Process Management

Goals of this Lecture

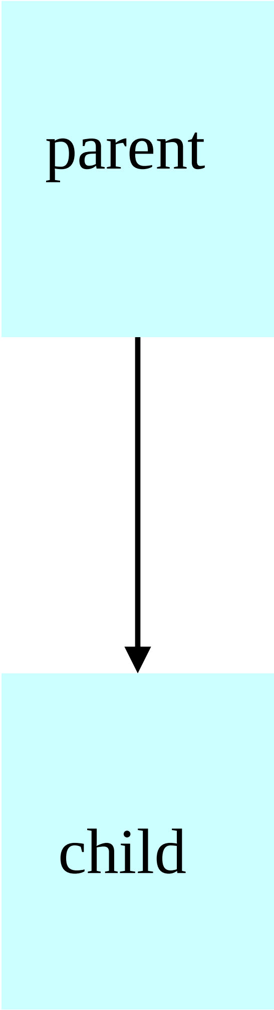
- Help you learn about:
  - Creating new processes
  - Programmatically redirecting stdin, stdout, and stderr
  - (Appendix) communication between processes via pipes
- Why?
  - Creating new processes and programmatic redirection are fundamental tasks of a Unix **shell** (see Assignment 6)
  - A power programmer knows about Unix shells, and thus about creating new processes and programmatic redirection

Why Create a New Process?

- Run a new program
  - E.g., shell executing a program entered at command line
  - Or, even running an entire pipeline of commands
  - Such as "**wc –l * | sort | uniq -c | sort –nr**"
- Run a new thread of control for the same program
  - E.g., a Web server handling a new Web request
  - While continuing to allow more requests to arrive
  - Essentially time sharing the computer
- Underlying mechanism
  - A process executes **fork()** to create a child process
  - (Optionally) child process does **exec()** of a new program

Creating a New Process

- Cloning an existing process
  - Parent process creates a new child process
  - The two processes then run concurrently
- Child process inherits state from parent
  - Identical (but separate) copy of virtual address space
  - Copy of the parent's open file descriptors
  - Parent and child share access to open files
- Child then runs independently
  - Executing independently, including invoking a new program
  - Reading and writing its own address space



Fork System-Level Function

- **`fork()`** is called once
  - But returns twice, once in each process
- Telling which process is which
  - Parent: **`fork()`** returns the child's process ID
  - Child: **`fork()`** returns 0

```
pid = fork();
if (pid != 0) {
   /* in parent */
  …
} else {
   /* in child */
   …
}
```

Fork and Process State

- Inherited
  - User and group IDs
  - Signal handling settings
  - Stdio
  - File pointers
  - Root directory
  - File mode creation mask
  - Resource limits
  - Controlling terminal
  - All machine register states
  - Control register(s)
  - …
- Separate in child
  - Process ID
  - Address space (memory)
  - File descriptors
  - Parent process ID
  - Pending signals
  - Time signal reset times
  - …

Example: What Output?

```
int main(void)
{
    pid_t pid;
    int x = 1;

    pid = fork();
    if (pid != 0) {
        printf("parent: x = %d\n", --x);
        exit(0);
    } else {
        printf("child: x = %d\n", ++x);
        exit(0);
    }
}
```

Executing a New Program

- `fork()` copies the state of the parent process
  - Child continues running the parent program
  - … with a copy of the process memory and registers
- Need a way to invoke a new program
  - In the context of the newly-created child process
- Example

program

NULL-terminated array
Contains command-line arguments
(to become "argv[]" of ls)

```
execvp("ls", argv);
fprintf(stderr, "exec failed\n");
exit(EXIT_FAILURE);
```

