CS111, Lecture 8
Multiprocessing Introduction

Optional reading:

Operating Systems: Principles and Practice (2nd Edition): Chapter 4

Lecture 7 Recap: Filesystem System Calls

- **open**, **close**, **read** and **write** are 4 system calls for interacting w/ the filesystem
- These functions work with *file descriptors* – unique numbers assigned by the operating system to refer to that instance of that file in this program.
- **read** and **write** may not read/write all requested bytes – not necessarily an error (e.g. may be interrupted), but we may need to call them multiple times.

File descriptors are a powerful abstraction for working with files and other resources.

File Descriptors and I/O

- What if we could use the same code that writes to a file to also write output to the terminal? Or write to a network connection?
- What if we could use the same code that reads from a file to read input from the user? Or read from a network connection?

File descriptors let us do this! A file descriptor can represent more than a file – it is a number representing a currently-open resource. That resource could be a file, or something that behaves like a file.

- When you connect to the network, you get back a file descriptor – you can read/write with it to read/write on the network!
- There are special reserved file descriptor numbers 0,1,2 – reading from 0 reads input from the terminal, writing to 1 writes to the terminal STDOUT, and writing to 2 writes to the terminal STDERR!

File Descriptors and I/O

There are 3 special file descriptors provided by default to each program:

- 0: standard input (user input from the terminal) - `STDIN_FILENO`
- 1: standard output (output to the terminal) - `STDOUT_FILENO`
- 2: standard error (error output to the terminal) - `STDERR_FILENO`

These aren't *really* files – however, they are set up to behave just like they are. E.g. **read(0, buf, nbytes)** gets input from the user!

Programs always assume that 0,1,2 represent STDIN/STDOUT/STDERR. E.g. cin in C++ is essentially a nicer version of read(0, buf, nbytes)!

Example: Copy

What is the smallest 1 line change/hack we could make to this code to make it print the contents of the source file to the terminal instead of copying it to the destination file?

```
static const int kDefaultPermissions = 0644;
int main(int argc, char *argv[]) {
    int sourceFD = open(argv[1], O_RDONLY);
    int destinationFD = open(argv[2],
        O_WRONLY | O_CREAT | O_EXCL, kDefaultPermissions);

    copyContents(sourceFD, destinationFD);

    close(sourceFD);
    close(destinationFD);
    return 0;
}
```

Example: Copy

What is the smallest 1 line change/hack we could make to this code to make it print the contents of the source file to the terminal instead of copying it to the destination file?

```
static const int kDefaultPermissions = 0644;
int main(int argc, char *argv[]) {
    int sourceFD = open(argv[1], O_RDONLY);
    int destinationFD = open(argv[2],
            O_WRONLY | O_CREAT | O_EXCL, kDefaultPermissions);

    copyContents(sourceFD, STDOUT_FILENO);

    close(sourceFD);
    close(destinationFD);
    return 0;
}
```

Topic 2: Multiprocessing - How can our program create and interact with other programs? How does the operating system manage user programs?

CS111 Topic 2: Multiprocessing

Multiprocessing - *How can our program create and interact with other programs? How does the operating system manage user programs?*

Why is answering this question important?

- Helps us understand how programs are spawned and run (e.g. shells, web servers)
- Introduces us to the challenges of *concurrency* – managing concurrent events
- Allows us to understand how shells work and implement our own!

assign3: implement your own shell program!

CS111 Topic 2: Multiprocessing

assign3: implement your own shell!

Learning Goals

- Learn how to use the **fork()** function to create a new process
- Understand how a process is cloned and run by the OS

Plan For Today

- Multiprocessing overview
- Introducing **fork()**
- Cloning Processes

```
cp -r /afs/ir/class/cs111/lecture-code/lect8 .
```

Plan For Today

- **Multiprocessing overview**
- Introducing **fork()**
- Cloning Processes

```
cp -r /afs/ir/class/cs111/lecture-code/lect8 .
```

Multiprocessing Terminology

Program: code you write to execute tasks

Process: an instance of your program running; consists of program and execution state.

Key idea: multiple processes can run the same program

Process 5621

```
int main(int argc, char *argv[]) {
    printf("Hello, world!\n");
    printf("Goodbye!\n");
    return 0;
}
```

Multiprocessing

Your computer runs many processes simultaneously - even with just 1 processor core (how?)

