System-Level I/O

15-213/14-513/15-513: Introduction to Computer Systems
20th Lecture, July 18, 2023

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System level: below standard level

```c
#include <stdio.h>

int main(void) {
    FILE *fp = fopen("output.txt", "w");
    if (!fp) {
        perror("output.txt");
        return 1;
    }
    fputs("baby shark (do doo dooo)\n", fp);
    if (fclose(fp)) {
        perror("output.txt");
        return 1;
    }
    return 0;
}
```

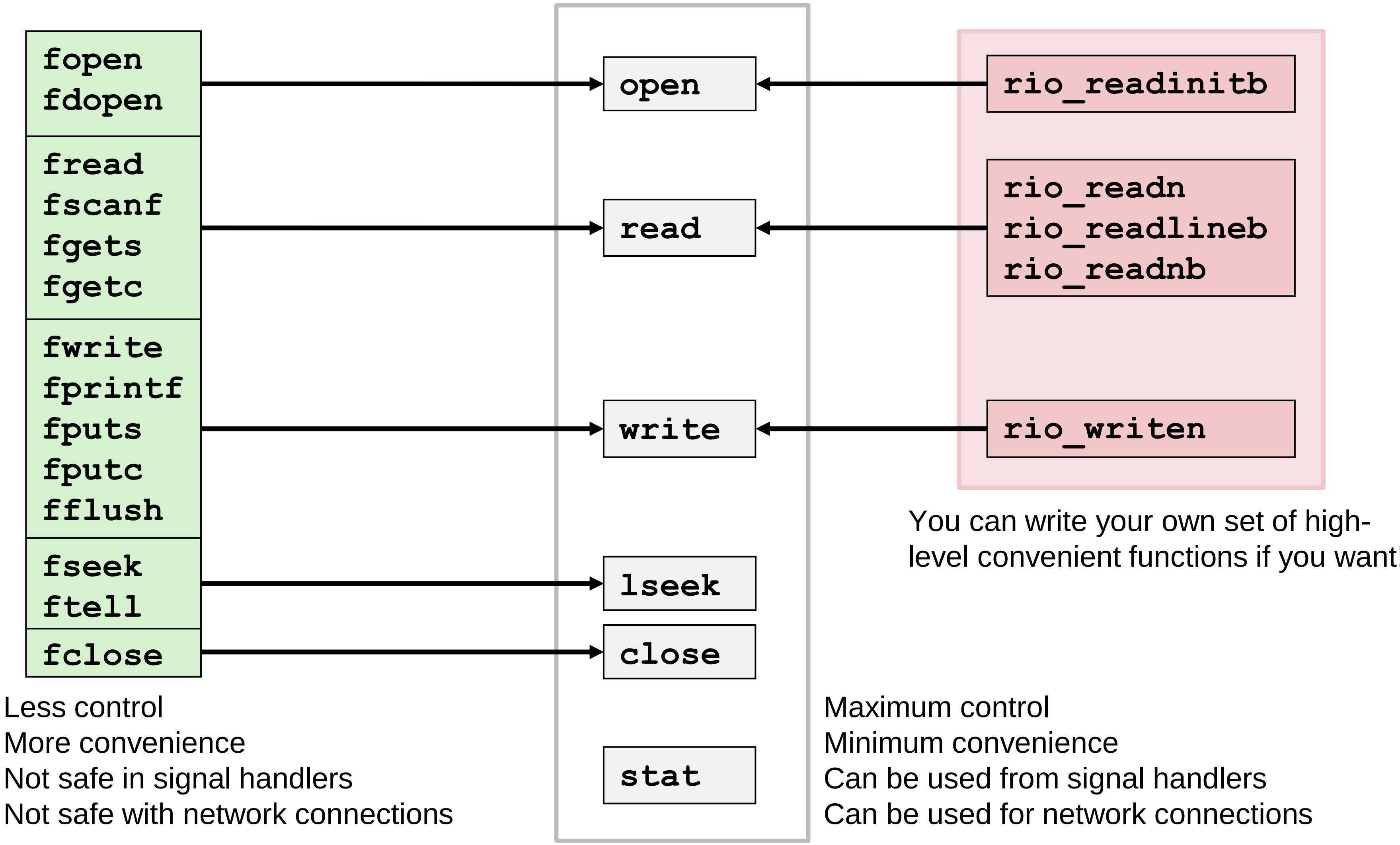
```c
FILE *fopen(const char *fname,
            const char *mode) {
    int fd = open(fname,
                  __mode2flags(mode),
                  DEFFILEPERMS);
    if (fd == -1) {
        return NULL;
    }
    return fdopen(fd, mode);
}
```

```c
int fputs(const char *s, FILE *fp) {
    size_t n = strlen(s);
    while (n > 0) {
        ssize_t written =
            write(fp->fd, s, n);
        if (written < 0) return EOF;
        n -= written;
        s += written;
    }
    return 0;
}
```

```c
int fclose(FILE *fp) {
    int rv = close(fp->fd);
    __ffree(fp);
    return rv;
}
```

```
.globl close
close:
    mov $3, %eax
    syscall
    cmp $-4096, %rax
    jae __syscall_error
    ret
```

Why do we have two sets?



