Basic OS Programming Abstractions (and Lab 1 Overview)

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Portions courtesy Kevin Jeffay

Recap

- We've introduced the idea of a process as a container for a running program
- This lecture: Introduce key OS APIs for a process
  - Some may be familiar from lab 0
  - Some will help with lab 2

Lab 1: A (Not So) Simple Shell

- Lab 1: Parsing for a shell
  - You will extend in lab 2
- I'm giving you some boilerplate code that does basics
- My goal: Get some experience using process APIs
  - Most of what you will need discussed in this lecture
- You will incrementally improve the shell

Tasks

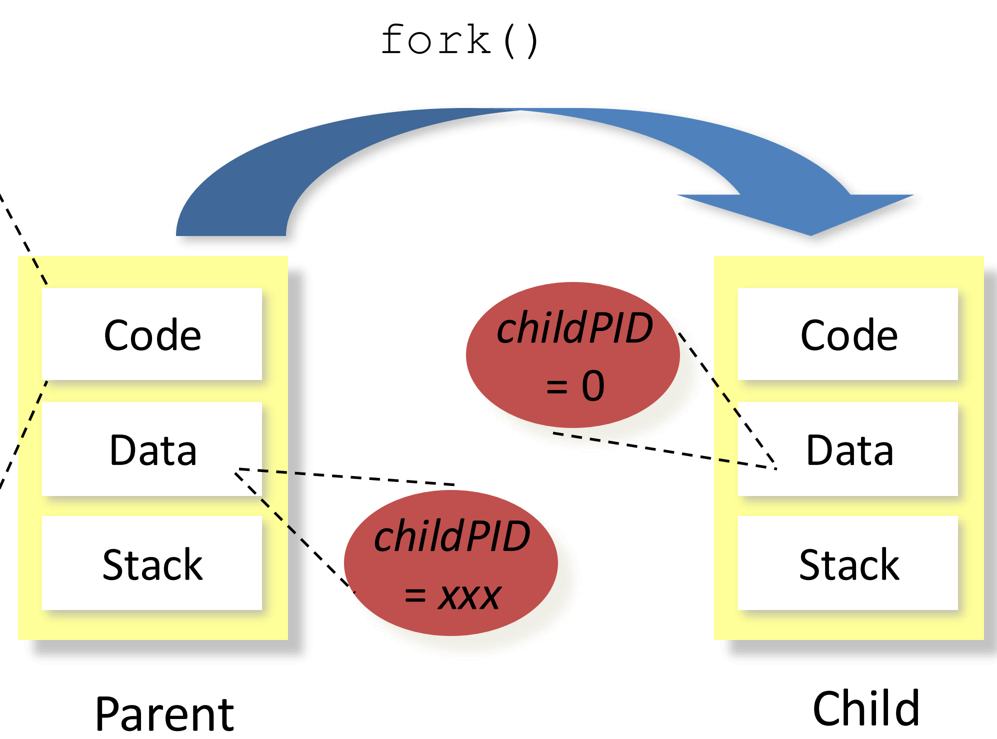
- Turn input into commands; execute those commands
  - Support **`PATH`** variables
- Be able to change directories
- Print the working directory at the command line
- Add debugging support
- Add scripting support
- Pipe indirection: <, >, and |
- **`goheels`** – draw an ASCII art Tar Heel

Significant work – start early!