- "simultaneously" = switch between them so fast humans don't notice
- Your program thinks it's the only thing running
- OS *schedules* tasks - who gets to run when
- Each gets a little time, then has to wait
- Many times, waiting is good! E.g. waiting for key press, waiting for disk
- *Caveat*: multicore computers can truly multitask

Playing with Processes

When you run a program from the terminal, it runs in a new process.

- The OS gives each process a unique "process ID" number (PID)
- PIDs are useful once we start managing multiple processes
- **getpid()** returns the PID of the current process (**pid_t** is a numeric type)

```c
// getpid.c
#include <stdio.h>
#include <unistd.h>
int main(int argc, char *argv[]) {
      pid_t myPid = getpid();
      printf("My process ID is %d\n", myPid);
      return 0;
}
```

```
$ ./getpid
My process ID is 18814

$ ./getpid
My process ID is 18831
```

Plan For Today

- Multiprocessing overview
- **Introducing fork()**
- Cloning Processes

```
cp -r /afs/ir/class/cs111/lecture-code/lect8 .
```

Fork is a system call that creates a second process which is a clone of the first.

fork()

fork() creates a second process that is a **clone** of the first:

```
pid_t fork();
```

Process A

```
int main(int argc, char *argv[]) {
    printf("Hello, world!\n");
    fork();
    printf("Goodbye!\n");
    return 0;
}
```

```
$ ./myprogram
```

fork()

fork() creates a second process that is a **clone** of the first:

```
pid_t fork();
```

Process A

```
int main(int argc, char *argv[]) {
    printf("Hello, world!\n");
    fork();
    printf("Goodbye!\n");
    return 0;
}
```

```
$ ./myprogram
Hello, world!
```

fork()

fork() creates a second process that is a **clone** of the first:

```
pid_t fork();
```

Process A

```
int main(int argc, char *argv[]) {
    printf("Hello, world!\n");
    fork();
    printf("Goodbye!\n");
    return 0;
}
```

```
$ ./myprogram
Hello, world!
```

fork()

fork() creates a second process that is a **clone** of the first: `pid_t fork();`

Process A

```
int main(int argc, char *argv[]) {
    printf("Hello, world!\n");
    fork();
    printf("Goodbye!\n");
    return 0;
}
```

Process B

```
int main(int argc, char *argv[]) {
    printf("Hello, world!\n");
    fork();
    printf("Goodbye!\n");
    return 0;
}
```

```
$ ./myprogram
Hello, world!
```

fork()

fork() creates a second process that is a **clone** of the first: `pid_t fork();`

Process A

```
int main(int argc, char *argv[]) {
    printf("Hello, world!\n");
    fork();
    printf("Goodbye!\n");
    return 0;
}
```

Process B

```
int main(int argc, char *argv[]) {
    printf("Hello, world!\n");
    fork();
    printf("Goodbye!\n");
    return 0;
}
```

```
$ ./myprogram
Hello, world!
Goodbye!
Goodbye!
```

fork()

fork() creates a second process that is a **clone** of the first: `pid_t fork();`

Process A

```
int main(int argc, char *argv[]) {
    int x = 2;
    printf("Hello, world!\n");
    fork();
    printf("Goodbye, %d!\n", x);
    return 0;
}
```

```
$ ./myprogram
```

fork()

fork() creates a second process that is a **clone** of the first: `pid_t fork();`

Process A

```
int main(int argc, char *argv[]) {
    int x = 2;
    printf("Hello, world!\n");
    fork();
    printf("Goodbye, %d!\n", x);
    return 0;
}
```

```
$ ./myprogram
Hello, world!
```

fork()

fork() creates a second process that is a **clone** of the first: `pid_t fork();`

Process A

```
int main(int argc, char *argv[]) {
    int x = 2;
    printf("Hello, world!\n");
    fork();
    printf("Goodbye, %d!\n", x);
    return 0;
}
```

Process B

```
int main(int argc, char *argv[]) {
    int x = 2;
    printf("Hello, world!\n");
    fork();
    printf("Goodbye, %d!\n", x);
    return 0;
}
```

```
$ ./myprogram
Hello, world!
```

fork()

fork() creates a second process that is a **clone** of the first: `pid_t fork();`

Process A

```
int main(int argc, char *argv[]) {
    int x = 2;
    printf("Hello, world!\n");
    fork();
    printf("Goodbye, %d!\n", x);
    return 0;
}
```

Process B

```
int main(int argc, char *argv[]) {
    int x = 2;
    printf("Hello, world!\n");
    fork();
    printf("Goodbye, %d!\n", x);
    return 0;
}
```

```
$ ./myprogram
Hello, world!
Goodbye, 2!
Goodbye, 2!
```

fork()

fork() creates a second process that is a **clone** of the first: `pid_t fork();`

- **parent** (original) process forks off a **child** (new) process
- The child **starts** execution on the next program instruction. The parent **continues** execution with the next program instruction. *The order from now on is up to the OS!*
- **fork()** is called once, but returns twice (why?)

