Process Management

Goals of this Lecture

- Help you learn about:
  - Creating new processes
  - Programmatically redirecting stdin, stdout, and stderr
  - Unix system-level functions for I/O
  - The Unix **stream** concept
  - Standard C I/O functions and their use of Unix functions
  - (Appendix) communication between processes via pipes
- Why?
  - Creating new processes and programmatic redirection are fundamental tasks of a Unix **shell** (Assignment 7)
  - A power programmer knows these things as well as I/O
  - **Streams** are a beautiful Unix abstraction

Why a Process Creates a New One

- 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
- Underlying mechanism
  - A process executes **`fork()`** to create a child process
  - (Optionally) child process does **`exec()`** of new program

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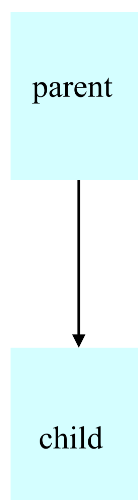
Creating a New Process

- 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 some resources, like open files
- Child then runs independently
  - Including perhaps 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 control twice, once in ("to") each process
  - Returns different values to the two processes
- How to tell 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

- Shared with parent
  - 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
  - …

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Example: What's the 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
- What if child process wants to run a new program
  - Solution: child does exec()
  - Note: exec() does not return. If it does, it failed.
- Example

Program to run

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 (any) child of this process terminates
  - Returns the process ID of that 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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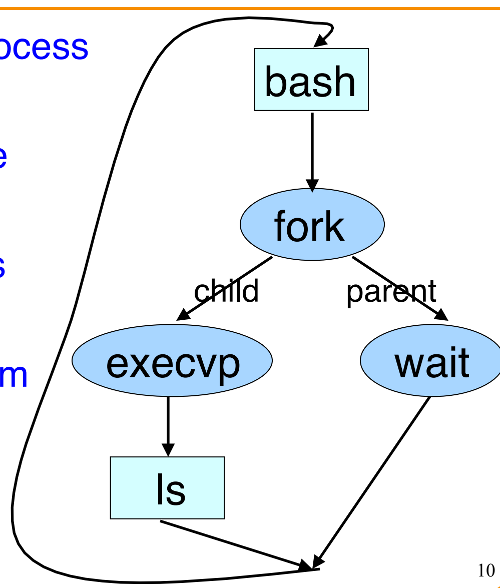
Example: A Simple Shell

- Shell is the parent process
  - E.g., bash
- Parses command line
  - E.g., “ls –l”
- Invokes child process
  - **`fork()`**
- Child runs “ls” program
  - **`execvp()`**
- Parent 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 above
```


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 above
```

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…

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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

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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
```

executing concurrently

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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()`**

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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
```

