three-second intervals. **`reapChild`**, handles each of the **`SIGCHLD`** signals delivered as each child process exits.
  - The **`signal`** prototype doesn't allow for state to be shared via parameters, so we have no choice but to use global variables.

```c
  // code below is a continuation of that presented on the previous slide
  while (numDone < kNumChildren) {
    printf("At least one child still playing, so dad nods off.\n");
    sleep(5);
    printf("Dad wakes up! ");
  }
  printf("All children accounted for.  Good job, dad!\n");
  return 0;
}

static void reapChild(int unused) {
  waitpid(-1, NULL, 0);
  numDone++;
}
```

Signals at Disneyland

- Here's the output of the above program.
  - Dad's wakeup times (at t = 5 sec, t = 10 sec, etc.) interleave the various finish times (3 sec, 6 sec, etc.) of the children, and the output published below reflects that.
  - Understand that the **`SIGCHLD`** handler is invoked 5 times, each in response to some child process finishing up.

```
cgregg@myth60$ ./five-children
Let my five children play while I take a nap.
At least one child still playing, so dad nods off.
Child #1 tired... returns to dad.
Dad wakes up! At least one child still playing, so dad nods off.
Child #2 tired... returns to dad.
Child #3 tired... returns to dad.
Dad wakes up! At least one child still playing, so dad nods off.
Child #4 tired... returns to dad.
Child #5 tired... returns to dad.
Dad wakes up! All children accounted for.  Good job, dad!
cgregg@myth60$
```

Signal Handling Semantics

- A signal is **not** like a function call
  - Signals aren't handled immediately (there can be delays)
  - If a signal is delivered multiple times, the handler is only called once
  - There's a bitmask in the kernel
    - Delivering a signal sets the bit
    - Handling the signal clears the bit
    - If multiple instances of the signal are delivered before handling, handler executes **once**
- Signals execute asynchronously: the kernel can push a stack frame onto the process stack that causes it to execute a handler, then return back to what it was doing
  - This is very creepy
  - This makes signals sort-of-concurrent (technically, preemptive)
  - Keep your signal handlers simple or you will regret it
- This is much like how hardware behaves with interrupts -- POSIX brings that model to software

Example of Tricky Signal Semantics

- Consider the scenario where the five kids run about Disneyland for the same amount of time. Restated, **`sleep(3 * kid)`** is now **`sleep(3)`** so all five children flashmob dad when they're all done.
  - Dad never detects all five kids are present and accounted for, and the program runs forever because dad keeps going back to sleep. Why?

```
cgregg*@myth60$ ./broken-pentuplets
Let my five children play while I take a nap.
At least one child still playing, so dad nods off.
Kid #1 done playing... runs back to dad.
Kid #2 done playing... runs back to dad.
Kid #3 done playing... runs back to dad.
Kid #4 done playing... runs back to dad.
Kid #5 done playing... runs back to dad.
Dad wakes up! At least one child still playing, so dad nods off.
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Dad wakes up! At least one child still playing, so dad nods off.
^C # I needed to hit ctrl-c to kill the program that loops forever!
cgregg@myth60$
```

Waiting without blocking

- Calling **`waitpid`** repeatedly fixes the problem, but it changes the behavior of the program.
  - Calls to **`waitpid`** can prevent dad from returning to his nap. For real programs, this means they can't continue to do work (e.g., respond to shell commands.
- We need to instruct **`waitpid`** to only reap children that have exited but to return without blocking, even if there are more children still running. We use **`WNOHANG`** for this, as with:

```
static void reapChild(int unused) {
  while (true) {
    pid_t pid = waitpid(-1, NULL, WNOHANG);
    if (pid <= 0) break; // note the < is now a <=
    numDone++;
  }
}
```

- Why not just call **`waitpid`** with **`WNOHANG`** in the main loop?
  - Mostly a style question: keeps main loop logic simpler.
  - Also means **`waitpid`** is called promptly, not determined by main loop.
  - Also, it means we learn about more than just termination (stopped, resumed, etc.).