Process Creation: fork/join in Linux

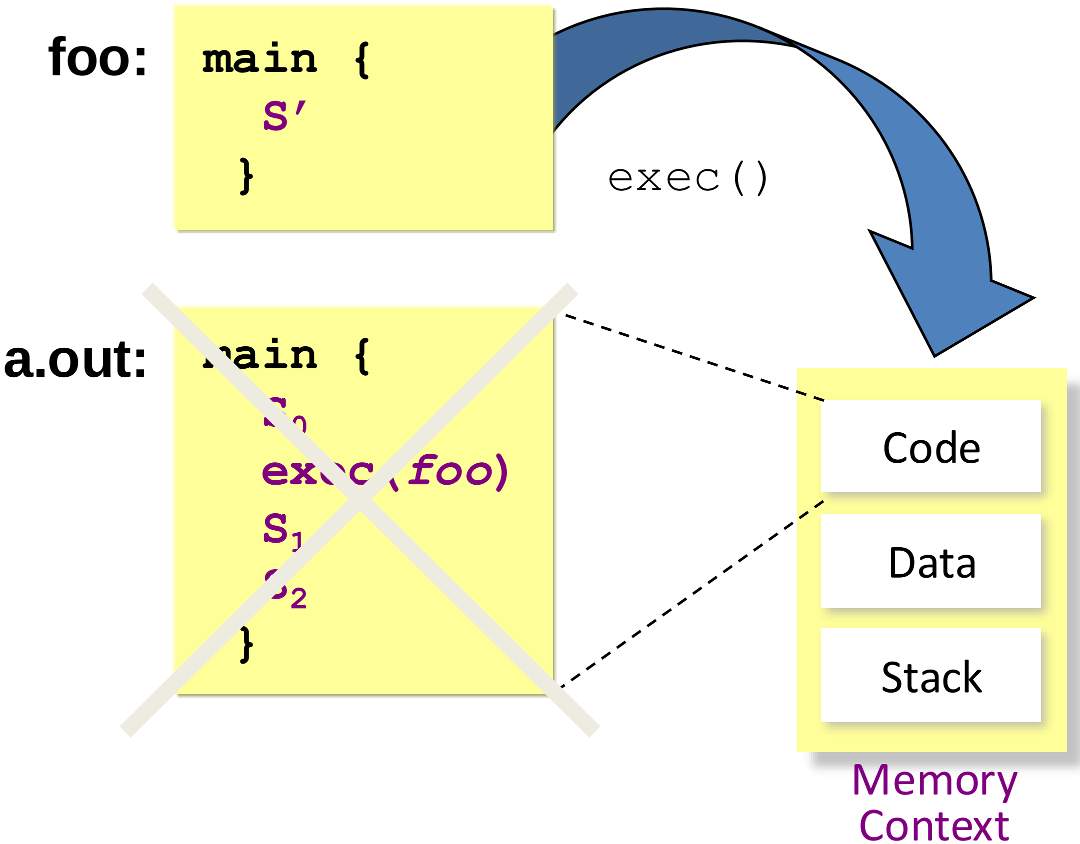
- The execution context for the child process is a *copy* of the parent’s context at the time of the call

```
main {
  int childPID;
  S1;

  childPID = fork();

  if(childPID == 0)
     <code for child process>
  else {
      <code for parent process>
      wait();
   }

  S2;
 }
```



Process Creation: exec in Linux

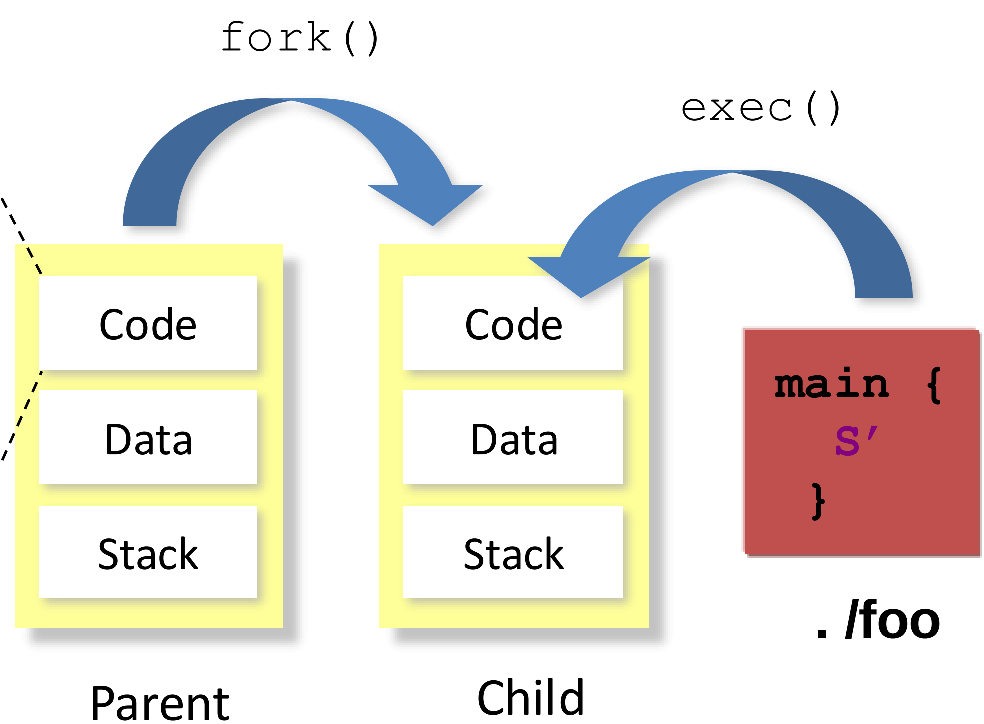
- *exec* allows a process to replace itself with another program
  - (The contents of another binary file)



Process Creation: Abstract fork in Linux

- Common case: **`fork()`** followed by an **`exec()`**

```
main {
   int childPID;
   S1;

   childPID = fork();

   if(childPID == 0)
     exec(filename)
   else {
       <code for parent process>
       wait();
    }

   S2;
 }
```



Outline

- **Files and File Handles**
- Inheritance
- Pipes & Sockets
- Signals
- Synthesis Example: The Shell