executing concurrently

Child Process

somepgm

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
```

executing concurrently

Child Process

somepgm

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

- 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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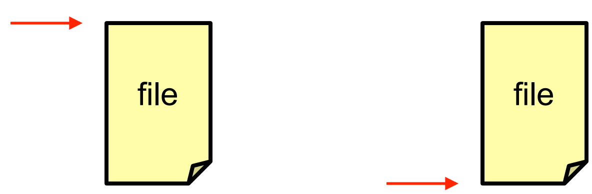
Fork and I/O

- Child process gets a copy of parent's file descriptors
- File descriptor: integer that uniquely represents an open file
  - Passed to and returned by system-level I/O functions
- A file is a stream
  - An ordered sequence of characters
  - Can read or write a stream; can read while someone is writing, …
  - A beautiful abstraction for I/O
- Can create, open, close, read, write or seek into a file
  - Using file descriptor

Streams

- Each stream has an associated file position
  - Starts at beginning of file, if file opened to read or write
  - Or, starts at end of file, if file opened to append



- Read/write operations advance the file position
  - Allows sequencing through the file in sequential manner
- Support for random access to the stream
  - Functions to learn current position and seek to new one

System-Level Functions for I/O

`int creat(char *pathname, mode_t mode);`
- Create a new file named **`pathname`**, and return a file descriptor

`int open(char *pathname, int flags, mode_t mode);`
- Open the file **`pathname`** and return a file descriptor

`int close(int fd);`
- Close **`fd`**

`int read(int fd, void *buf, int count);`
- Read up to **`count`** bytes from **`fd`** into the buffer at **`buf`**

`int write(int fd, void *buf, int count);`
- Writes up to **`count`** bytes into **`fd`** from the buffer at **`buf`**

`int lseek(int fd, int offset, int whence);`
- Assigns the file pointer of **`fd`** to a new value by applying an **`offset`**

Example: `open()`

- Takes a path name, returns file descriptor
  - **`int open(const char *pathname, int flags, mode_t mode);`**
- Arguments
  - Pathname: name of the file
  - Flags: bit flags for **`O_RDONLY, O_WRONLY, O_RDWR`**
  - Mode: permissions to set if file must be created
- Returns
  - File descriptor (or a -1 if an error)
- Performs a variety of checks
  - E.g., whether the process is entitled to access the file
- Underlies **`fopen()`** call in C stdio library

Example: `read()`

- Reads bytes from a file descriptor
  - `int read(int fd, void *buf, int count);`
- Arguments
  - File descriptor: integer descriptor returned by `open()`
  - Buffer: pointer to memory to store the bytes it reads
  - Count: maximum number of bytes to read
- Returns
  - Number of bytes read
    - 0 if nothing more to read
    - -1 if error occurred
- Performs a variety of checks
  - Whether file has been opened, whether reading is okay
- Underlies `getchar()` , `fgets()`, `scanf()` , etc.

Stream Abstraction and C stdio

- Built on top of system-level functions
- Stream: any source of input or destination for output
  - keyboard, screen, files on disk/CD, network/printer port …
- Accessed in C programs through file pointers
  - E.g., `FILE *fp1 = fopen("myfile.txt", "r");`
- Three streams provided by stdio.h
  - Streams **stdin**, **stdout**, and **stderr**
    - Typically map to keyboard, screen, and screen
  - Can redirect to correspond to other streams
    - E.g., stdin can be named file or output of another pgm
    - E.g., stdout can be named file or input to another pgm

Redirection

- Unix allows programmatic redirection of stdin, stdout, stderr
- How?
  - Use **`open()`**, **`creat()`**, and **`close()`** system calls
  - 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. dup() uses the lowest-numbered unused descriptor for the new descriptor. Return the new descriptor, or -1 if an error occurred.

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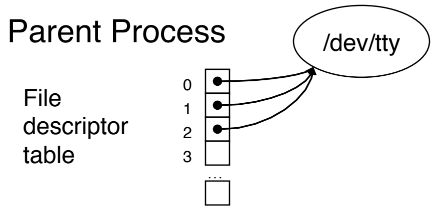
Redirection Example

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)




```
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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);
```
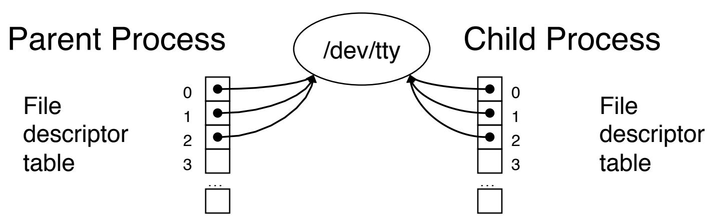

Parent has file descriptor table; first three point to “terminal”

Redirection Example Trace (2)




```
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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);
```
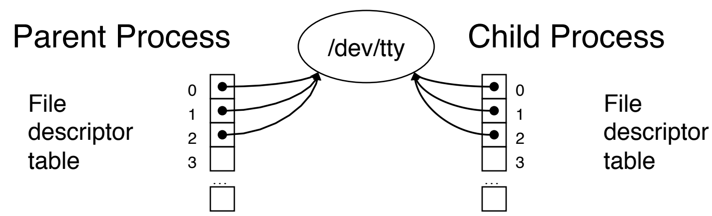

```
pid = fork();
if (pid == 0) {
   /* in child */
   fd = creat("somefile", 0640);
   close(1);
   dup(fd);
   close(fd);
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
pid = wait(&status);
```

Parent forks child; child has identical file descriptor table

Redirection Example Trace (3)




```
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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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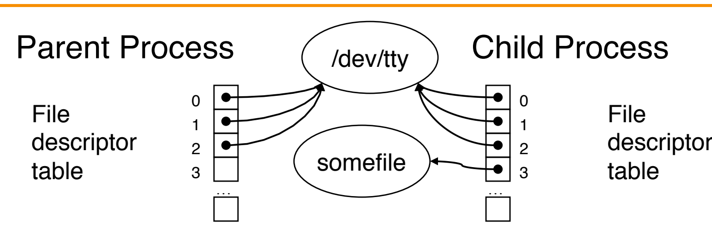
Redirection Example Trace (4)




```
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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

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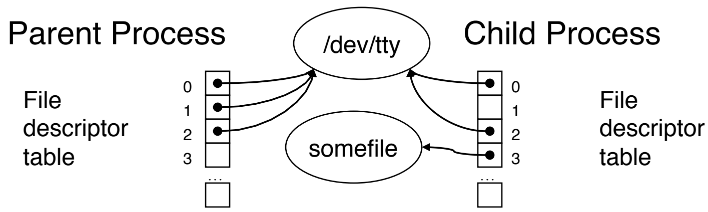
Redirection Example Trace (5)