How the Kernel Calls Userspace Handlers

- The kernel pushes a stack frame onto the process, so that the process calls the handler then returns to the kernel
- It does this when:
  - The process is running userspace code (i.e., your code)
  - The process returns from a system call
  - Can also interrupt some-long running system calls (e.g., read, which may never return)

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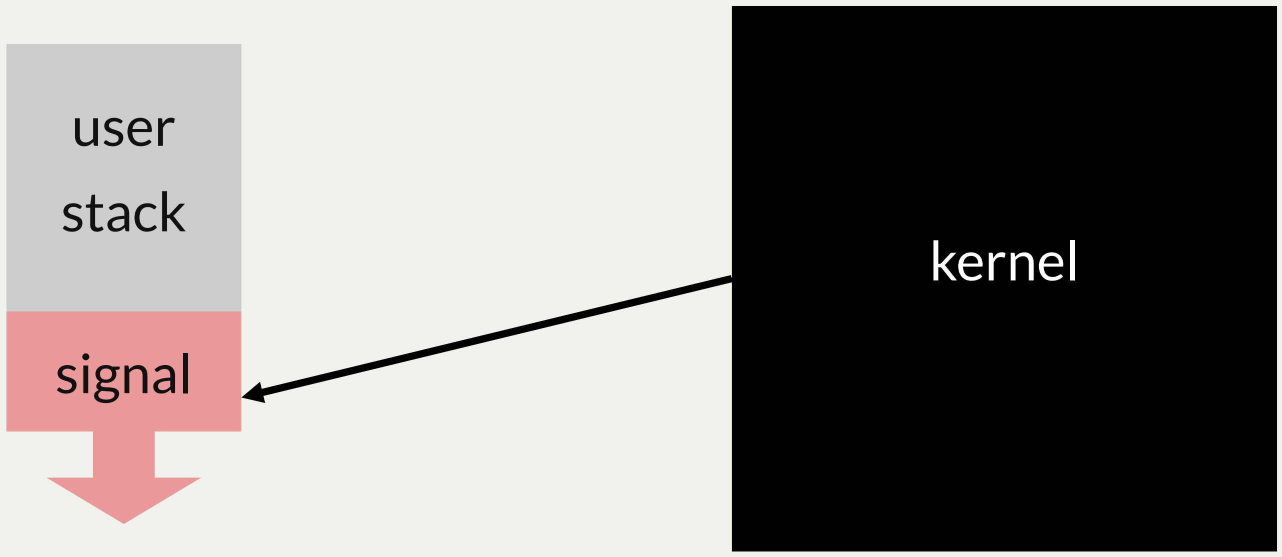

Two Stacks

- Every process actually has two stacks: a user stack and a kernel stack
- When a system call traps to the kernel, the kernel executes on its own stack
  - User program can't see or change kernel stack, otherwise it could control kernel, all security and isolation is thrown out the window
- When a system call traps to the kernel, the kernel saves the state of the user process on its own stack, so it can properly restore the user process

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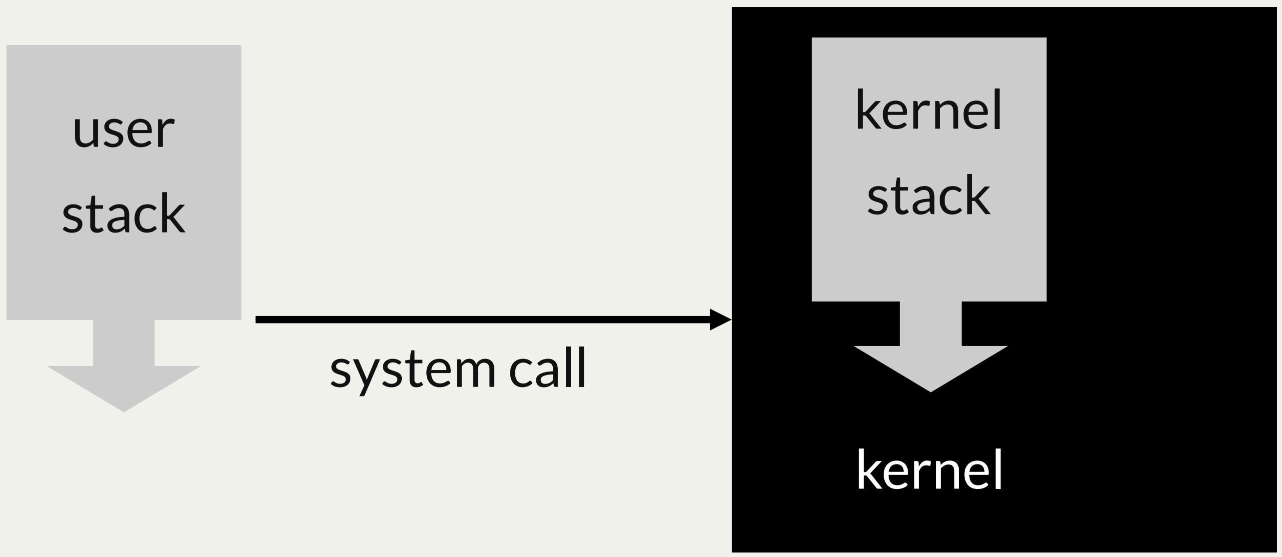