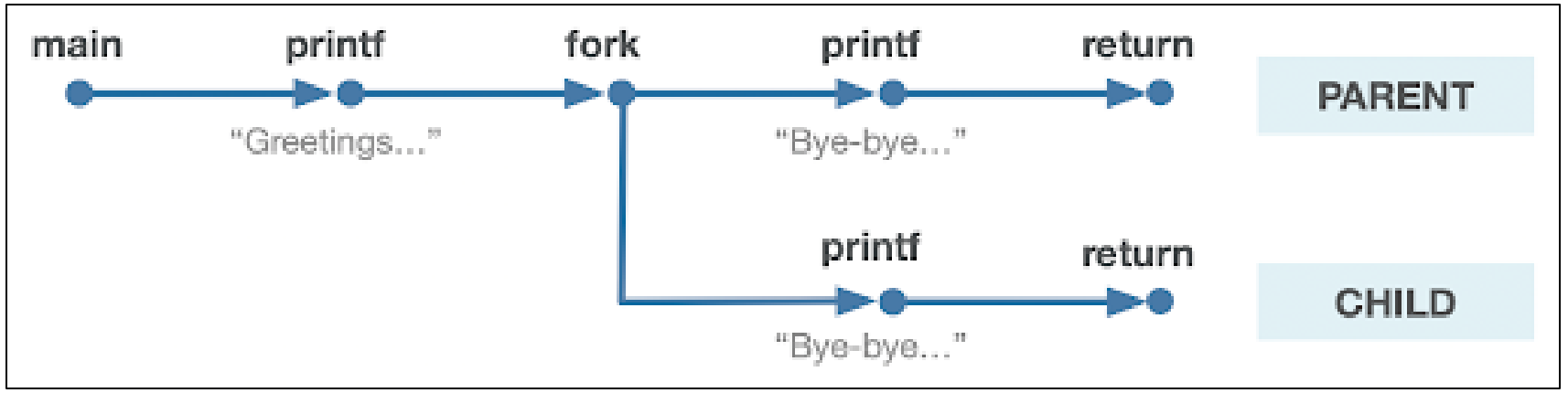


Illustration courtesy of Roz Cyrus.

fork()

fork() creates a second process that is a **clone** of the first: `pid_t fork();`

- **parent** (original) process forks off a **child** (new) process
- A child process could also then later call **fork**, thus being a parent itself
- Everything is duplicated in the child process (except PIDs are different)
  - File descriptor table - this explains how the child can still output to the same terminal!
  - Mapped memory regions (the address space) - regions like stack, heap, etc. are copied

fork()

(Am I the parent or the child?)

Process A

```
int main(int argc, char *argv[]) {
    int x = 2;
    printf("Hello, world!\n");
    fork();
    printf("Goodbye, %d!\n", x);
    return 0;
}
```

Process B

```
int main(int argc, char *argv[]) {
    int x = 2;
    printf("Hello, world!\n");
    fork();
    printf("Goodbye, %d!\n", x);
    return 0;
}
```

Is there a way for the processes to tell which is the parent and which is the child?

fork()

Key Idea: **the return value of fork() is different in the parent** (original) **and the child** (new)**.**

- **fork** returns the child's PID in the parent, and 0 in the child
- 0 is not the child's PID – just a sentinel value to indicate it is the child
- For the parent, this is the only way to get the child's PID

This allows us to assign different tasks to the parent and child!

fork()

In the **parent**, **fork()** will return the PID of the child. In the **child, fork()** will return 0 (this is not the child's PID, it's just 0).