Today

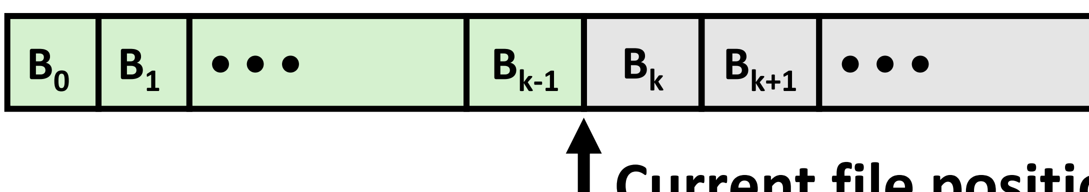
- **Unix I/O**
- **Standard I/O**
- **Which I/O when**
- **Metadata, sharing, and redirection**

Unix I/O Overview

- A *file* is a sequence of bytes:
  - $B_0, B_1, \ldots, B_k, \ldots, B_{m-1}$
- Cool fact: All I/O devices are represented as files:
  - `/dev/sda2` (disk partition)
  - `/dev/tty2` (terminal)
  - `/dev/null` (discard all writes / read empty file)
- Cool fact: Kernel data structures are exposed as files
  - `cat /proc/$$/status`
  - `ls -l /proc/$$/fd/`
  - `ls –RC /sys/devices | less`

Unix I/O Overview

- **Kernel offers a set of basic operations for all files**
  - Opening and closing files
    - `open()` and `close()`
  - Reading and writing a file
    - `read()` and `write()`
  - Look up information about a file (size, type, last modification time, …)
    - `stat()`, `lstat()`, `fstat()`
  - Changing the ***current file position*** (seek)
    - indicates next offset into file to read or write
    - `lseek()`



Current file position = k

(*in between* bytes k-1 and k)

File Types

- **Each file has a *type* indicating its role in the system**
  - *Regular file:* Stores arbitrary data
  - *Directory:* Index for a related group of files
  - *Socket:* For communicating with a process on another machine

- **Other file types beyond our scope**
  - *Named pipes (FIFOs)*
  - *Symbolic links*
  - *Character and block devices*