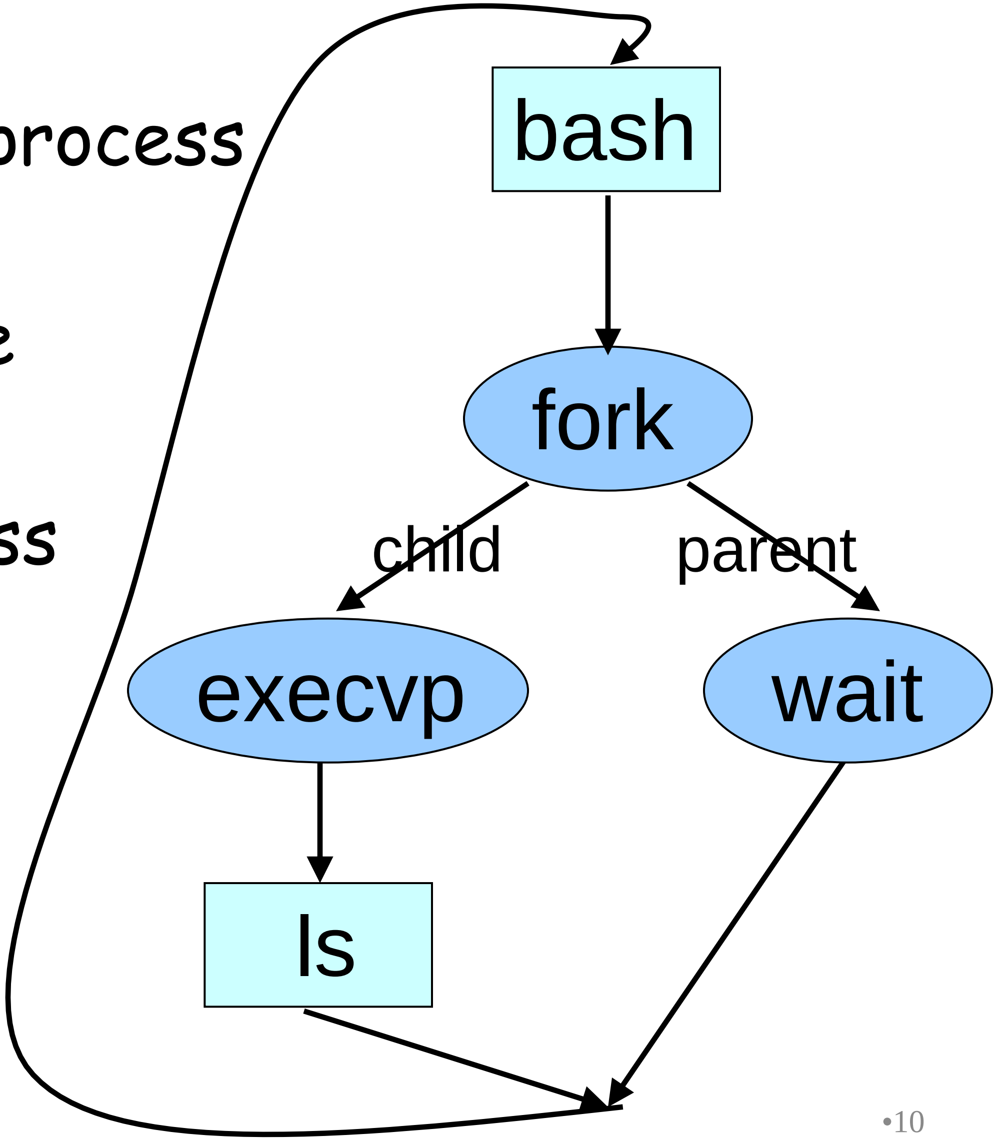
Waiting for the Child to Finish

- Parent should wait for children to finish
  - Example: a shell waiting for operations to complete
- Waiting for a child to terminate: **`wait()`**
  - Blocks until some child terminates
  - Returns the process ID of the child process
  - Or returns -1 if no children exist (i.e., already exited)
- Waiting for specific child to terminate: **`waitpid()`**
  - Blocks till a child with particular process ID terminates

```
#include <sys/types.h>
#include <sys/wait.h>
pid_t wait(int *status);
pid_t waitpid(pid_t pid, int *status, int options);
```

Example: A Simple Shell

- Shell is the parent process
  - E.g., bash
- Parses command line
  - E.g., "ls -l"
- Invokes child process
  - **`fork()`**, **`execvp()`**
- Waits for child
  - **`wait()`**



Simple Shell Code

```
Parse command line
Assign values to somepgm, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
Repeat the previous
```

Simple Shell Trace (1)

Parent Process

```
Parse command line
Assign values to somepgm, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
Repeat the previous
```

Parent reads and parses command line

Parent assigns values to **somepgm** and **someargv**

Simple Shell Trace (2)

Parent Process

```
Parse command line
Assign values to somepgm, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
Repeat the previous
```

executing concurrently

Child Process

```
Parse command line
Assign values to somefile, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
Repeat the previous
```

`fork()` creates child process

Which process gets the CPU first? Let's assume the parent…

Simple Shell Trace (3)

Parent Process

child's pid

```
Parse command line
Assign values to somepgm, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
Repeat the previous
```

executing concurrently

Child Process

```
Parse command line
Assign values to somefile, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
Repeat the previous
```

In parent, pid != 0; parent waits; OS gives CPU to child

Simple Shell Trace (4)

Parent Process

```
Parse command line
Assign values to somepgm, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
Repeat the previous
```

executing concurrently

0

Child Process

```
Parse command line
Assign values to somefile, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
Repeat the previous
```

In child, pid == 0; child calls **execvp()**

Simple Shell Trace (5)

Parent Process

```
Parse command line
Assign values to somepgm, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
Repeat the previous
```

executing concurrently

Child Process

somepgm

In child, somepgm overwrites shell program;
`main()` is called with someargv as argv parameter

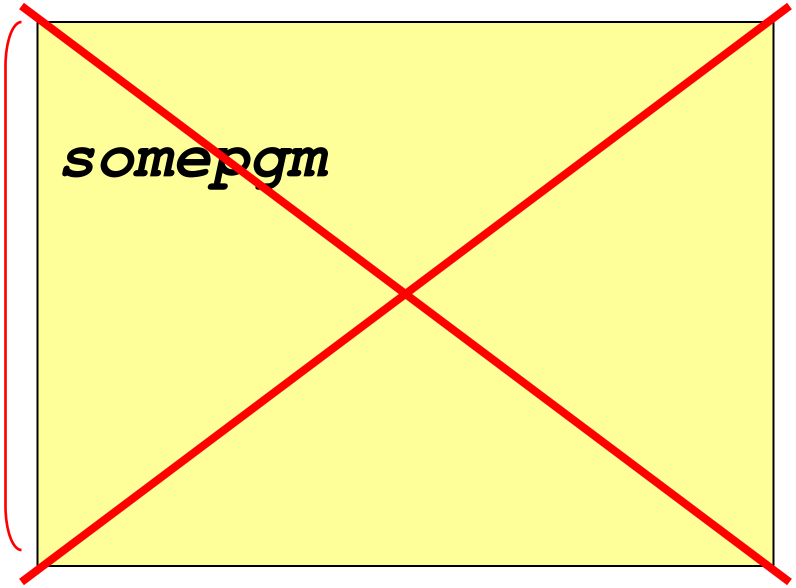
Simple Shell Trace (6)