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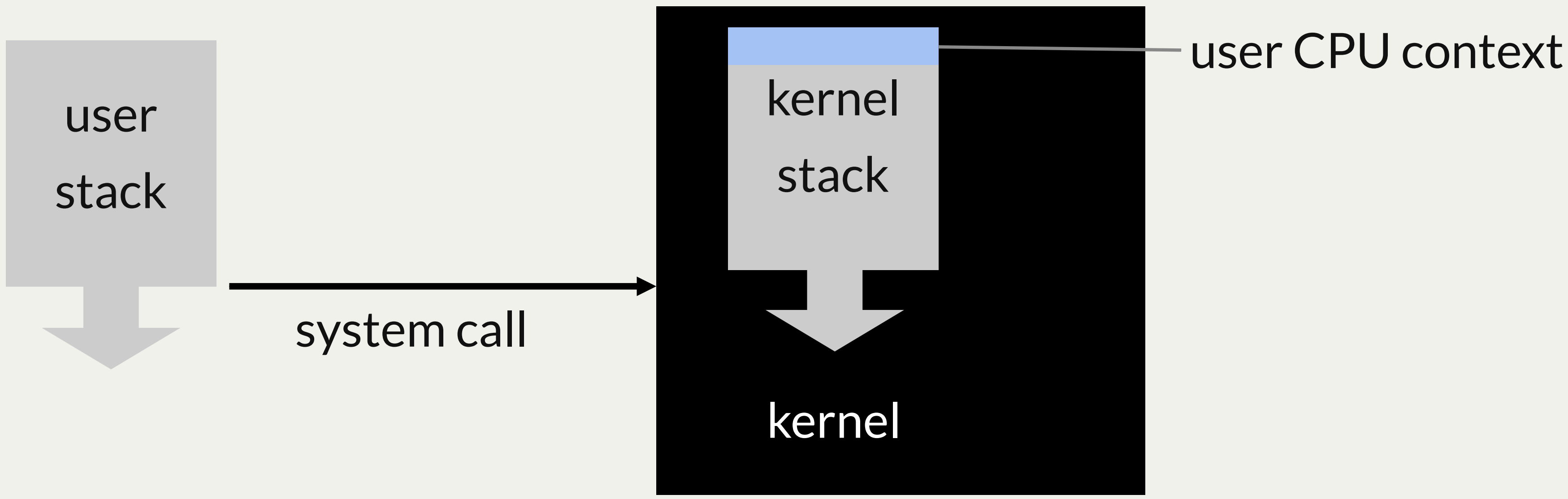
  - E.g., of the user registers, so they can be fully restored