2 Ways to Refer to a File

- Path, or hierarchical name, of the file
  - Absolute: "**`/home/porter/foo.txt`**"
    - Starts at system root
  - Relative: "**`foo.txt`**", "**`../porter/foo.txt`**"
    - Assumes file is in the program's **current working directory (CWD)**
- A **handle** to an open file
  - A **handle** keeps track of process access to the file:
    - an offset for read/write operations
    - file status, and flags
    - file reference count
    - access permission

Path-based calls

- Functions that operate on the directory tree
  - **rename**, **unlink** (delete), **chmod** (change permissions), etc.
- Open – creates a handle to a file
  - `int open (char *path, int flags, mode_t mode);`
    - Flags include `O_RDONLY, O_RDWR, O_WRONLY`
    - Permissions are generally checked only at open
  - **opendir()** – variant for a directory

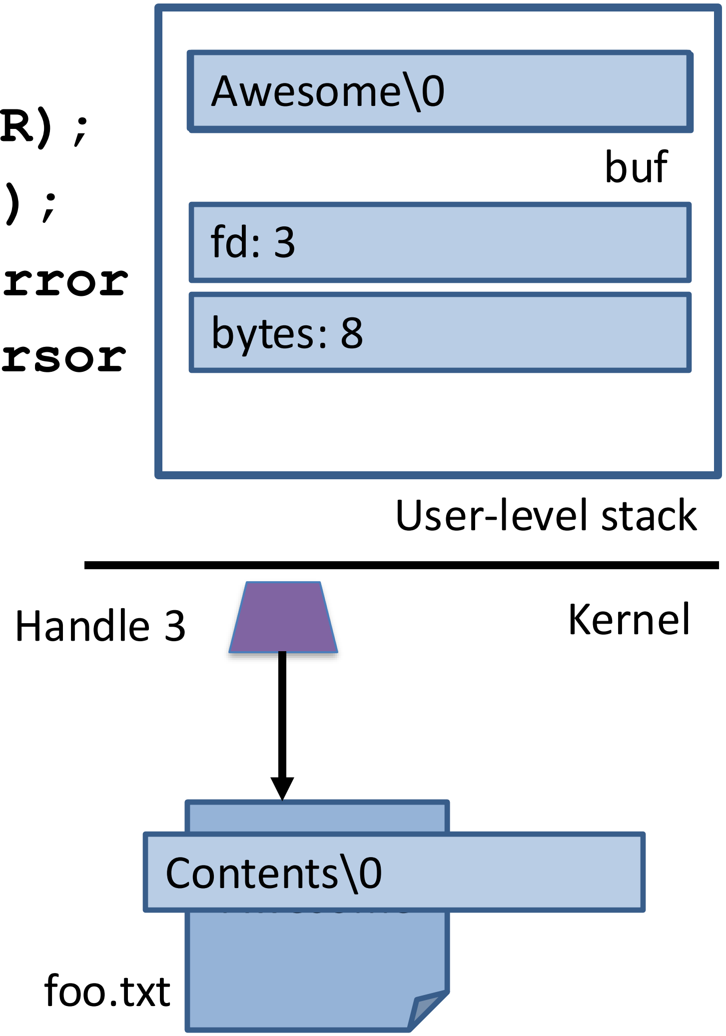
Handle-based calls

- `ssize_t read(int fd, void *buf, size_t count)`
  - Fd is the handle
  - Buf is a user-provided buffer to receive count bytes of the file
  - Returns how many bytes read
- `ssize_t write(int fd, void *buf, size_t count)`
  - Same idea, other direction
- `int close(int fd)`
  - Close an open file
- `int lseek(int fd, size_t offset, int flags)`
  - Change the cursor position

Example

PC

```
char buf[9];
int fd = open ("foo.txt", O_RDWR);
ssize_t bytes = read(fd, buf, 8);
if (bytes != 8) // handle the error
lseek(fd,0,SEEK_SET); // set cursor
memcpy(buf, "Awesome", 7);
buf[7] = '\0';
bytes = write(fd, buf, 8);
if (bytes != 8) // error
close(fd);
```