Parent Process

```
Parse command line
Assign values to somepgm, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
Repeat the previous
```

executing concurrently

Child Process



Somepgm executes in child, and eventually exits

Simple Shell Trace (7)

Parent Process

```
Parse command line
Assign values to somepgm, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
Repeat the previous
```

Parent returns from **`wait()`** and proceeds

Combined Fork/Exec/Wait

- Common combination of operations
  - **`fork()`** to create a new child process
  - **`exec()`** to invoke new program in child process
  - **`wait()`** in the parent process for the child to complete
- Single call that combines all three
  - **`int system(const char *cmd);`**
- Example

```
int main(void) {
    system("echo Hello world");
    return 0;
}
```

Fork and Virtual Memory

- Incidentally…
- Question:
  - **`fork()`** duplicates an entire process (text, bss, data, rodata, stack, heap sections)
  - Isn't that *very* inefficient???!!!
- Answer:
  - Using virtual memory, not really!
  - Upon **`fork()`**, OS creates virtual pages for child process
  - Each child virtual page points to real page (in memory or on disk) of parent
  - OS duplicates real pages incrementally, and only if/when "write" occurs

Redirection

- Unix allows programmatic redirection of stdin, stdout, or stderr
- How?
  - Use **`open()`**, **`creat()`**, and **`close()`** system calls
    - Described in **I/O Management** lecture
  - Use **`dup()`** system call…

```
int dup(int oldfd);
```

- Create a copy of the file descriptor oldfd. After a successful return from dup() or dup2(), the old and new file descriptors may be used interchangeably. They refer to the same open file description and thus share file offset and file status flags. Uses the lowest-numbered unused descriptor for the new descriptor. Return the new descriptor, or -1 if an error occurred.

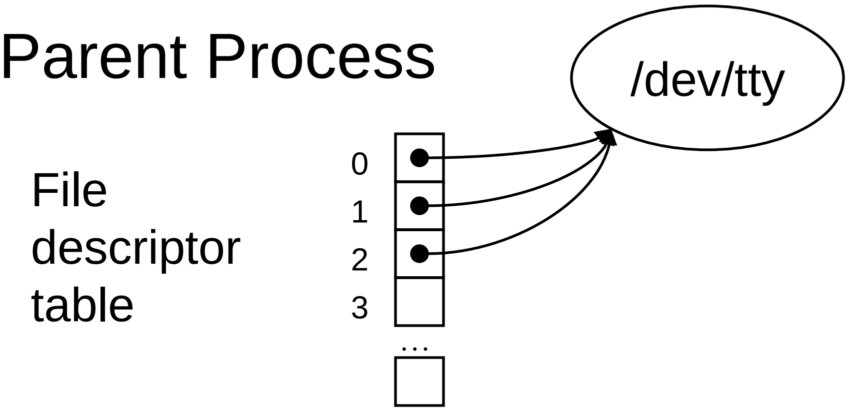
Redirection Example

How does shell implement “somepgm > somefile”?

```
pid = fork();
if (pid == 0) {
   /* in child */
   fd = creat("somefile", 0640);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

Redirection Example Trace (1)

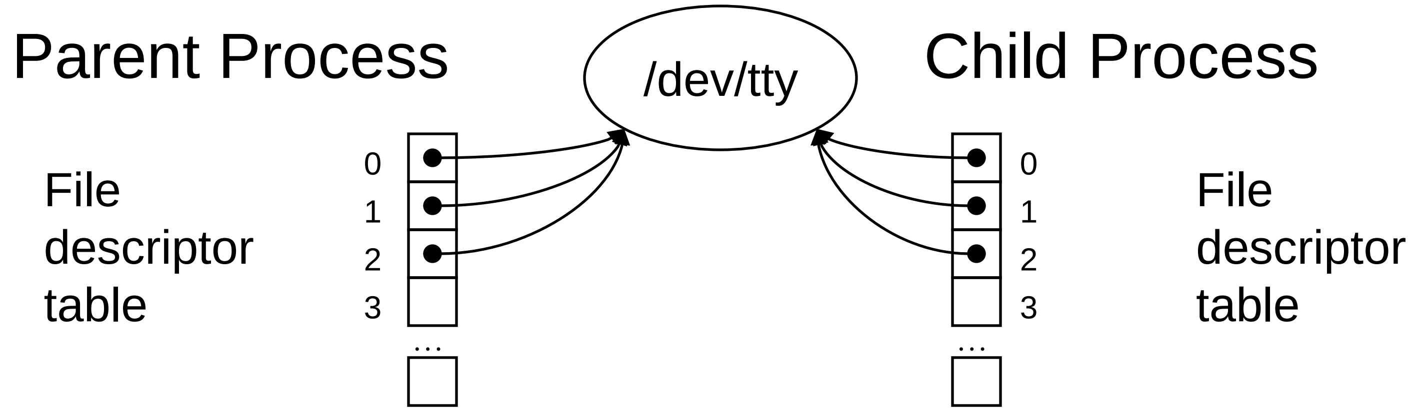
Parent Process




```
pid = fork();
if (pid == 0) {
   /* in child */
   fd = creat("somefile", 0640);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

Parent has file descriptor table; first three point to “terminal”

Redirection Example Trace (2)