Regular Files

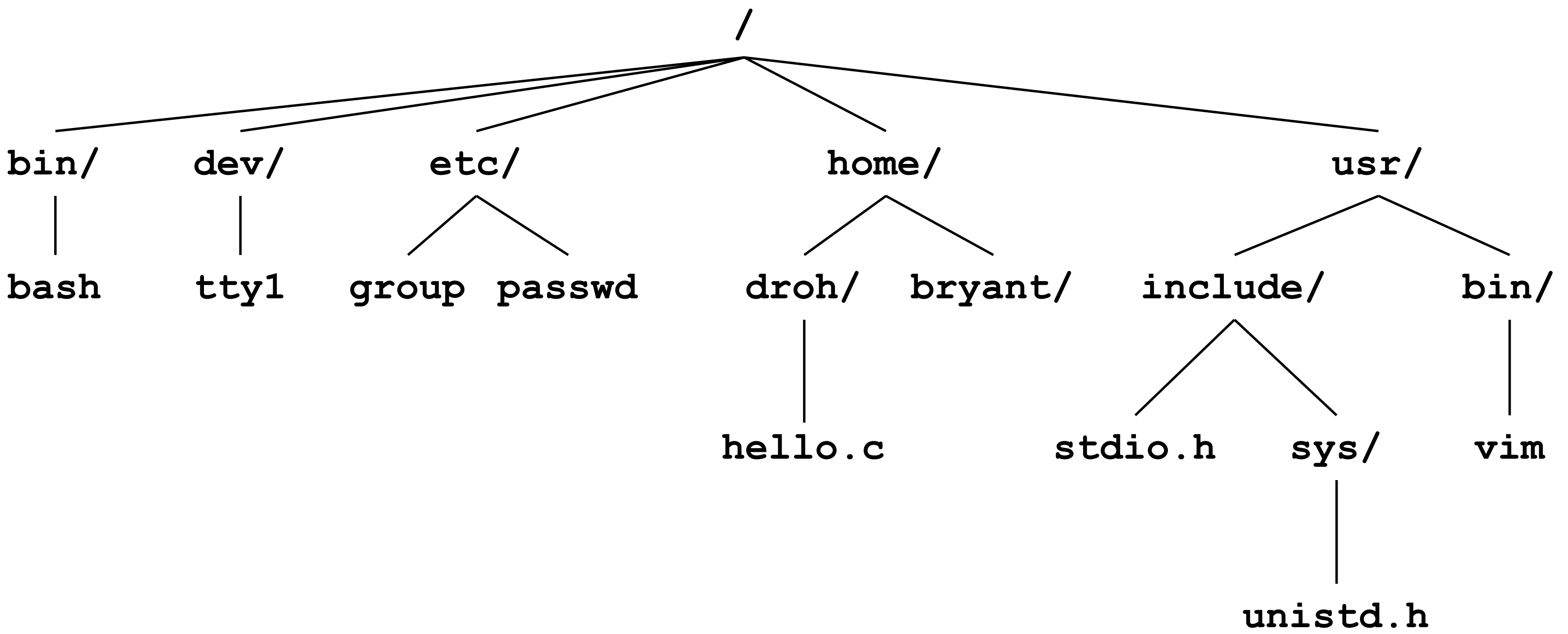
- **A regular file contains arbitrary data**
- **Applications often distinguish between *text* and *binary files***
  - Text files contain human-readable text
  - Binary files are everything else (object files, JPEG images, …)
  - Kernel doesn't care! It's all just bytes!
- **Text file is sequence of *text lines***
  - Text line is sequence of characters terminated (not separated!) by *end of line indicator*
  - Characters are defined by a *text encoding* (ASCII, UTF-8, EUC-JP, …)
- **End of line (EOL) indicators:**
  - All "Unix": Single byte **`0x0A`**
    - line feed (LF)
  - DOS, Windows: Two bytes **`0x0D 0x0A`**
    - Carriage return (CR) followed by line feed (LF)
    - Also used by many Internet protocols
  - C library translates to '\n'

Directories

- **Directory consists of an array of *entries* (also called *links*)**
  - Each entry maps a *filename* to a file
- **Each directory contains at least two entries**
  - `.` (dot) maps to the directory itself
  - `..` (dot dot) maps to *the parent directory* in the *directory hierarchy* (next slide)
- **Commands for manipulating directories**
  - **`mkdir`**: create empty directory
  - **`ls`**: view directory contents
  - **`rmdir`**: delete empty directory

Directory Hierarchy

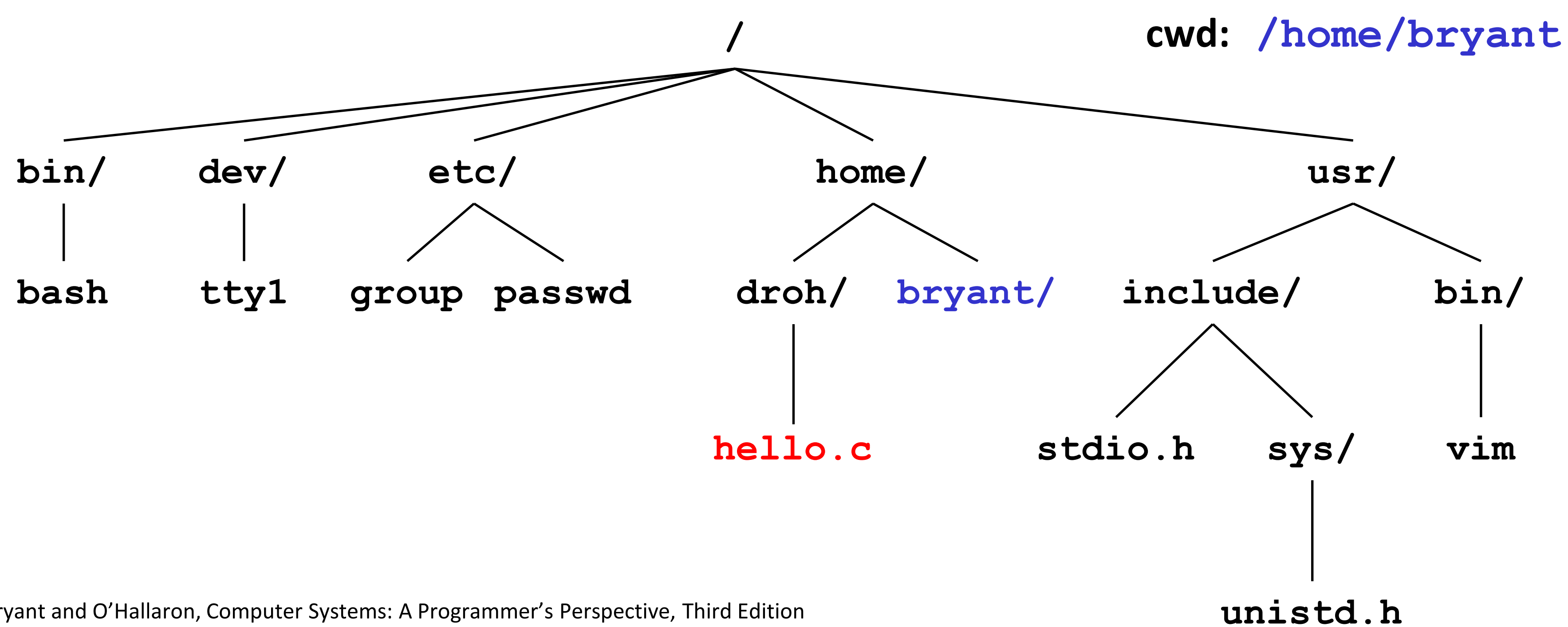
- All files are organized as a hierarchy anchored by root directory named / (slash)