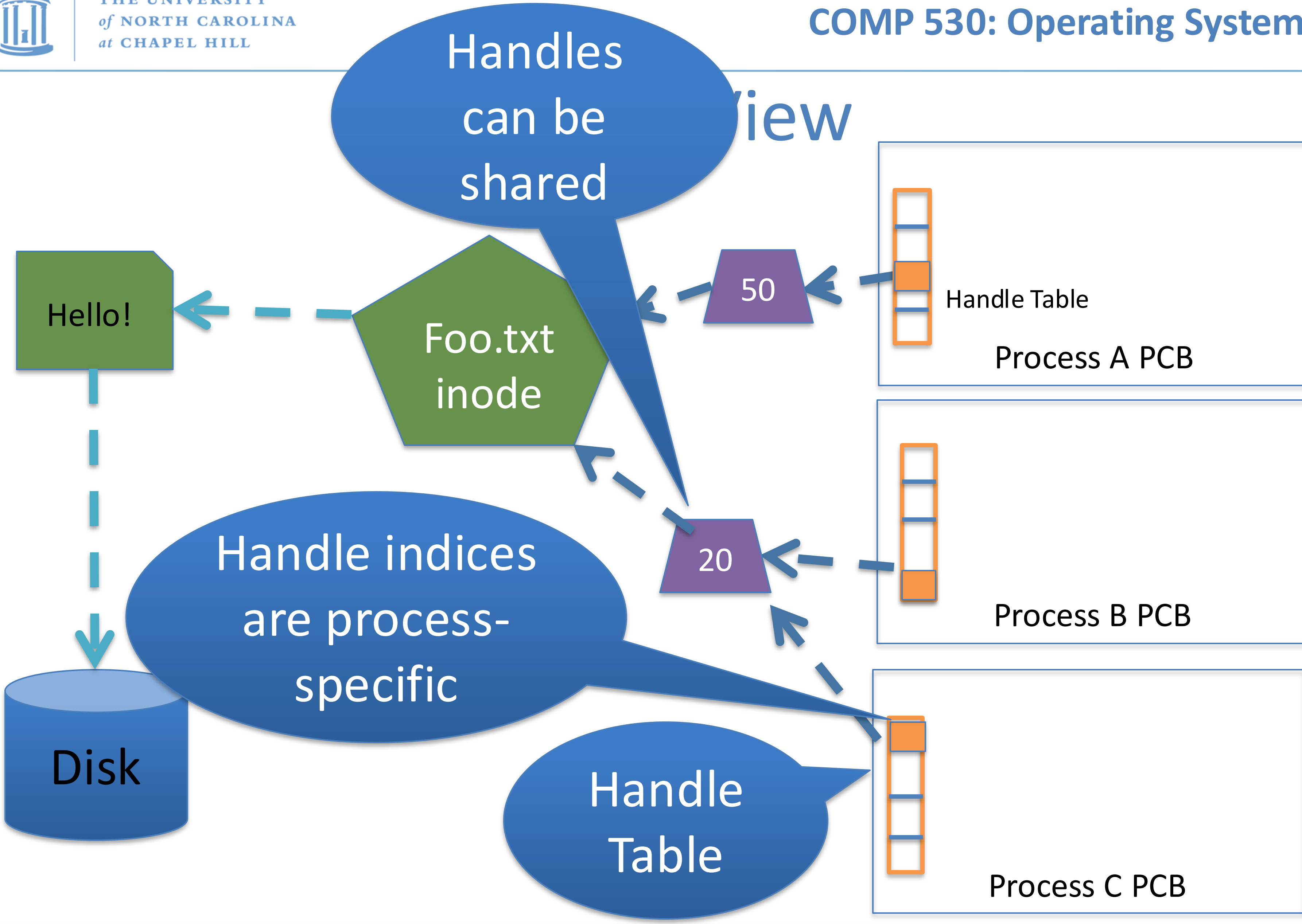
Why handles?

- Handles in Unix/Linux serve three purposes:

1. Track the offset of last read/write
   - Alternative: Application explicitly passes offset
2. Cache the access check from **`open()`**
3. Hold a reference to a file
   - Unix idiom: Once a file is open, you can access the contents as long as there is an open handle --- even if the file is deleted from the directory

But what is a handle?

- A reference to an open file or other OS object
  - For files, this includes a cursor into the file
- In the application, a handle is just an integer
  - This is an offset into an OS-managed table


Handles can be shared
iew
Hello!
Foo.txt inode
50
Handle Table
Process A PCB
20
Process B PCB
Handle indices are process-specific
Disk
Handle Table
Process C PCB

Handle Recap

- Every process has a table of pointers to kernel handle objects
  - E.g., a file handle includes the offset into the file and a pointer to the kernel-internal file representation (inode)
- Applications can't directly read these pointers
  - Kernel memory is protected
  - Instead, make system calls with the indices into this table
  - Index is commonly called a handle

Rearranging the table

- The OS picks which index to use for a new handle
- An application explicitly copy an entry to a specific index with **`dup2(old, new)`**
  - Be careful if new is already in use…

Other useful handle APIs

- **`mmap()`** – can map part or all of a file into memory
- **`seek()`** – adjust the cursor position of a file
  - Like rewinding a cassette tape

https://www.pexels.com/photo/yellow-pencil-on-white-cassette-tape-8040775/

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Inheritance

- By default, a child process gets a reference to every handle the parent has open
  - Very convenient
  - Also a security issue: may accidentally pass something the program shouldn't
- Between **`fork()`** and **`exec()`**, the parent has a chance to clean up handles it doesn't want to pass
  - See also **`FD_CLOEXEC`** flag, used as follows with **`fcntl()`**:
    `fcntl(fd, F_SETFD, fcntl(fd, F_GETFD) | FD_CLOEXEC);`