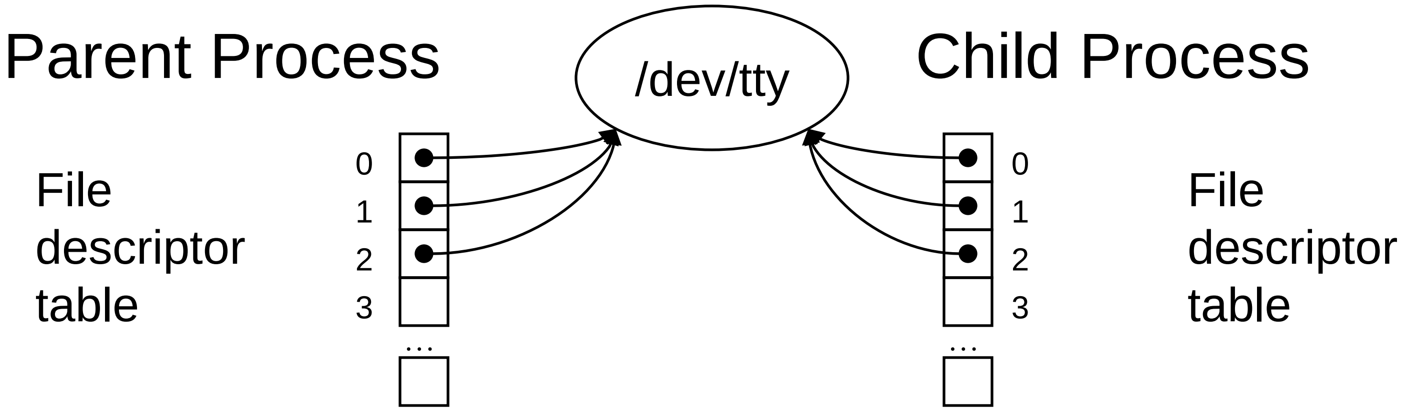



```
pid = fork();
if (pid == 0) {
   /* in child */
   fd = creat("somefile", 0640);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

```
pid = fork();
if (pid == 0) {
   /* in child */
   fd = creat("somefile", 0640);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

Parent forks child; child has identical file descriptor table

Redirection Example Trace (3)




```
pid = fork();
if (pid == 0) {
   /* in child */
   fd = creat("somefile", 0640);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

```
pid = fork();
if (pid == 0) {
   /* in child */
   fd = creat("somefile", 0640);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

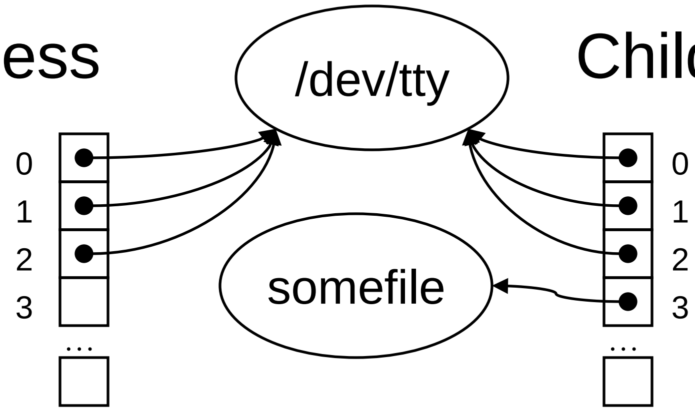
Let’s say parent gets CPU first; parent waits

Redirection Example Trace (4)

Parent Process

Child Process

File descriptor table



File descriptor table

```
pid = fork();
if (pid == 0) {
   /* in child */
   fd = creat("somefile", 0640);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

3

```
pid = fork();
if (pid == 0) {
   /* in child */
   fd = creat("somefile", 0640);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

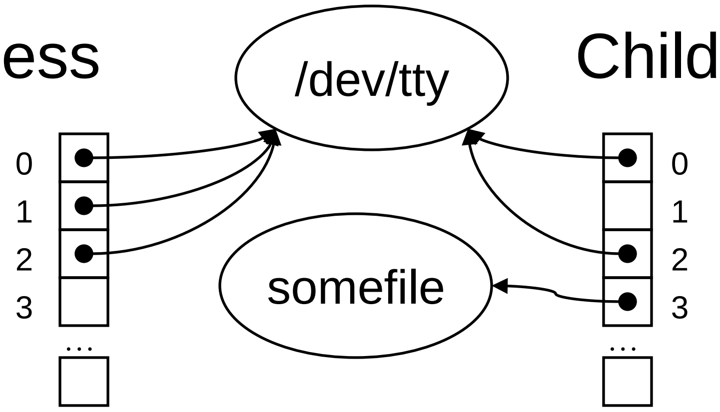
Child gets CPU; child creates somefile

Redirection Example Trace (5)