Process 111

```
int main(int argc, char *argv[]) {
    printf("Hello, world!\n");
    pid_t pidOrZero = fork();
    printf("fork returned %d\n",
            pidOrZero);
    return 0;
}
```

```
$ ./myprogram
```

fork()

In the **parent**, **fork()** will return the PID of the child. In the **child, fork()** will return 0 (this is not the child's PID, it's just 0).

Process 111

```
int main(int argc, char *argv[]) {
    printf("Hello, world!\n");
    pid_t pidOrZero = fork();
    printf("fork returned %d\n",
            pidOrZero);
    return 0;
}
```

```
$ ./myprogram
Hello, world!
```

fork()

In the **parent**, **fork()** will return the PID of the child. In the **child, fork()** will return 0 (this is not the child's PID, it's just 0).

Process 111

```
int main(int argc, char *argv[]) {
    printf("Hello, world!\n");
    pid_t pidOrZero = fork();
    printf("fork returned %d\n",
            pidOrZero);
    return 0;
}
```

Process 112

```
int main(int argc, char *argv[]) {
    printf("Hello, world!\n");
    pid_t pidOrZero = fork();
    printf("fork returned %d\n",
            pidOrZero);
    return 0;
}
```

```
$ ./myprogram
Hello, world!
```

fork()

In the **parent**, **fork()** will return the PID of the child. In the **child, fork()** will return 0 (this is not the child's PID, it's just 0).

Process 111

```
int main(int argc, char *argv[]) {
    printf("Hello, world!\n");
    pid_t pidOrZero = fork();
    printf("fork returned %d\n",
            pidOrZero);
    return 0;
}
```

Process 112

```
int main(int argc, char *argv[]) {
    printf("Hello, world!\n");
    pid_t pidOrZero = fork();
    printf("fork returned %d\n",
            pidOrZero);
    return 0;
}
```

```
$ ./myprogram
Hello, world!
fork returned 112
fork returned 0
```

fork()

In the **parent**, **fork()** will return the PID of the child. In the **child, fork()** will return 0 (this is not the child's PID, it's just 0).

Process 111

```
int main(int argc, char *argv[]) {
    printf("Hello, world!\n");
    pid_t pidOrZero = fork();
    printf("fork returned %d\n",
            pidOrZero);
    return 0;
}
```

Process 112

```
int main(int argc, char *argv[]) {
    printf("Hello, world!\n");
    pid_t pidOrZero = fork();
    printf("fork returned %d\n",
            pidOrZero);
    return 0;
}
```

```
$ ./myprogram
Hello, world!
fork returned 112
fork returned 0
```

OR

```
$ ./myprogram
Hello, world!
fork returned 0
fork returned 112
```

We can no longer assume the order in which our program will execute! The OS decides the order.

fork()

```
pid_t pidOrZero = fork();
if (pidOrZero == 0) {
    // Only executed by the child
} else {
    // Only executed by the parent
}

// Executed by both parent and child (if they get here)
```

fork()

- In the **parent**, **fork()** will return the PID of the child
- In the **child, fork()** will return 0 (this is not the child's PID, it's just 0)
- if **fork()** returns < 0, that means an error occurred (e.g. out of processes)
- **getppid()** gets the PID of your parent and **getpid()** gets your own PID
- **fork** allows us to implement a *shell* - a program that prompts the user for a command to run, runs that command, waits for the command to finish, and then prompts the user again.
  - shell (parent) forks off child process to run a command you enter. When you run a command, its parent is the shell.
  - **Key Idea**: we can only run one program per process, so to keep the shell running we need to run the user's command in another process.

Our Goal: Shell

A *shell* is a program that prompts the user for a command to run, runs that command, waits for the command to finish, and then prompts the user again.

```
while (true) {
        char *user_command = … // user input
        pid_t pidOrZero = fork();
        if (pidOrZero == 0) {
                // run user's command in the child, then terminate
                        ???
        }

        // parent waits for child before continuing
                        ???
}
```

Our Goal: Shell

A *shell* is a program that prompts the user for a command to run, runs that command, waits for the command to finish, and then prompts the user again.

```
while (true) {
        char *user_command = … // user input
        pid_t pidOrZero = fork();
        if (pidOrZero == 0) {
                // run user's command in the child,
                                ???
        }

        // parent waits for child before continui
                                ???
}
```

Key idea: we can only run one program per process, so we need to run the user's command in another process – otherwise, the shell will go away!