- Kernel maintains *current working directory (cwd)* for each process
  - Modified using the **`cd`** command

Pathnames

- **Locations of files in the hierarchy denoted by *pathnames***
  - *Absolute pathname* starts with '/' and denotes path from root
    - **`/home/droh/hello.c`**
  - *Relative pathname* denotes path from current working directory
    - **`../droh/hello.c`**



Opening Files

- **Opening a file informs the kernel that you are getting ready to access that file**

```
int fd;   /* file descriptor */

if ((fd = open("/etc/hosts", O_RDONLY)) < 0) {
   perror("open");
   exit(1);
}
```

- **Returns a small identifying integer *file descriptor***
  - `fd == -1` indicates that an error occurred
- **Each process begins life with three open files**
  - 0: standard input (stdin)
  - 1: standard output (stdout)
  - 2: standard error (stderr)
  - These could be files, pipes, your terminal, or even a network connection!

Lots of ways to call `open`

Open an existing file:

`open(path, flags)`

`flags` must include exactly one of:

`O_RDONLY`	Only want to read from file
`O_WRONLY`	Only want to write to file
`O_RDWR`	Want to do both

Flags may also include (use | to combine)

`O_APPEND`	All writes go to the very end
`O_TRUNC`	Delete existing contents if any
`O_CLOEXEC`	Close this file if execve() is called

Open or create a file:

`open(path, flags, mode)`

`flags` must include

`O_CREAT`	Create the file if it doesn't exist

and exactly one of:

`O_WRONLY`	Only want to write to file
`O_RDWR`	Want to write and read

and maybe also some of:

`O_EXCL`	Fail if file does exist
`O_APPEND`	All writes go to the very end
`O_TRUNC`	Delete existing contents if any
`O_CLOEXEC`	Close this file if execve() is called

(and many more… consult the open() manpage)

The third argument to open

- **Yes, open takes either two or three arguments**
  - Bet you thought you couldn't do that in C
  - Look through `/usr/include/fcntl.h` and try to figure out how it's done
  - Third argument must be present when O_CREAT appears in second argument; ignored otherwise
- **Third argument gives *default access permissions* for newly created files**
  - Modified by *umask* setting (see `man umask`)
  - Use DEFFILEMODE (from `sys/stat.h`) unless you have a specific reason to want something else
  - More explanation:
    - https://linuxfoundation.org/blog/classic-sysadmin-understanding-linux-file-permissions/
    - https://linuxcommand.org/lc3_lts0090.php
    - https://devconnected.com/linux-file-permissions-complete-guide/

Closing Files

- **Closing a file informs the kernel that you are finished accessing that file**

```
if (close(fd) < 0) {
   fprintf(stderr, "%s: write error: %s",
           filename, strerror(errno));
   exit(1);
}
```

- **Take care not to close any file more than once**
  - Same as not calling free() twice on the same pointer

- **Closing a file can fail!**
  - Well, not exactly *fail*—the file is still closed
  - The OS is taking this opportunity to report a *delayed error* from a previous write operation
  - You might silently lose data if you don't check!