Parent Process

Child Process

File descriptor table



File descriptor table

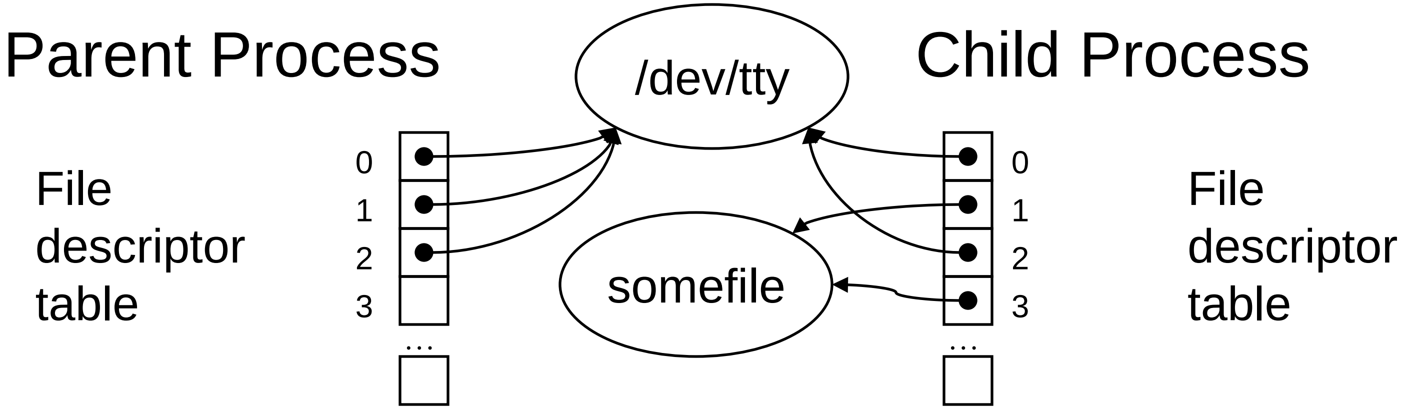
```
pid = fork();
if (pid == 0) {
   /* in child */
   fd = creat("somefile", 0640);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

3

```
pid = fork();
if (pid == 0) {
   /* in child */
   fd = creat("somefile", 0640);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

Child closes file descriptor 1 (stdout)

Redirection Example Trace (6)



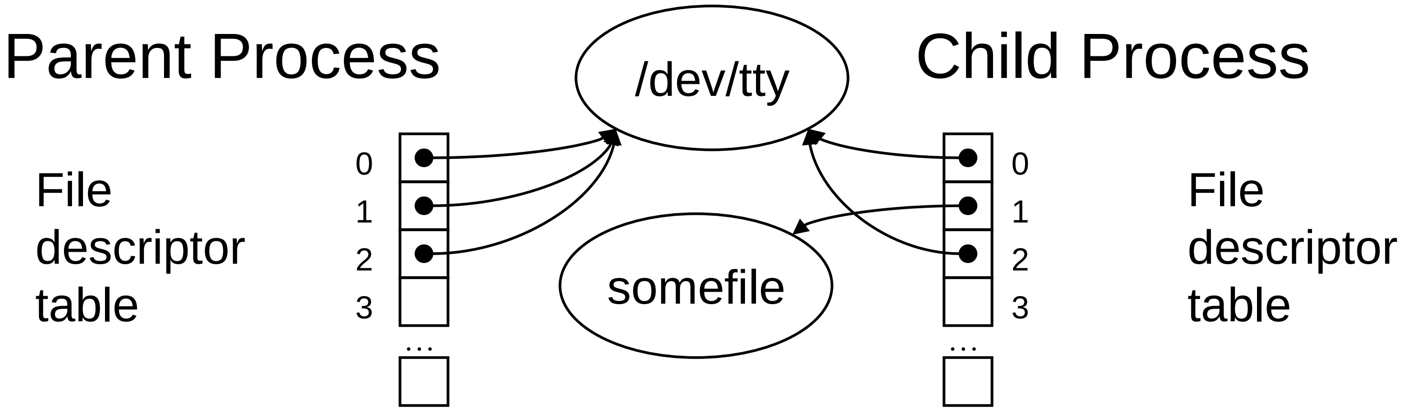

```
pid = fork();
if (pid == 0) {
   /* in child */
   fd = creat("somefile", 0640);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

3

```
pid = fork();
if (pid == 0) {
   /* in child */
   fd = creat("somefile", 0640);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

Child duplicates file descriptor 3 into first unused spot

Redirection Example Trace (7)



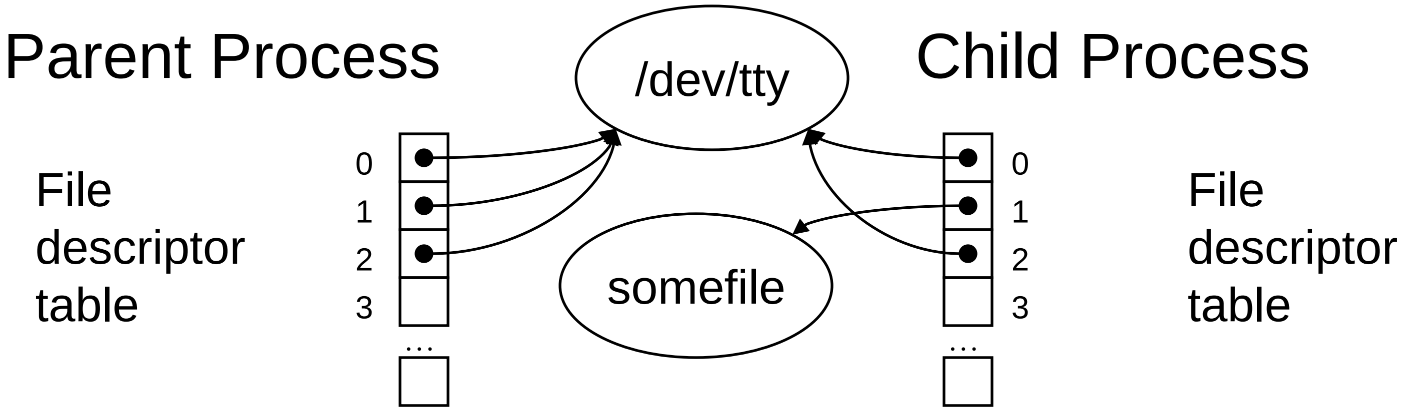

```
pid = fork();
if (pid == 0) {
   /* in child */
   fd = creat("somefile", 0640);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

3

