



# Process Management

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## 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 7)
  - A power programmer knows about Unix shells, and thus about creating new processes and programmatic redirection

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## Why Create a New Process?



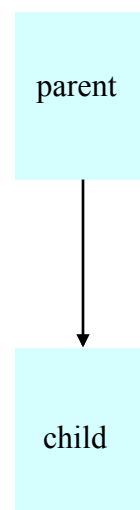
- Run a new program
  - E.g., shell executing a program entered at command line
  - Or, even running an entire pipeline of commands
  - Such as `“wc -l * | sort | uniq -c | sort -nr”`
- Run a new thread of control for the same program
  - E.g., a Web server handling a new Web request
  - While continuing 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

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## 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



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## 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 */
    ...
}
```

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## Fork and Process State



- |   |  |
|---|--|
| <ul style="list-style-type: none"><li>• <b>Inherited</b><ul style="list-style-type: none"><li>• User and group IDs</li><li>• Signal handling settings</li><li>• Stdio</li><li>• File pointers</li><li>• Root directory</li><li>• File mode creation mask</li><li>• Resource limits</li><li>• Controlling terminal</li><li>• All machine register states</li><li>• Control register(s)</li><li>• ...</li></ul></li></ul> | <ul style="list-style-type: none"><li>• <b>Separate in child</b><ul style="list-style-type: none"><li>• Process ID</li><li>• Address space (memory)</li><li>• File descriptors</li><li>• Parent process ID</li><li>• Pending signals</li><li>• Time signal reset times</li><li>• ...</li></ul></li></ul> |
|---|--|

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## 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);
    }
}
```

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## 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);
```

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## 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

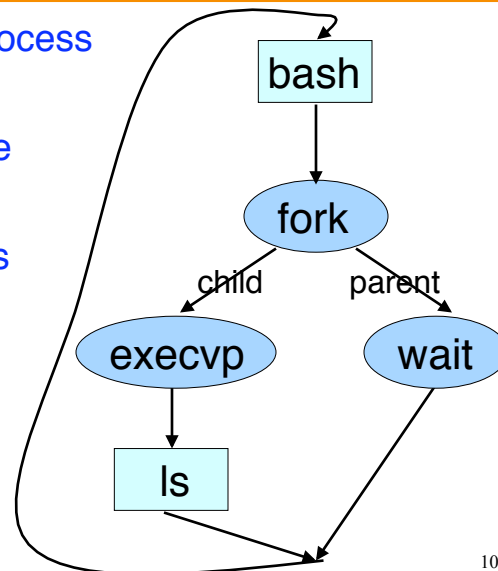
```
#include <sys/types.h>
#include <sys/wait.h>
pid_t wait(int *status);
pid_t waitpid(pid_t pid, int *status, int options);
```

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## 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()`



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## 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
```

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## 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**

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## 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...

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## Simple Shell Trace (3)



### 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
```

child's pid

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

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## 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
```

### 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
```

0  
executing  
concurrently

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

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## 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
```

### Child Process

`somepgm`

executing  
concurrently

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

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## 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
```

### Child Process

~~somepgm~~

executing  
concurrently

Somepgm executes in child, and eventually exits

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## 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

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## 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;  
}
```

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## 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

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## 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.

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## Redirection Example



How does shell implement “`somepgm > somefile`”?

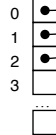
```
pid = fork();
if (pid == 0) {
    /* in child */
    fd = creat("somefile", 0640);
    close(1);
    dup(fd);
    close(fd);
    execvp(somepgm, someargv);
    fprintf(stderr, "exec failed\n");
    exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

## Redirection Example Trace (1)



Parent Process

File  
descriptor  
table



/dev/tty

```
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);
```

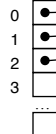
Parent has file descriptor table; first three point to "terminal"

## Redirection Example Trace (2)



Parent Process

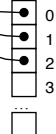
File  
descriptor  
table



/dev/tty

Child Process

File  
descriptor  
table

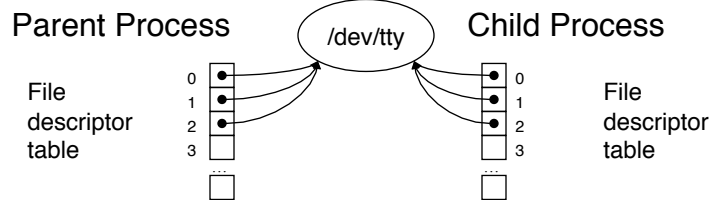