```
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)

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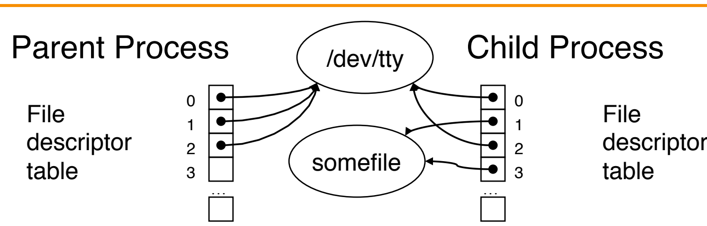
Redirection Example Trace (6)




```
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

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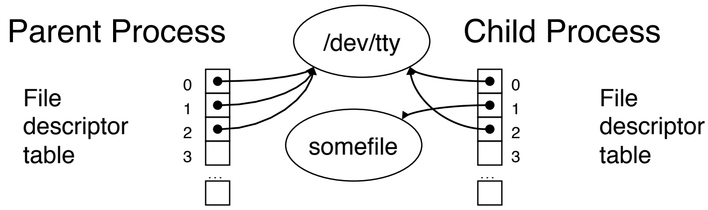
Redirection Example Trace (7)




```
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);
```

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

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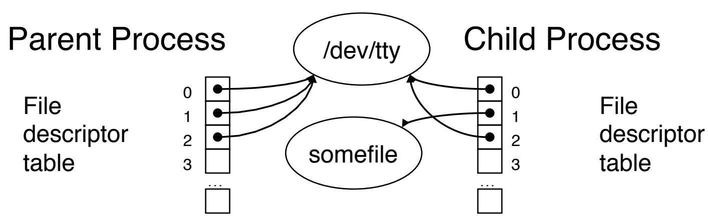
Redirection Example Trace (8)