```
pid = fork();
if (pid == 0) {
   /* in child */
   fd = creat("somefile", 0640);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

Child closes file descriptor 3

Redirection Example Trace (8)



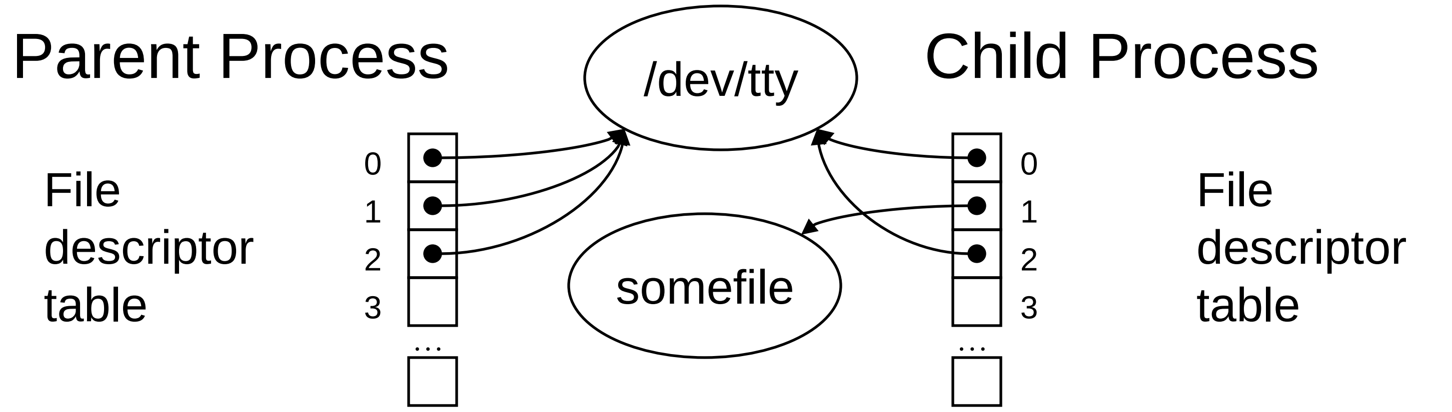

```
pid = fork();
if (pid == 0) {
   /* in child */
   fd = creat("somefile", 0640);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

3

```
pid = fork();
if (pid == 0) {
   /* in child */
   fd = creat("somefile", 0640);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

Child calls execvp()

Redirection Example Trace (9)

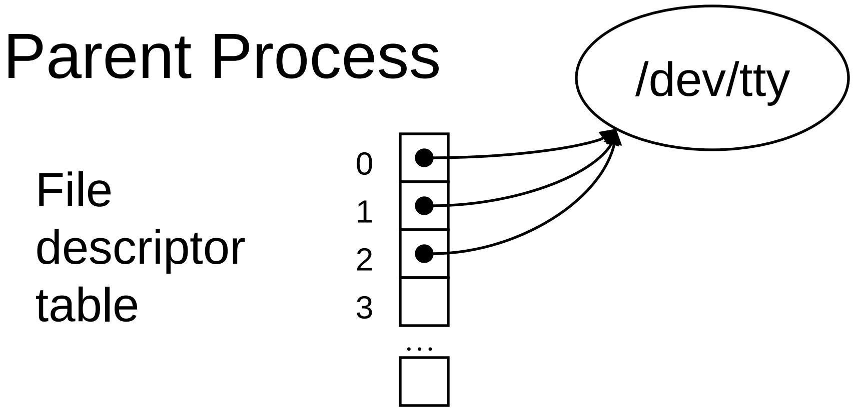



```
pid = fork();
if (pid == 0) {
   /* in child */
   fd = creat("somefile", 0640);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepfm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

somepgm

Somepgm executes with stdout redirected to somefile

Redirection Example Trace (10)




```
pid = fork();
if (pid == 0) {
   /* in child */
   fd = creat("somefile", 0640);
   close(1);
   dup(fd);
   close(fd);
   execvp(somefile, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

Somepgm exits; parent returns from **`wait()`** and proceeds

The Beginnings of a Unix Shell

- A shell is mostly a big loop
  - Parse command line from stdin
  - Expand wildcards (‘*’)
  - Interpret redirections (‘<’, and ‘>’)
  - **`fork()`**, **`dup()`**, **`exec()`**, and **`wait()`**, as necessary
- Start from the code in earlier slides
  - And edit till it becomes a Unix shell
  - This is the heart of the last programming assignment