fork()

```c
int main(int argc, char *argv[]) {
    printf("Hello from process %d! (parent %d)\n", getpid(), getppid());
    pid_t pidOrZero = fork();
    assert(pidOrZero >= 0);
    printf("Bye from process %d! (parent %d)\n", getpid(), getppid());
    return 0;
}
```

```
$ ./intro-fork
Hello from process 29686! (parent 29351)
Bye from process 29686! (parent 29351)
Bye from process 29688! (parent 29686)

$ ./intro-fork
Hello from process 29690! (parent 29351)
Bye from process 29691! (parent 29690)
Bye from process 29690! (parent 29351)
```

- The parent of the original process is the *shell* - the program that you run in the terminal.
- The ordering of the parent and child output is *up to the OS!*

Which of these outputs is not possible?

```
// Assume parent PID 111, child PID 112
pid_t pidOrZero = fork();
printf("hello, world!\n");
printf("goodbye! (fork returned %d)\n", pidOrZero);
```

A)
hello, world!
hello, world!
goodbye! (fork returned 0)
goodbye! (fork returned 112)

C)
hello, world!
goodbye! (fork returned 112)
hello, world!
goodbye! (fork returned 0)

B)
hello, world!
hello, world!
goodbye! (fork returned 112)
goodbye! (fork returned 0)

D)
hello, world!
goodbye! (fork returned 112)
goodbye! (fork returned 0)
hello, world!

Respond on PollEv:
pollev.com/cs111

Processes all the way down

Even a child process can call **fork** to spawn its own child process!

```
int main(int argc, char *argv[]) {
    printf("Hello!\n");
    fork();
    printf("Howdy!\n");
    fork();
    printf("Hey there!\n");
    return 0;
}
```

- How many total processes are there (including the parent) in this program?

- How many times is each printf statement printed?

Which of these outputs is *not* possible?

A

0%

B

0%

C

0%

D

0%

Processes all the way down

Even a child process can call **fork** to spawn its own child process!

```
int main(int argc, char *argv[]) {
    printf("Hello!\n");
    fork();
    printf("Howdy!\n");
    fork();
    printf("Hey there!\n");
    return 0;
}
```

Parent

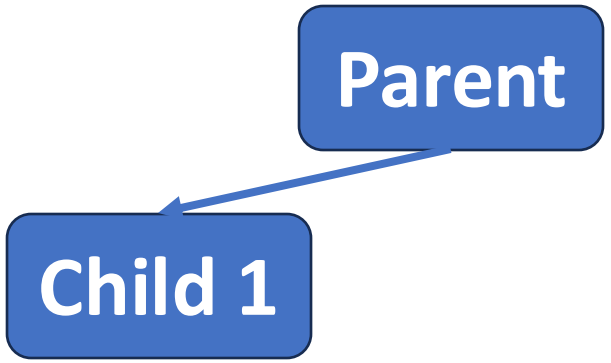
- How many total processes are there (including the parent) in this program?

- How many times is each printf statement printed?

Processes all the way down

Even a child process can call **fork** to spawn its own child process!

```
int main(int argc, char *argv[]) {
    printf("Hello!\n");
    fork();
    printf("Howdy!\n");
    fork();
    printf("Hey there!\n");
    return 0;
}
```



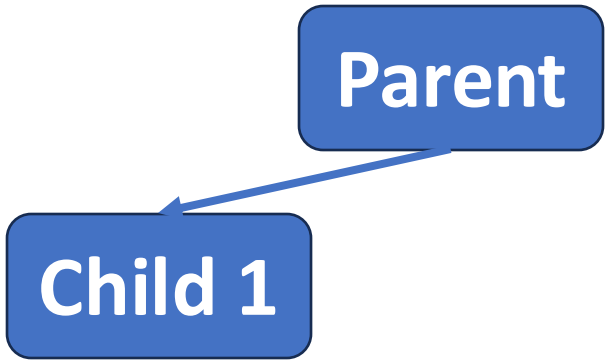
- How many total processes are there (including the parent) in this program?

- How many times is each printf statement printed?