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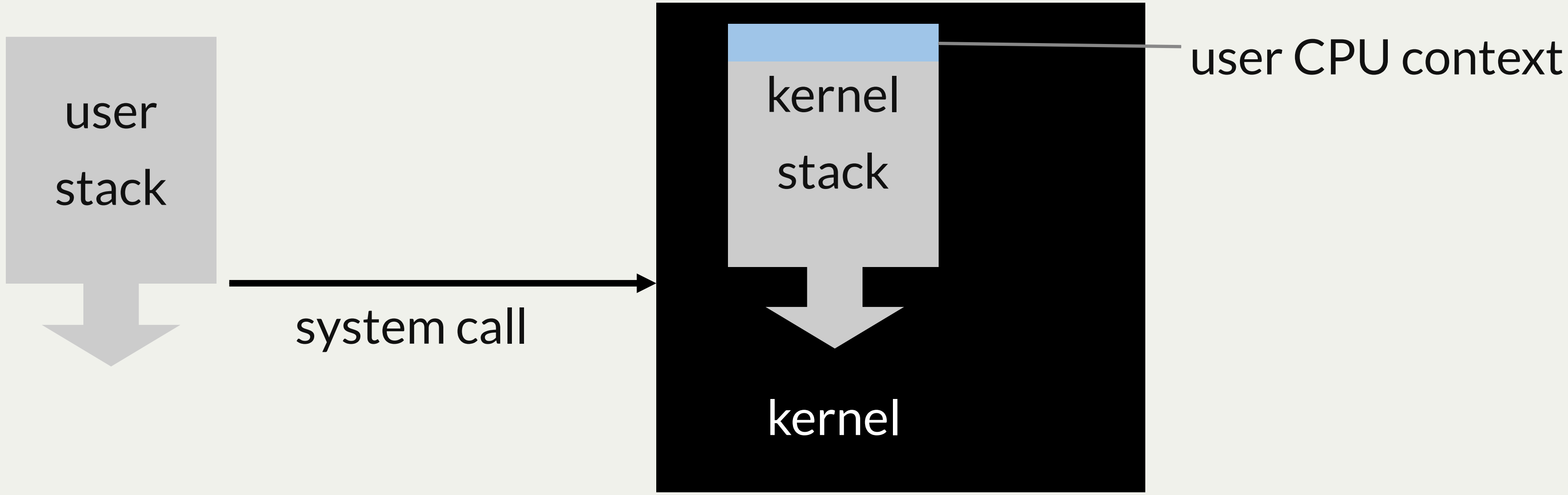
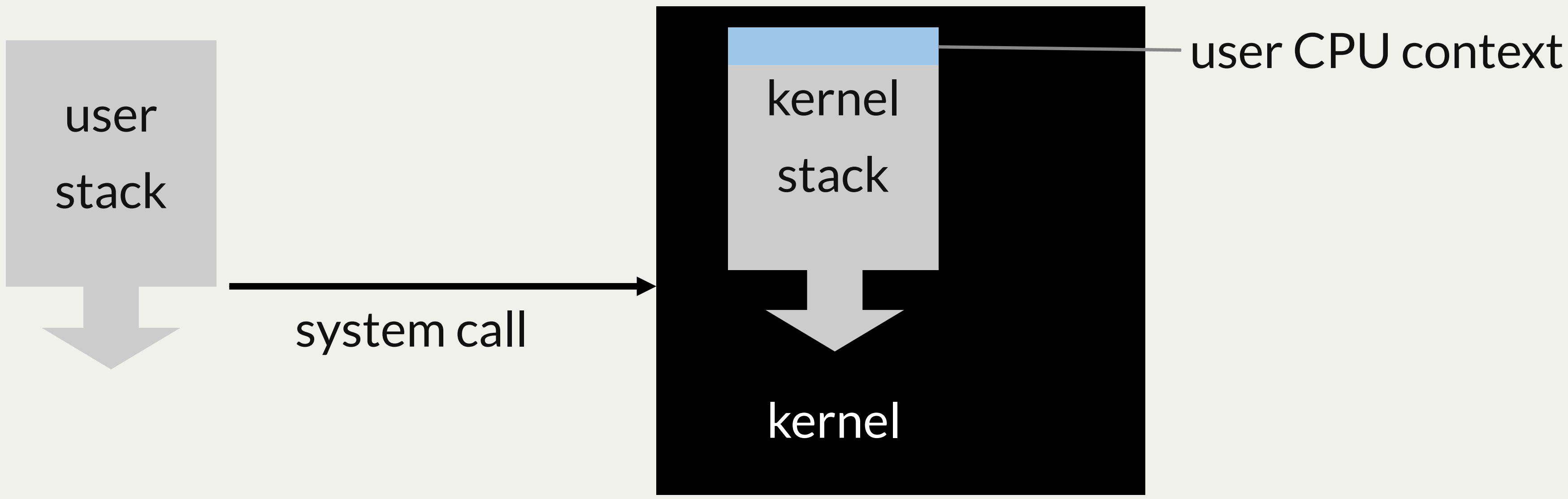
- When a system call traps to the kernel, the kernel saves the state of the user process on its own stack, so it can properly restore the user process
- With a signal, the kernel needs to complete and return to the user process, but this user process state is still needed, after the signal