Standard in, out, error

- Handles 0, 1, and 2 are special by convention
  - 0: standard input (**`STDIN_FILENO`** in **`<stdio.h>`**)
  - 1: standard output (**`STDOUT_FILENO`**)
  - 2: standard error output (**`STDERR_FILENO`**)
- Command-line programs use this convention
  - Parent program (shell) is responsible to use **`open`**/**`close`**/**`dup2`** to set these handles appropriately between **`fork()`** and **`exec()`**

Example

```
int pid = fork();
if (pid == 0) {
	// Opens "in.txt" for reading.
	int fd = open (“in.txt”, O_RDONLY);
	// Redirects standard input to come from
	"in.txt" by duplicating the file descriptor.
	dup2(fd, 0);
	// Executes the grep command, which will
	search for the string "quack" in the file
	"in.txt".
	exec(“grep”, “quack”);
}
```

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Pipes

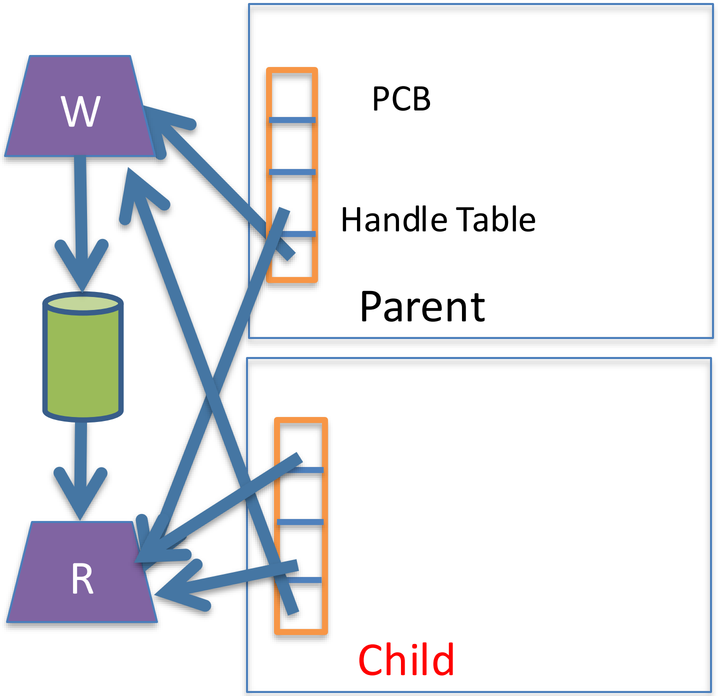
- FIFO stream of bytes between two processes
- Read and write like a file handle
  - But not anywhere in the hierarchical file system
  - And not persistent
  - And no cursor or seek()-ing
  - Actually, 2 handles: a read handle and a write handle
- Primarily used for parent/child communication
  - Parent creates a pipe, child inherits it

Example

PC

PC

```
int pipe_fd[2];
int rv = pipe(pipe_fd);
int pid = fork();
if (pid == 0) {
        close(pipe_fd[1]);
        dup2(pipe_fd[0], 0);
        close(pipe_fd[0]);
        exec("grep", "quack");
} else {
        close (pipe_fd[0]);
        ...
```



execlp("grep", "grep", "quack", NULL);

Goal: Create a pipe; parent writes, child reads

Sockets

- Similar to pipes, except for network connections
- Setup and connection management is a bit trickier
  - A topic for another day (or class)

Select

- What if I want to block until one of several handles has data ready to read?
- Read will block on one handle, but perhaps miss data on a second…
- Select will block a process until a handle has data available
  - Useful for applications that use pipes, sockets, etc.

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Signals

- Similar concept to an application-level interrupt
  - Unix-specific (more on Windows later)
- Each signal has a number assigned by convention
  - Just like interrupts
- Application specifies a handler for each signal
  - OS provides default

Signals, cont.

- Can occur for:
  - Exceptions: divide by zero, null pointer, etc.
  - IPC: Application-defined signals (**`USR1`**, **`USR2`**)
  - Control process execution (**`KILL`**, **`TERM`**, **`STOP`**, **`CONT`**)
- Send a signal using **`kill(pid, signo)`**
  - Killing an errant program is common, but you can also send a non-lethal signal using **`kill()`**
- Use **`signal()`** or **`sigaction()`** to set the **handler** for a signal

How signals work

- If process survives, control is returned to the application
- Although signals appear to be delivered immediately…
  - They are actually delivered lazily…
  - Whenever the OS happens to be returning to the process from an interrupt, system call, etc.
- If I signal another process, the other process may not receive it until it is scheduled again
- Does this matter?