Processes all the way down

Even a child process can call **fork** to spawn its own child process!

```
int main(int argc, char *argv[]) {
    printf("Hello!\n");
    fork();
    printf("Howdy!\n");
    fork();
    printf("Hey there!\n");
    return 0;
}
```



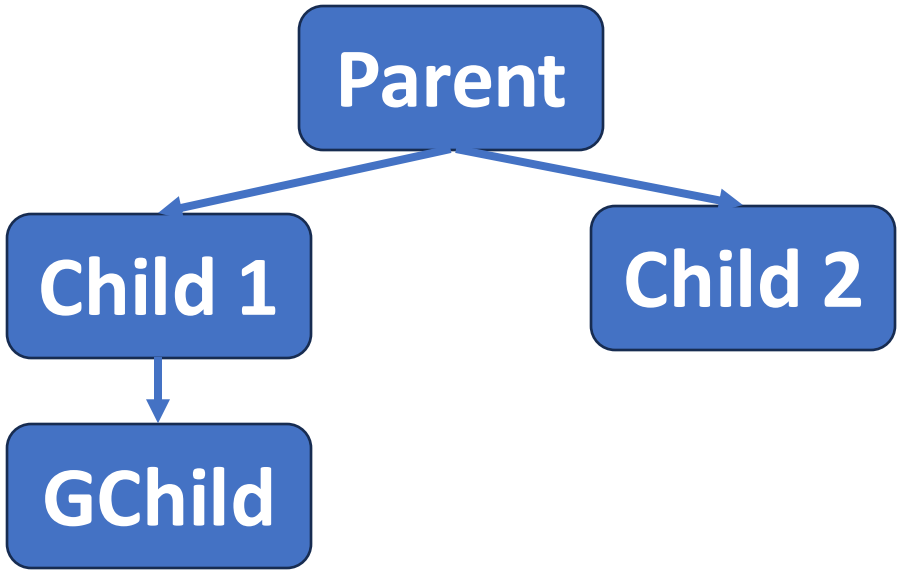
- How many total processes are there (including the parent) in this program?

- How many times is each printf statement printed?

Processes all the way down

Even a child process can call **fork** to spawn its own child process!

```
int main(int argc, char *argv[]) {
    printf("Hello!\n");
    fork();
    printf("Howdy!\n");
    fork();
    printf("Hey there!\n");
    return 0;
}
```



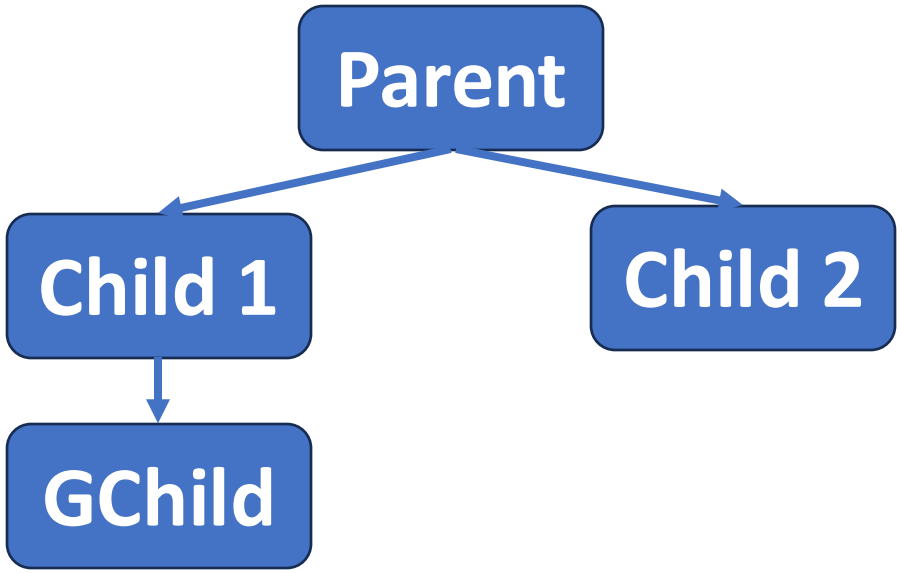
- How many total processes are there (including the parent) in this program?

- How many times is each printf statement printed?