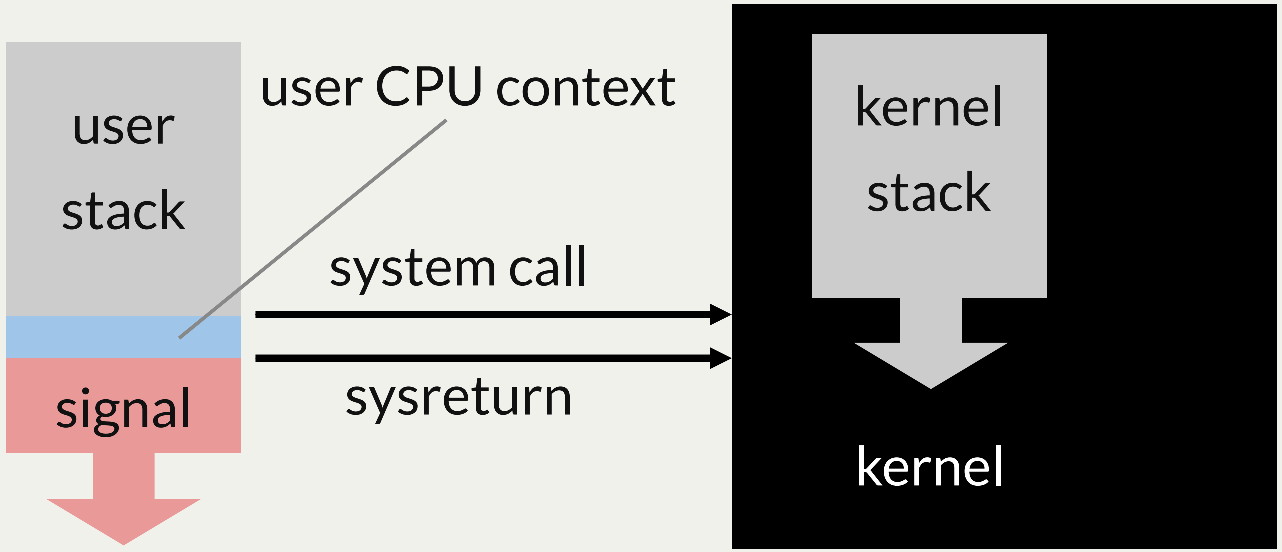
Properly Resuming a Process After a Signal

- When it pushes the stack frame for the signal, it pushes also all of the state needed to resume the user process properly



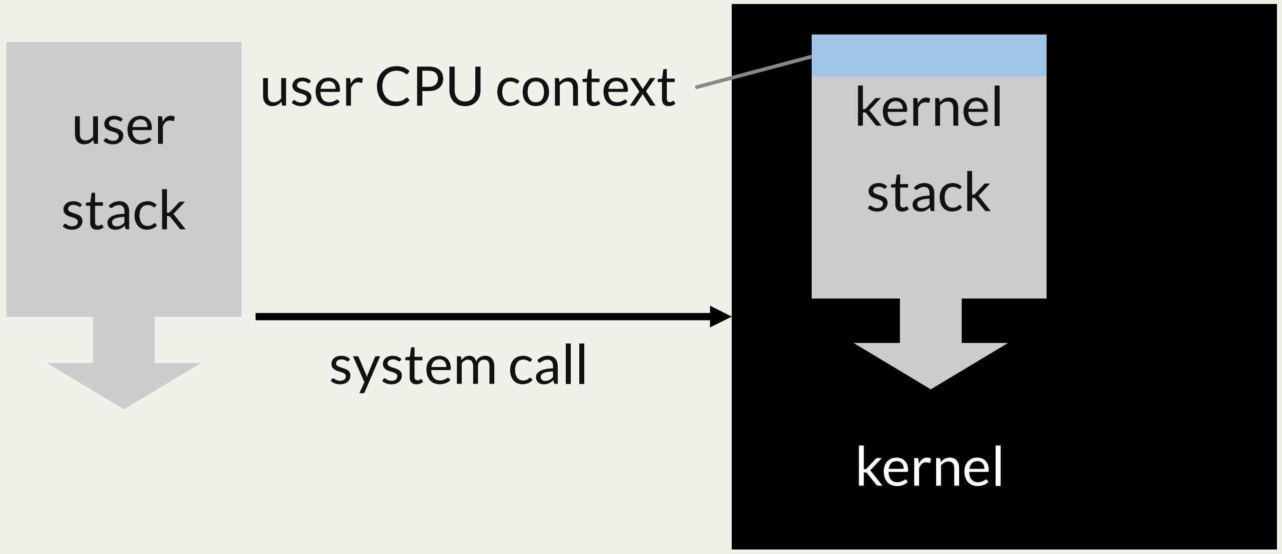
Properly Resuming a Process After a Signal