More details

- When a process receives a signal, it is added to a pending mask of pending signals
  - Stored in PCB
- Just before scheduling a process, the kernel checks if there are any pending signals
  - If so, return to the appropriate handler
  - Save the original register state for later
  - When handler is done, call **`sigreturn()`** system call
    - Then resume execution

Meta-lesson

- Laziness rules!
  - Not on homework
  - But in system design
- Procrastinating on work in the system often reduces overall effort
  - Signals: Why context switch immediately when it will happen soon enough?

Language Exceptions

- Signals are the underlying mechanism for Exceptions and catch blocks
- JVM or other runtime system sets signal handlers
  - Signal handler causes execution to jump to the catch block

Windows comparison

- Exceptions have specific upcalls from the kernel to ntdll
- IPC is done using Events
  - Shared between processes
  - Handle in table
  - No data, only 2 states: set and clear
  - Several variants: e.g., auto-clear after checking the state

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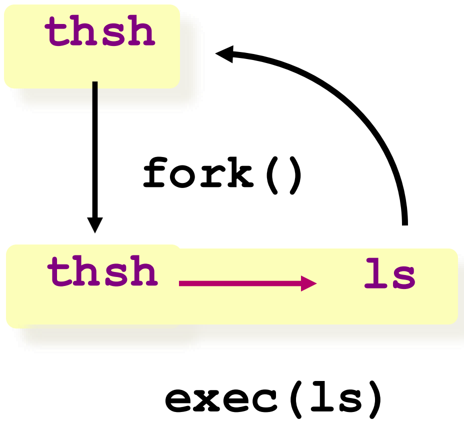
- Pipes & Sockets
- Signals
- **Synthesis Example: The Shell**

Shell Recap

- Almost all ‘commands’ are really binaries
  - /bin/ls
- Key abstraction: Redirection over pipes
  - ‘>’, ‘<‘, and ‘|’implemented by the shell itself

Shell Example

- Ex: **`ls | grep foo`**
- Shell pseudocode:




```
while(EOF != read_input) {
    parse_input();
    // Sets up chain of pipes
    // Forks and exec’s ‘ls’ and ‘grep’ separately
    // Wait on output from ‘grep’, print to console
    // print console prompt
}
```

Lab 1 Overview

- C programming on Linux refresher
- Parser for your shell (Lab 1)

Shells

- Shell: aka the command prompt
- At a high level:

```
while (more input) {
    read a line of input
    parse the line into a command
    if valid command: execute it
}
```

We will give you this

Lab 1

Lab 2

Detour: Environment Variables

- Nearly all shell commands are actually binary files
  - Very few commands actually implemented in the shell
  - A few built-ins that change the shell itself (exit, cd)
- Example: **`ls`** is actually in **`/bin/ls`**
  - For fun, play with **`which`**, as in **`which ls`**

```
enrico@localhost [13:44:30] [~]
-> % which ls
/usr/bin/ls
```

```
enrico@localhost [13:44:30] [~]
-> % whereis ls
```

- So where to look for a given command?
  - Note that we want some flexibility system-to-system
  - **Idea**: dynamically set a variable that controls which directories to search

Environment Variables

- A set of key-value pairs
  - Passed to main() as a third argument
  - Often ignored by programmers
- Serves many different purposes
- For Lab 1, we need to look at PATH
  - By convention, a single, colon-delimited set of prefixes
- Example:

`/usr/local/sbin:/usr/local/bin:/usr/sbin:/usr/bin:/sbin:/bin`

PATH in a shell

- If my PATH is

`/usr/local/sbin:/usr/local/bin:/usr/sbin:/usr/bin:/sbin:/bin`

- Then, for a given command (**`ls`**), the shell will check, in order, until found:

```
/usr/local/sbin/ls
/usr/local/bin/ls
/usr/sbin/ls
/usr/bin/ls
/sbin/ls
/bin/ls
```