Processes all the way down

Even a child process can call **fork** to spawn its own child process!

```
int main(int argc, char *argv[]) {
    printf("Hello!\n");
    fork();
    printf("Howdy!\n");
    fork();
    printf("Hey there!\n");
    return 0;
}
```



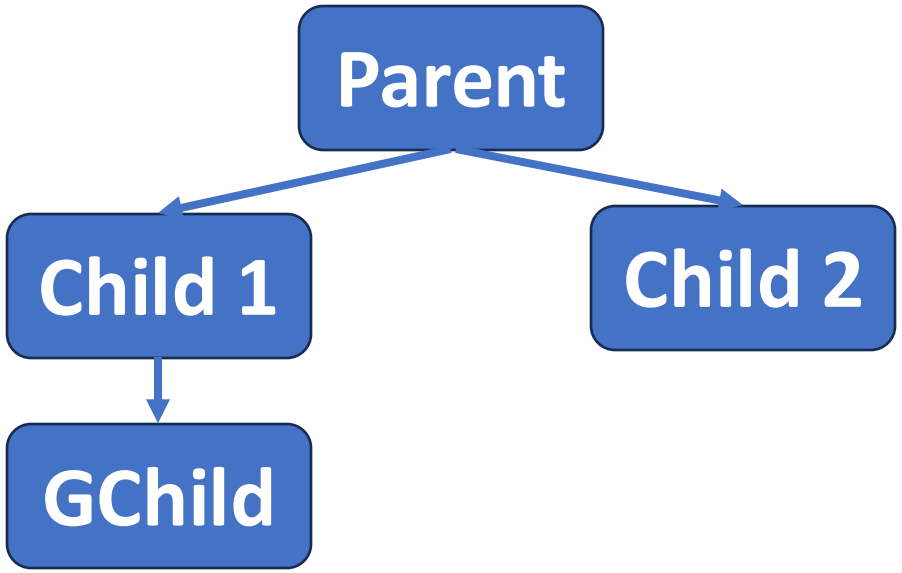
- How many total processes are there (including the parent) in this program?

- How many times is each printf statement printed?

Processes all the way down

Even a child process can call **fork** to spawn its own child process!

```
int main(int argc, char *argv[]) {
    printf("Hello!\n");
    fork();
    printf("Howdy!\n");
    fork();
    printf("Hey there!\n");
    return 0;
}
```

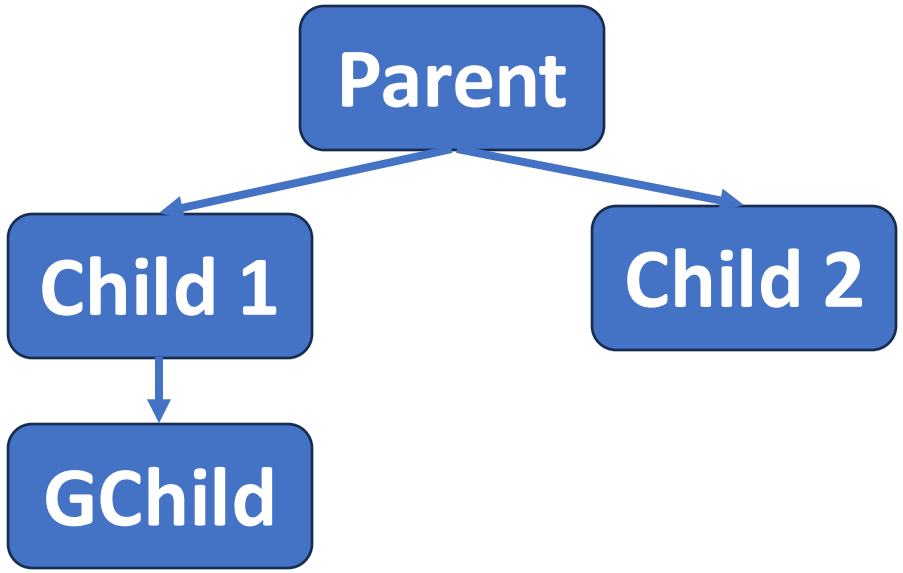


- How many total processes are there (including the parent) in this program?
  - 4
- How many times is each printf statement printed?

Processes all the way down

Even a child process can call **fork** to spawn its own child process!

```
int main(int argc, char *argv[]) {
    printf("Hello!\n");
    fork();
    printf("Howdy!\n");
    fork();
    printf("Hey there!\n");
    return 0;
}
```



- How many total processes are there (including the parent) in this program?
  - 4
- How many times is each printf statement printed?
  - Hello x 1, Howdy x 2, Hey there x 4, could be intermingled

Plan For Today

- Multiprocessing overview
- Introducing **fork()**
- **Cloning Processes**

```
cp -r /afs/ir/class/cs111/lecture-code/lect8 .
```