Summary

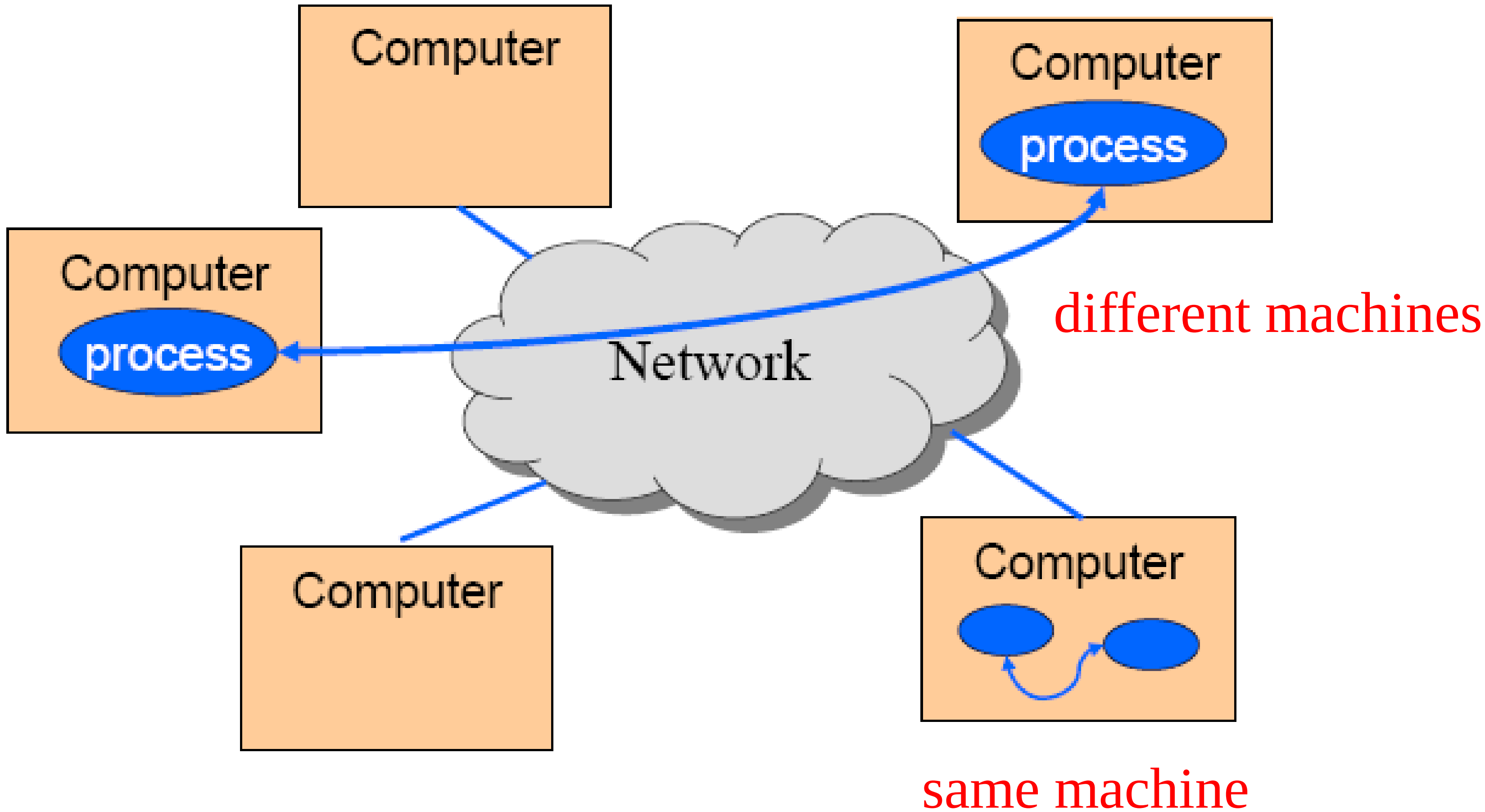
- System-level functions for creating processes
  - **`fork()`**: process creates a new child process
  - **`wait()`**: parent waits for child process to complete
  - **`exec()`**: child starts running a new program
  - **`system()`**: combines fork, wait, and exec all in one
- System-level functions for redirection
  - **`open()`** / **`creat()`**: to open a file descriptor
  - **`close()`**: to close a file descriptor
  - **`dup()`**: to duplicate a file descriptor

Appendix

Inter-Process Communication (IPC)

IPC

- Mechanism by which two processes exchange information and coordinate activities



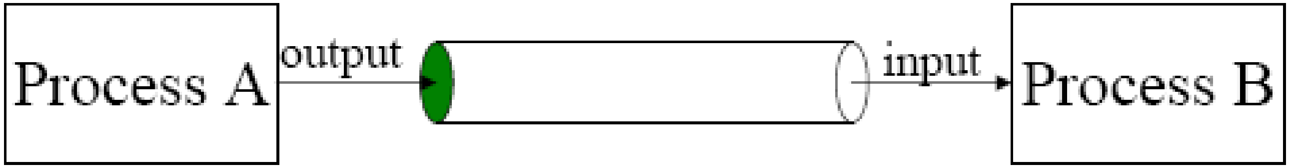
IPC Mechanisms

- Pipes
  - Processes on the same machine
  - Allows parent process to communicate with child process
  - Allows two "sibling" processes to communicate
  - Used mostly for a pipeline of filters
- Sockets
  - Processes on any machines
  - Processes created independently
  - Used for client/server communication (e.g., Web)

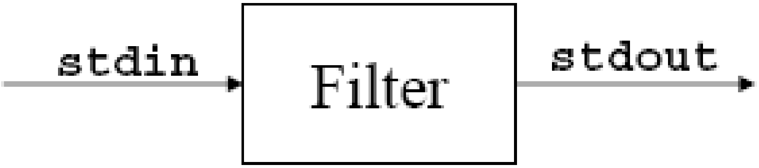
Both provide abstraction of an "ordered stream of bytes"