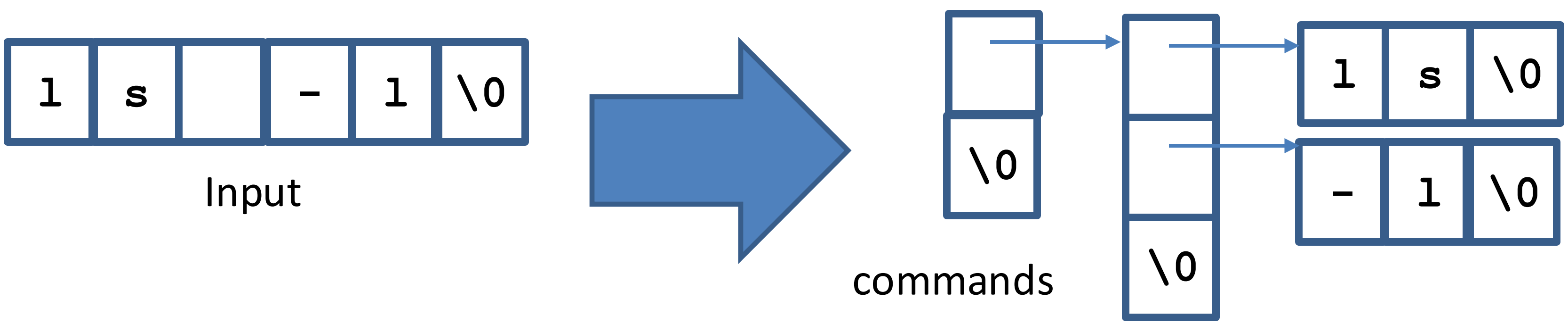
Lab 1, Exercise 1

- Your first job will be to write parsing code that takes in a colon-delimited set of prefixes, and to create a table of prefixes to try in future commands
  - See path_table in jobs.c
  - We wrote a test harness test_env.c

```
$ PATH=/foo:/bar ./test_env
===== Begin Path Table =====
Prefix 0: [/foo]
Prefix 1: [/bar]
===== End Path Table =====
```

Exercise 2: Parsing commands

- A typical shell command includes a main binary (e.g., ‘ls’)
  – and 0+ whitespace-separated arguments (e.g., ‘-l’)
  – and possibly extra whitespace
- You will get this as a single character array
- Your job is to break this up into individual ‘tokens’



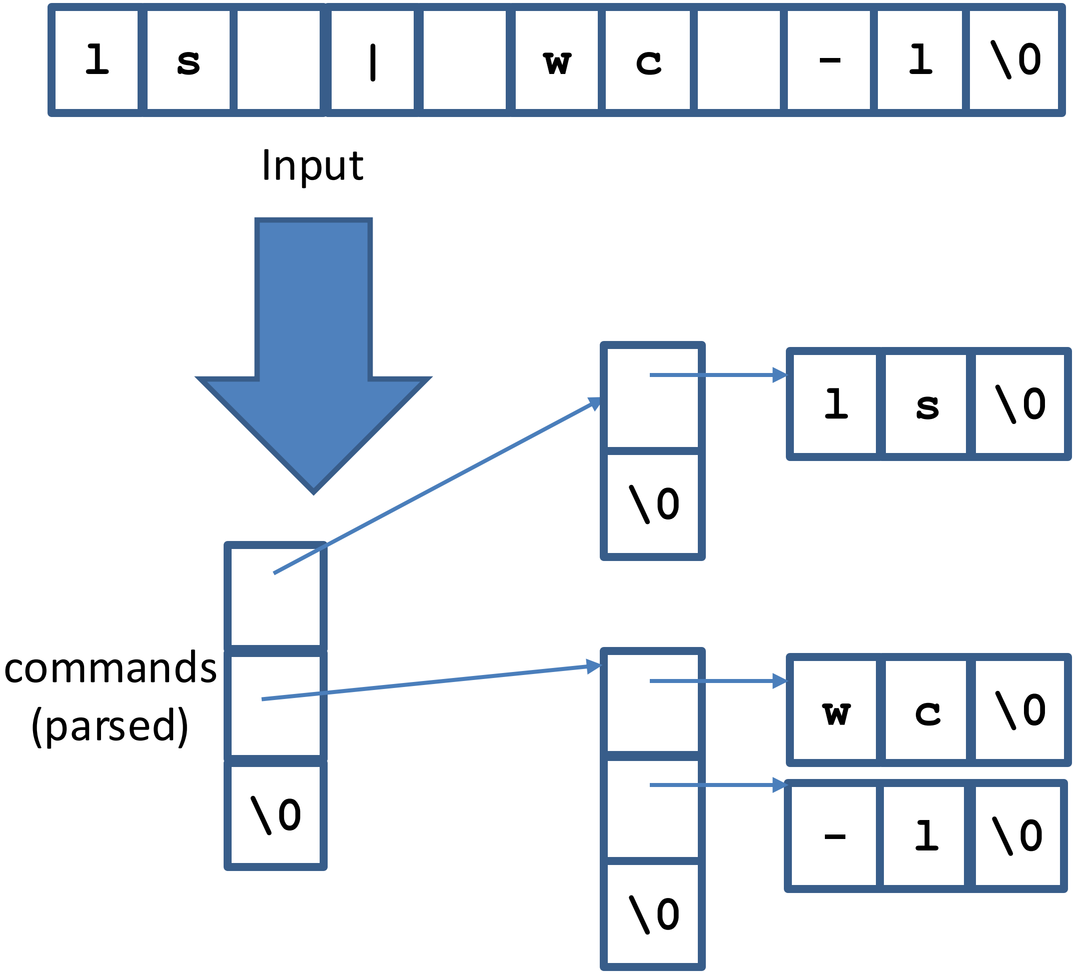
Pipelines

- A shell can compose multiple commands using pipelines
  - Key idea: standard output of one command becomes standard input of next
- Example: **`ls | wc -l`**
  - List a directory (ls) – send listing output to a wordcount utility (wc) to count how many entries in directory
- The vertical bar (|) is a special character
  - May not appear in any other valid commands
  - Does not need whitespace: **`ls|wc -l`** is valid

parse.c:parse_line()