```
pid = fork();
if (pid == 0) {
    /* in child */
    fd = creat("somefile", 0640);
    close(1);
    dup(fd);
    close(fd);
    execvp(somepgm, someargv);
    fprintf(stderr, "exec failed\n");
    exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

```
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 24

## Redirection Example Trace (3)



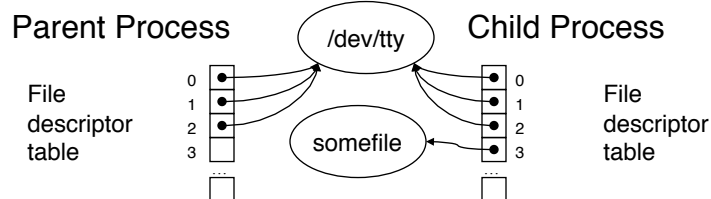
```
pid = fork();
if (pid == 0) {
    /* in child */
    fd = creat("somefile", 0640);
    close(1);
    dup(fd);
    close(fd);
    execvp(somepgm, someargv);
    fprintf(stderr, "exec failed\n");
    exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

```
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

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## Redirection Example Trace (4)



```
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);
```

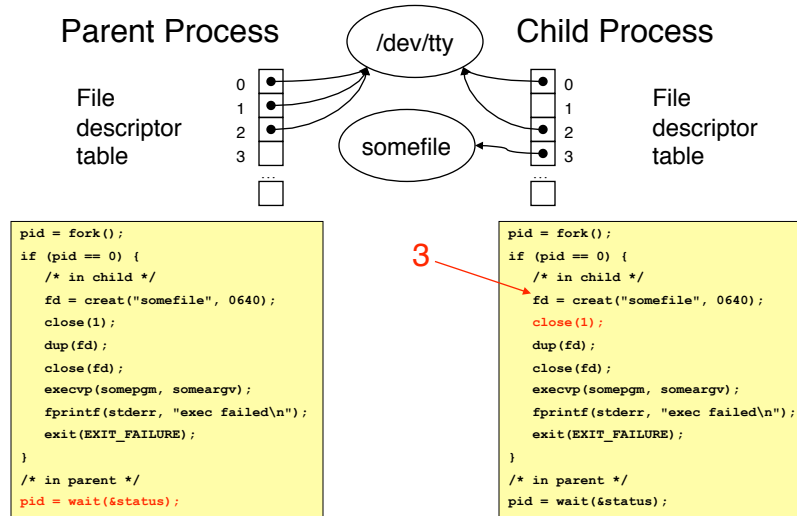
```
pid = fork();
if (pid == 0) {
    /* in child */
    fd = creat("somefile", 0640);
    close(1);
    dup(fd);
    close(fd);
    execvp(somepgm, someargv);
    fprintf(stderr, "exec failed\n");
    exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

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Child gets CPU; child creates somefile

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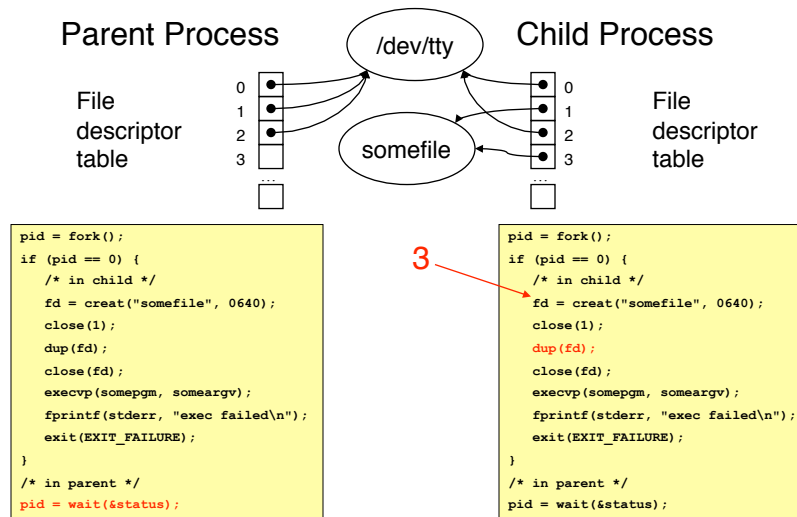
## Redirection Example Trace (5)



Child closes file descriptor 1 (stdout)

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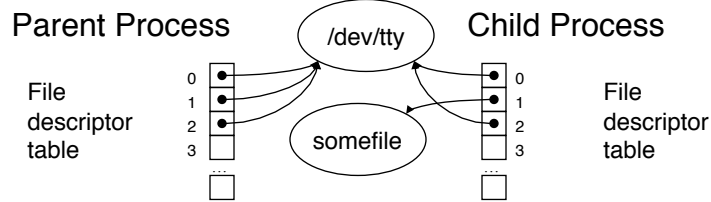
## Redirection Example Trace (6)



Child duplicates file descriptor 3 into first unused spot

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## 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);
    
```

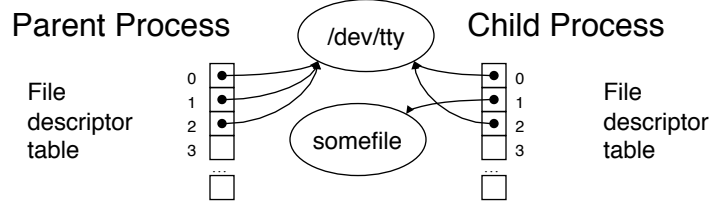
```

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

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## 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);
    