What happens to variables/addresses?

```
int main(int argc, char *argv[]) {
    char str[128];
    strcpy(str, "Hello");
    printf("str's address is %p\n", str);
    pid_t pidOrZero = fork();
    if (pidOrZero == 0) { // The child should modify str
        printf("I am the child. str's address is %p\n", str);
        strcpy(str, "Howdy");
        printf("I am the child and I changed str to %s. str's address is
                still %p\n", str, str);
    } else { // The parent should sleep and print out str
        printf("I am the parent. str's address is %p\n", str);
        printf("I am the parent, and I'm going to sleep for 2sec.\n");
        sleep(2);
        printf("I am the parent. I just woke up. str's address is %p,
                and its value is %s\n", str, str);
    }
    return 0;
}
```

fork-copy.c

Process Clones

```
$ ./fork-copy
str's address is 0x7ffc8cfa9990
I am the parent. str's address is 0x7ffc8cfa9990
I am the parent, and I'm going to sleep for 2sec.
I am the child. str's address is 0x7ffc8cfa9990
I am the child and I changed str to Howdy. str's address is still
0x7ffc8cfa9990
I am the parent. I just woke up. str's address is 0x7ffc8cfa9990, and its
value is Hello
```

- How can the parent and child use the same address to store different data?
- Each program thinks it is given all memory addresses to use
- The operating system maps these *virtual* addresses to *physical* addresses
- When a process forks, its virtual address space stays the same
- The operating system will map the child's virtual addresses to different physical addresses than for the parent

Process Clones

```
$ ./fork-copy
str's address is 0x7ffc8cfa9990
I am the parent. str's address is 0x7ffc8cfa9990
I am the parent, and I'm going to sleep for 2sec.
I am the child. str's address is 0x7ffc8cfa9990
I am the child and I changed str to Howdy. str's address is still
0x7ffc8cfa9990
I am the parent. I just woke up. str's address is 0x7ffc8cfa9990, and its
value is Hello
```

Isn't it expensive to make copies of all memory when forking?

- The operating system only *lazily* makes copies.
- It will have them share physical addresses until one of them changes its memory contents to be different than the other.
- This is called *copy on write* (only make copies when they are written to).

fork() In Helper Functions

```
void helperFn() {
    pid_t pidOrZero = fork();
    if (pidOrZero == 0) {
        printf("I am the child\n");
    } else {
        printf("I am the parent\n");
    }
}

int main(int argc, char *argv[]) {
    helperFn();
    printf("This is printed twice!\n");
    return 0;
}
```

fork() In Helper Functions

```
// returns true if parent, false if child
bool helperFn() {
    pid_t pidOrZero = fork();
    if (pidOrZero == 0) {
        printf("I am the child\n");
        return false;
    } else {
        printf("I am the parent\n");
        return true;
    }
}

int main(int argc, char *argv[]) {
    bool amParent = helperFn();
    if (amParent) printf("This is printed once\n");
    return 0;
}
```

fork() In Helper Functions

```
void helperFn() {
    pid_t pidOrZero = fork();
    if (pidOrZero == 0) {
        printf("I am the child\n");
        exit(0); // like immediately returning 0 from main
    } else {
        printf("I am the parent\n");
    }
}

int main(int argc, char *argv[]) {
    helperFn();
    printf("This is printed once\n");
    return 0;
}
```

fork()

fork() is used pervasively in applications and systems. For example:

- A shell forks a new process to run an entered program command
- Most network servers run many copies of the server in different processes
- When your kernel boots, it starts the **system.d** program, which forks off all the services and systems for your computer

Processes are the first step in understanding *concurrency*, another key principle in computing systems.

Next time: how can we have the parent wait until the child is finished? And how can we tell the child to run another program?

Our Goal: Shell

A *shell* is a program that prompts the user for a command to run, runs that command, waits for the command to finish, and then prompts the user again.

```
while (true) {
        char *user_command = … // user input
        pid_t pidOrZero = fork();
        if (pidOrZero == 0) {
                // run user's command in the child, then terminate
                        execvp
        }

        // parent waits for child before continuing
                        waitpid
}
```

Recap

- Multiprocessing overview
- Introducing **fork()**
- Cloning Processes

Lecture 8 takeaway: fork() allows a process to fork off a cloned child process. The order of execution between parent and child is up to the OS! We can distinguish between parent and child using fork's return value (child PID in parent, 0 in child).

Next time: waiting on a child process, plus how to run other programs