- The workhorse for lab 1 (and 2)
- Takes in a line of input, outputs a 2-D array
- **First** dimension : one entry per pipeline stage
  - Simple commands just have one entry
- **Second** dimension : one entry per command token

How to parse a pipeline?



Other special cases

- Comments – anything past a ‘#’ character
- File redirection - sets standard input/output to a file
  - Example: `ls > mydir.txt`
    - Saves the output of ls into a file
  - Example: `wc –l < mydir.txt`
    - Sends the contents of mydir.txt into wc as standard input
- Built-in commands (see builtin.c)
  - For now, you just need to recognize them and call the appropriate handler function

Working on Homework Assignments

- Use the same learncli211 container as lab 0

Checking out the starter code

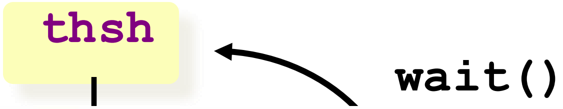
- Once you have a github account registered
  - Make sure you accept the invite:
    - Click https://github.com/comp530-f23
- Click the link in the homework to create a private repo
- Then, on your machine or classroom (substituting your team for ‘team-don’ – see the green clone button):

```
git clone git@github.com:comp530-f23/thsh-team-don.git
```

Submitting homework

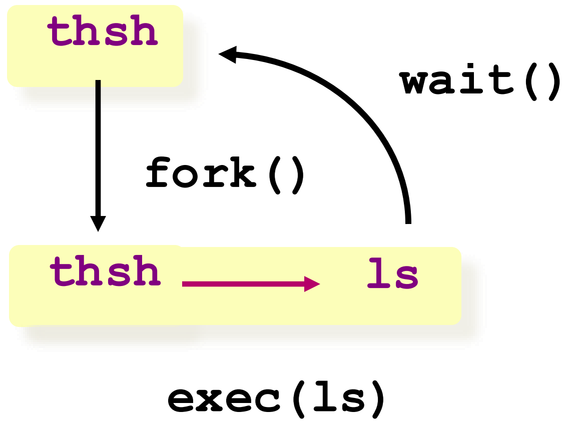
- We will be using gradescope to submit and autograde the homework
  - Challenge problems and late hours done manually
  - Submit challenges separately
- Ideally, use github connection to directly submit
- Feel free to try early to catch issues with grading

A note on Lab 2



- You … is assi…
- If y…
- You … S!!
  - Z … el
  - N…
  - This means no one can launch a shell to kill the zombies!

A note on Lab 1



- Be safe! Limit the number of processes you can create
  - add the command "*limit maxproc 10*" to the file ~/.cshrc
  - (remember to delete this line at the end of the course!)
- Periodically check for and KILL! zombie processes
  - *ps -ef | egrep -e PID -e YOUR-LOGIN-NAME*
  - *kill pid-number*
- Read the HW handout carefully for zombie-hunting details!

What about Ctrl-Z?

- Shell really uses select() to listen for new keystrokes
  - (while also listening for output from subprocess)
- Special keystrokes are intercepted, generate signals
  - Shell needs to keep its own “scheduler” for background processes
  - Assigned simple numbers like 1, 2, 3
- ‘fg 3’ causes shell to send a SIGCONT to suspended child

- Ctrl+C implemented using SIGKILL

Other hints

- Splice(), tee(), and similar calls are useful for connecting pipes together
  - Avoids copying data into and out-of application

Collaboration Policy Reminder

- You can work alone or as part of a team
  - Must be the same as lab 1; may change starting in lab 2
  - Every line of code handed in must be written by one of the pair (or the boilerplate)
    - No sharing code with other groups
    - No code from Internet
  - Any other collaboration must be acknowledged in writing
  - High-level discussion is ok (no code)
- See written assignment and syllabus for more details

Not following these rules is an Honor Code violation

Summary

- Understand how handle tables work
  - Survey basic APIs
- Understand signaling abstraction
  - Intuition of how signals are delivered
- Be prepared to start writing your shell in lab 2!

EXTRA SLIDES

```
enrico@localhost [13:44:30] [~]
-> % whereis ls
/usr/bin/ls
```