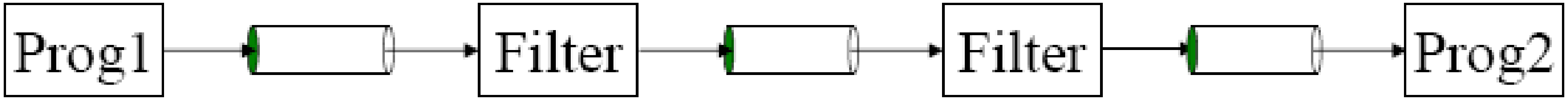
Pipes

- Provides an interprocess communication channel



- A <u>filter</u> is a process that reads from `stdin` and writes to `stdout`

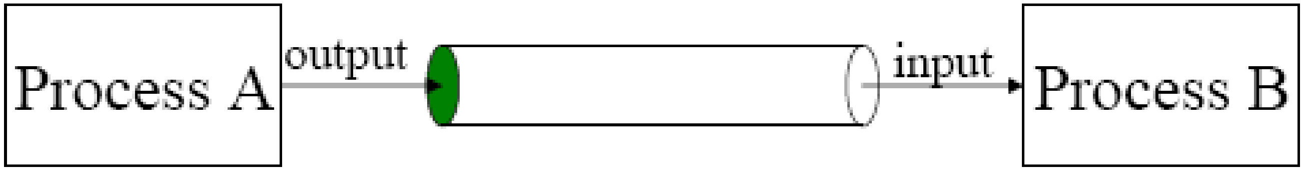




Example Use of Pipes

- Compute a histogram of content types in my e-mail
  - Many e-mail messages, consisting of many lines
  - Lines like "Content-Type: image/jpeg" indicate the type
- Pipeline of Unix commands
  - Identifying content type: **`grep -i Content-Type *`**
  - Extracting just the type: **`cut -d" " -f2`**
  - Sorting the list of types: **`sort`**
  - Counting the unique types: **`uniq -c`**
  - Sorting the counts: **`sort –nr`**

Creating a Pipe



- Pipe is a communication channel abstraction
  - Process A can write to one end using “write” system call
  - Process B can read from the other end using “read” system call
- System call

```
int pipe( int fd[2] );
return 0 upon success –1 upon failure
fd[0] is open for reading
fd[1] is open for writing
```

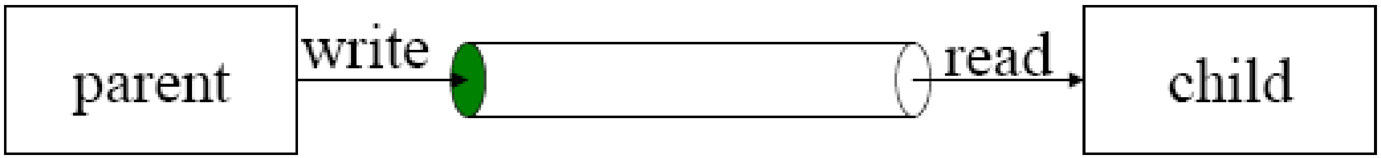
- Two coordinated processes created by `fork` can pass data to each other using a pipe.

Pipe Example

```
int pid, p[2];
...
if (pipe(p) == -1)
    exit(1);
pid = fork();
if (pid == 0) {
    close(p[1]);
    ... read using p[0] as fd until EOF ...
}
else {
    close(p[0]);
    ... write using p[1] as fd ...
    close(p[1]); /* sends EOF to reader */
    wait(&status);
}
```

child

parent

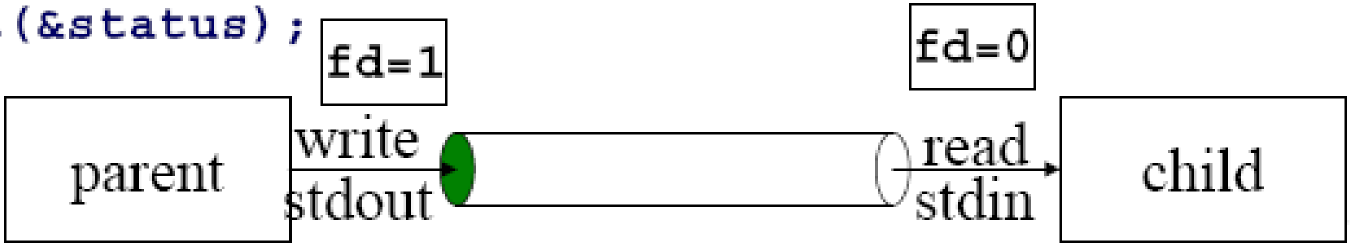


Pipes and Stdio

```
int pid, p[2];
if (pipe(p) == -1)
    exit(1);
pid = fork();
if (pid == 0) {
    close(p[1]);
    dup2(p[0],0);
    close(p[0]);
    ... read from stdin ...
}
else {
    close(p[0]);
    dup2(p[1],1);
    close(p[1]);
    ... write to stdout ...
    wait(&status);
}
```

child makes stdin (0) the read side of the pipe

parent makes stdout (1) the write side of the pipe



Pipes and Exec

```
int pid, p[2];
if (pipe(p) == -1)
    exit(1);
pid = fork();
if (pid == 0) {
    close(p[1]);
    dup2(p[0],0);
    close(p[0]);
    execl(...);
}
else {
    close(p[0]);
    dup2(p[1],1);
    close(p[1]);
    ... write to stdout ...
    wait(&status);
}
```

child process

invokes a new program