```
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);
```

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()

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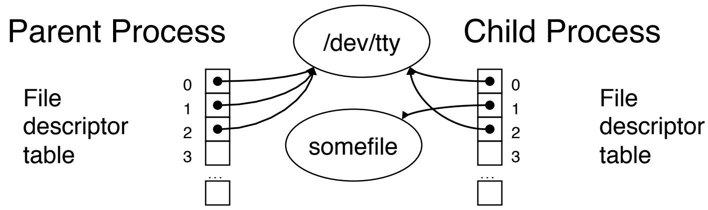
Redirection Example Trace (9)




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

somepgm

Somepgm executes with stdout redirected to somefile

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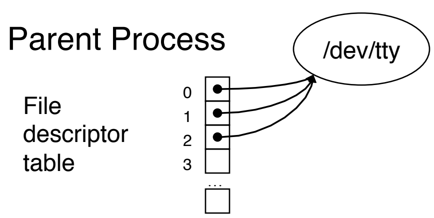
Redirection Example Trace (10)




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

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

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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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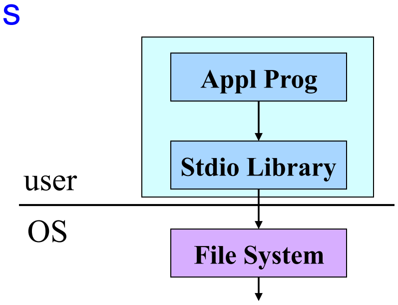
More on C Standard I/O Functions

- Portability
  - Generic I/O support for C programs
  - Specific implementations for various host OSes
  - Invokes the OS-specific system calls for I/O
- Abstractions for C programs
  - Streams
  - Line-by-line input
  - Formatted output
- Additional optimizations
  - Buffered I/O
  - Safe writing



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Example: Opening a File

- **`FILE *fopen("myfile.txt", "r")`**
  - Open the named file and return a stream
  - Includes a mode, such as "r" for read or "w" for write
- Creates a FILE data structure for the file
  - Mode, status, buffer, …
  - Assigns fields and returns a pointer
- Opens or creates the file, based on the mode
  - Write ('w'): create file with default permissions
  - Read ('r'): open the file as read-only
  - Append ('a'): open or create file, and seek to the end
- Uses underlying system calls supported by OS

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Example: Formatted I/O

- **`int fprintf(fp1, "Number: %d\n", i)`**
  - Convert and write output to stream in specified format
- **`int fscanf(fp1, "FooBar: %d", &i)`**
  - Read from stream in format and assign converted values
- Specialized versions
  - **`printf(…)`** is just **`fprintf(stdout, …)`**
  - **`scanf(…)`** is just **`fscanf(stdin, …)`**
- Use underlying syscalls: read, write

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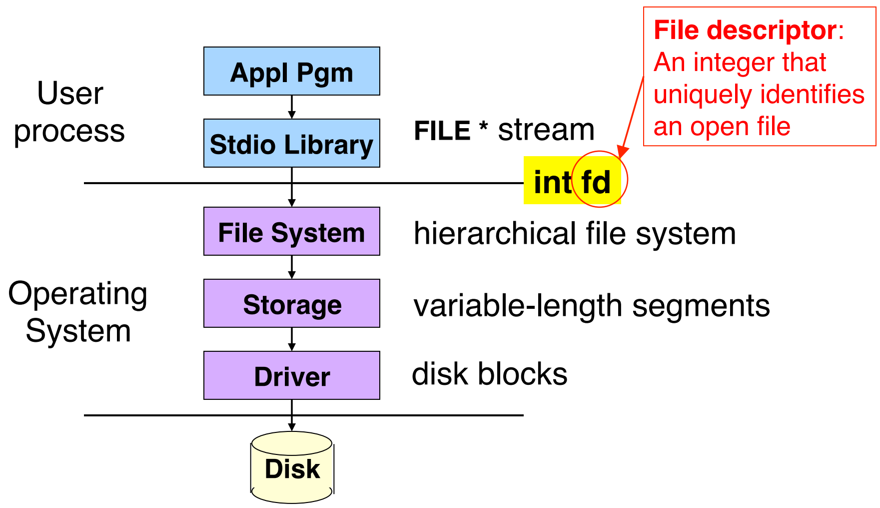
Abstraction: stdio built on syscalls



- stdio functions use create, open, close, read, write system calls

Example: A Simple `getchar()`

```
int getchar(void) {
   char c;
   if (read(0, &c, 1) == 1)
      return c;
   else return EOF;
}
```

- Read one character from **`stdin`**
  - File descriptor **`0`** is **`stdin`**
  - **`&c`** points to the buffer to read into
  - **`1`** is the number of bytes to read
- Read returns the number of bytes read
  - In this case, **`1`** byte means success

Making `getchar()` More Efficient

- Poor performance reading one byte at a time
  - Read system call is accessing the device (e.g., a disk)
  - Reading one byte from disk is very time consuming
  - Better to read and write in *larger chunks*
- Buffered I/O
  - Library reads large chunk from disk into a memory buffer
    - Doles out bytes to the user process as requested
    - Discard buffer contents when the stream is closed
  - Similarly, write individual bytes to a buffer in memory
    - And write to disk when full, or when stream is closed
      - Known as “flushing” the buffer

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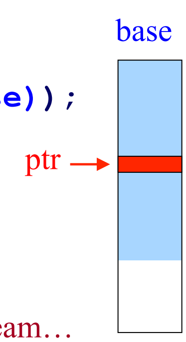
Better `getchar()` with Buffered I/O

```
int getchar(void) {
   static char base[1024];
   static char *ptr;
   static int cnt = 0;

   if (cnt--) return *ptr++;

   cnt = read(0, base, sizeof(base));
   if (cnt <= 0) return EOF;
   ptr = base;
   return getchar();
}
```

persistent variables for the buffer



But, many functions may read (or write) the stream…

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Details of FILE in stdio.h (K&R 8.5)

```
#define OPEN_MAX 20   /* max files open at once */

typedef struct _iobuf {
    int  cnt;      /* num chars left in buffer */
    char *ptr;     /* ptr to next char in buffer */
    char *base;    /* beginning of buffer */
    int  flag;     /* open mode flags, etc. */
    char fd;       /* file descriptor */
} FILE;
extern FILE _iob[OPEN_MAX];

#define stdin  (&_iob[0])
#define stdout (&_iob[1])
#define stderr (&_iob[2])
```

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Buffered Output

- When does it actually show up on I/O device?:

```
int main(void) {
   printf("Step 1\n");
   sleep(10);
   printf("Step 2\n");
   return 0;
}
```

- Run "a.out > out.txt &" and then "tail -f out.txt"
  - To run **a.out** in the background, outputting to **out.txt**
  - And then to see the contents on **out.txt**
- Neither line appears till ten seconds have elapsed
  - Because the output is being buffered
  - Add **fflush(stdout)** to flush the output buffer (often after printf)
  - **fclose()** also flushes the buffer before closing

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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 I/O and redirection
  - `open()` / `creat()`: to open a file descriptor
  - `close()`: to close a file descriptor
  - `dup()`: to duplicate a file descriptor

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Summary (contd.)

- System I/O functions provide simple abstractions
  - Stream as a source or destination of data
  - Functions for manipulating streams
- stdio library builds on system-level functions
  - Calls system-level functions for low-level I/O
  - Adds buffering
- Powerful examples of abstraction
  - Application programs interact with streams at high level
  - Standard I/O library interacts with streams at lower level
  - Only the OS deals with the device-specific details

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Appendix

Inter-Process Communication (IPC)

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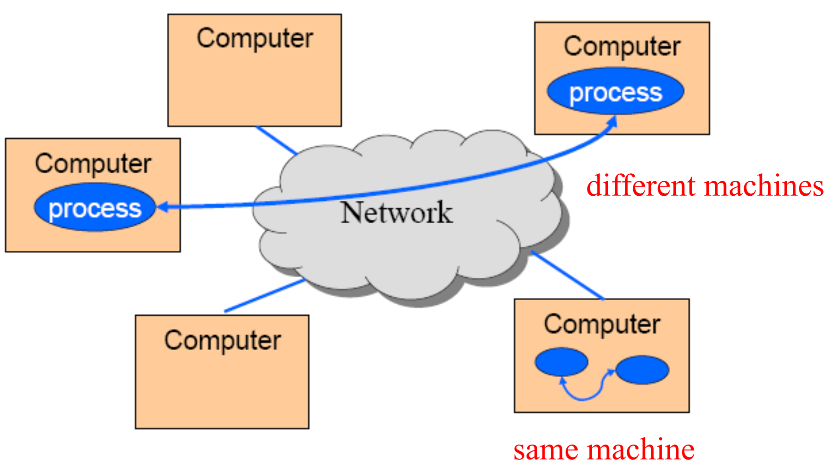
IPC

- Mechanism by which two processes exchange information and coordinate activities



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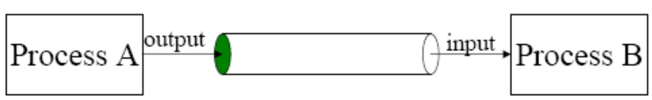
IPC Mechanisms

- 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)

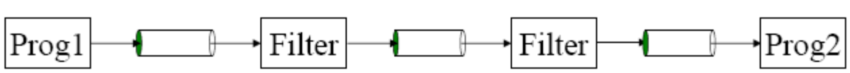
Both provide abstraction of an "ordered stream of bytes"

Pipes

- Provides an interprocess communication channel



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

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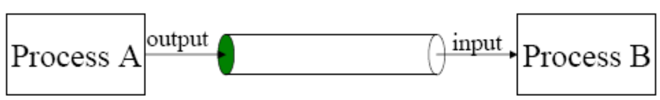
Creating a Pipe



- 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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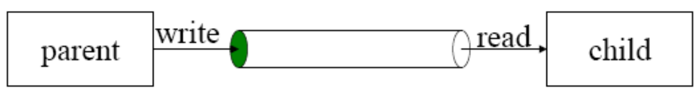
Pipe Example

```
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

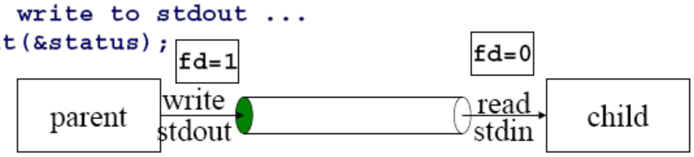


Pipes and Stdio

```
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

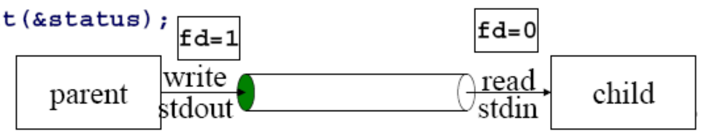


Pipes and Exec

```
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 (`if (pid == 0) {`)

invokes a new program (`execl(...);`)



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