- When it pushes the stack frame for the signal, it pushes also all of the state needed to resume the user process properly
- When the signal handler returns, it calls the system call **`sysreturn`**



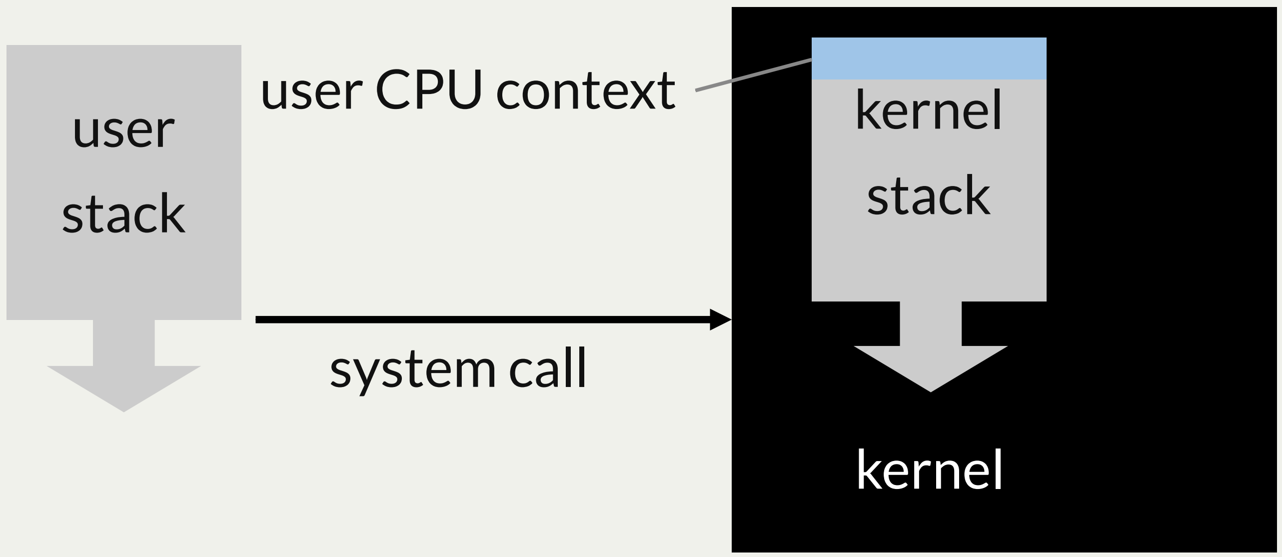
Properly Resuming a Process After a Signal

- When it pushes the stack frame for the signal, it pushes also all of the state needed to resume the user process properly
- When the signal handler returns, it calls the system call **`sysreturn`**
  - This passes the user CPU context back to the kernel, allowing it to restore the process



Concurrency

- A signal handler can be called at any point in the process execution
- You can be in the middle of executing some code and have your signal handler called



Playing With Fire

https://cplayground.com/?p=magpie-chinchilla-penguin

What Happened: Concurrency

- Recall, a signal handler can be called at any point in the process execution
- What if it executes right when we return from the system call:

```
counter_1++;
gettimeofday(&now, NULL);
counter_2++;
```

- counter_1 will be set to 0, counter_2 will be set to 0, then counter_2 will be incremented
- Because the signal handler can *preempt* your code, and run seemingly at any time, you need to be careful about any state they share
- This is a limited form of *concurrency*, but raises many of the same issues as when two pieces of code run at the same time (and share memory)

Concurrency

- One of the seven key systems principles we'll be covering this quarter
- Concurrency: performing multiple actions at the same time

- Concurrency is extremely powerful: it can make your systems faster, more responsive, and more efficient. It's fundamental to all modern software.
- But it's also very tricky to program -- we will spend a good deal of the quarter showing you all of the challenges and the mechanisms we use to tackle them (starting next lecture)
  - It boils down to shared data, and making sure code always sees that data in a consistent state, e.g., doesn't see counter_1 and counter_2 be different
  - Data analytics frameworks make it possible to massively parallelize computations by defining a data model where there is almost no shared data: the data is split into many independent chunks that are processed in parallel

This Lecture

- Pipes for interprocess communication
- Managing file descriptors
- subprocess example
- Signals and their semantics
- Using SIGCHLD to manage subprocesses
- Edge cases caused by signal semantics
- Signal execution model
- Concurrency