```

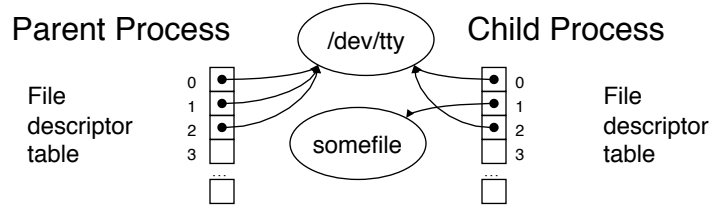
```

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()

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## Redirection Example Trace (9)



```

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

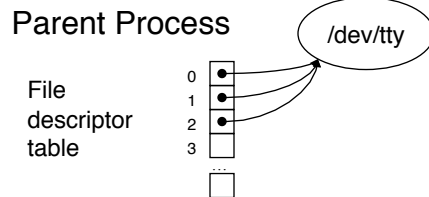
```

someprog
    
```

Someprog executes with stdout redirected to somefile

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## Redirection Example Trace (10)



```

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

Someprog exits; parent returns from `wait()` and proceeds<sup>32</sup>



## 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

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## 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

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# Appendix

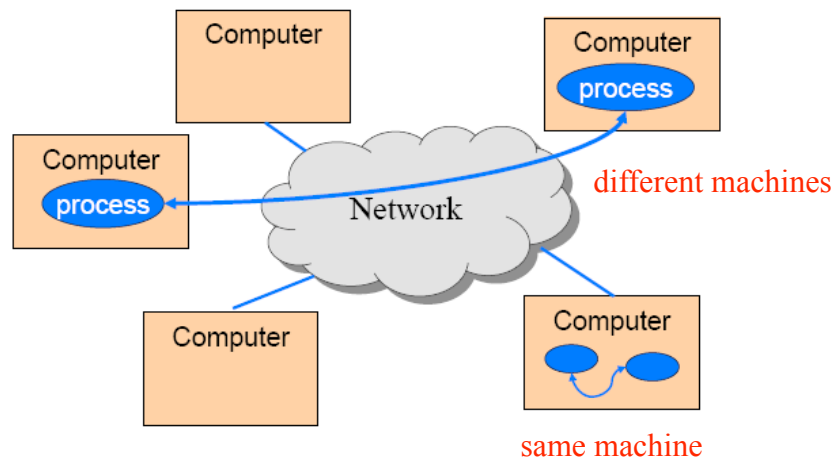


## Inter-Process Communication (IPC)

# 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)

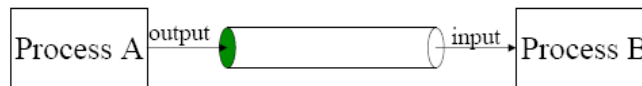
Both provide abstraction of an “ordered stream of bytes”

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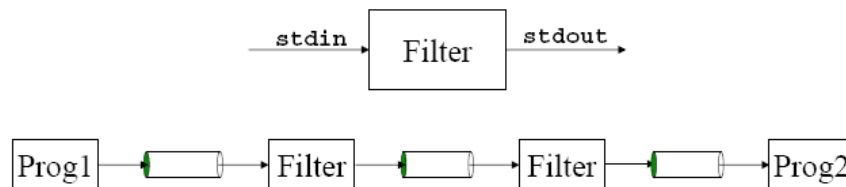
# Pipes



- Provides an interprocess communication channel



- A filter is a process that reads from `stdin` and writes to `stdout`



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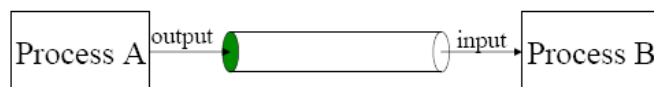
## Example Use of Pipes



- 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`
- Simply running this at the shell prompt:
  - `grep -i Content-Type * | cut -d" " -f2 | sort | uniq -c | sort -nr`

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## 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.

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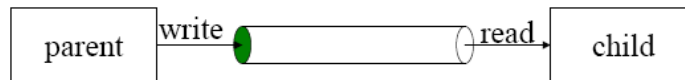
## Pipe Example



```
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



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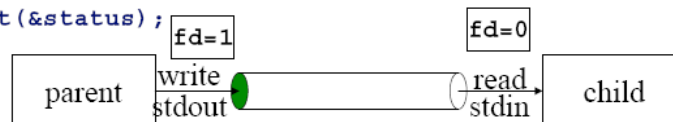
## Pipes and Stdio



```
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



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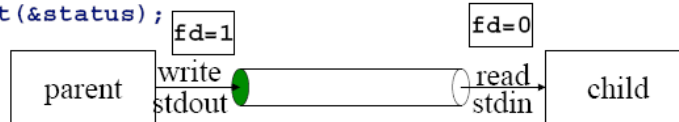
## Pipes and Exec



```
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



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