Reading Files

- **Reading a file copies bytes from the current file position to memory, and then updates file position**

```
char buf[512];
int fd;       /* file descriptor */
int nbytes;   /* number of bytes read */

/* Open file fd ...  */
/* Then read up to 512 bytes from file fd */
if ((nbytes = read(fd, buf, sizeof(buf))) < 0) {
   perror("read");
   exit(1);
}
```

- **Returns number of bytes read from file `fd` into `buf`**
  - Return type **`ssize_t`** is signed integer
  - **`nbytes < 0`** indicates that an error occurred
  - ***Short counts*** (**`nbytes < sizeof(buf)`**) are possible and are not errors!

Writing Files

- **Writing a file copies bytes from memory to the current file position, and then updates current file position**

```
char buf[512];
int fd;         /* file descriptor */
int nbytes;     /* number of bytes read */

/* Open the file fd ... */
/* Then write up to 512 bytes from buf to file fd */
if ((nbytes = write(fd, buf, sizeof(buf)) < 0) {
   perror("write");
   exit(1);
}
```

- **Returns number of bytes written from `buf` to file `fd`**
  - **`nbytes < 0`** indicates that an error occurred
  - As with reads, short counts are possible and are not errors!

Simple Unix I/O example

- Copying stdin to stdout, one byte at a time

```
#include <unistd.h>

int main(void) {
    char c;
    while(read(STDIN_FILENO, &c, 1) != 0)
        write(STDOUT_FILENO, &c, 1);
    return 0;
}
```

Always check return codes from system calls!

Simple Unix I/O example

- Copying stdin to stdout, one byte at a time

```
#include <unistd.h>
#include <stdio.h>

int main(void) {
    char c;
    for (;;) {
        ssize_t nread = read(STDIN_FILENO, &c, 1);
        if (nread == 0) {
            return 0;
        } else if (nread < 0) {
            perror("stdin");
            return 1;
        }
        if (write(STDOUT_FILENO, &c, 1) < 1) {
            perror("stdout: write error");
            return 1;
        }
    }
}
```

Simple Unix I/O example

- Copying stdin to stdout, one byte at a time

```
#include "csapp.h"

int main(void) {
    char c;
    while (Read(STDIN_FILENO, &c, 1) != 0) {
        Write(STDOUT_FILENO, &c, 1);
    }
    return 0;
}
```

"Stevens wrappers" make things shorter…

but they don't let you recover *from errors*

On Short Counts

- **Short counts can occur in these situations:**
  - Encountering (end-of-file) EOF on reads
  - Reading text lines from a terminal
  - Reading and writing network sockets, pipes, etc.

- **Short counts never occur in these situations:**
  - Reading from disk files (except for EOF)
  - Writing to disk files

- **Best practice is to always allow for short counts.**

Do activity 1 now
(“Unix I/O” section)

http://www.cs.cmu.edu/~213/activities/system-io.pdf
http://www.cs.cmu.edu/~213/activities/system-io.tar

Today

- Unix I/O
- **Standard I/O**
- Which I/O when
- Metadata, sharing, and redirection

Standard I/O Functions

- **The C standard library (`libc.so`) contains a collection of higher-level *standard I/O* functions**
  - Documented in Appendix B of K&R

- **Examples of standard I/O functions:**
  - Opening and closing files (**`fopen`** and **`fclose`**)
  - Reading and writing bytes (**`fread`** and **`fwrite`**)
  - Reading and writing text lines (**`fgets`** and **`fputs`**)
  - Formatted reading and writing (**`fscanf`** and **`fprintf`**)

Standard I/O Streams

- **Standard I/O models open files as *streams***
  - Abstraction for a file descriptor and a buffer in memory

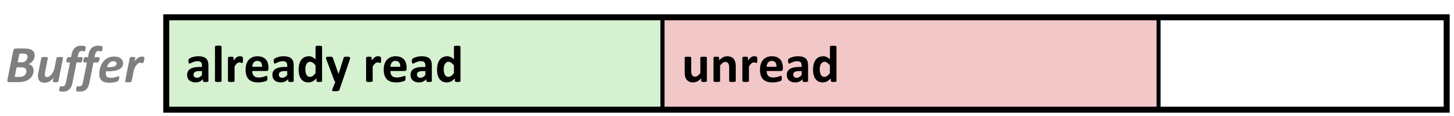
- **C programs begin life with three open streams (defined in `stdio.h`)**
  - **`stdin`** (standard input)
  - **`stdout`** (standard output)
  - **`stderr`** (standard error)

```
#include <stdio.h>
extern FILE *stdin;  /* standard input  (descriptor 0) */
extern FILE *stdout; /* standard output (descriptor 1) */
extern FILE *stderr; /* standard error  (descriptor 2) */

int main() {
    fprintf(stdout, "Hello, world\n");
}
```

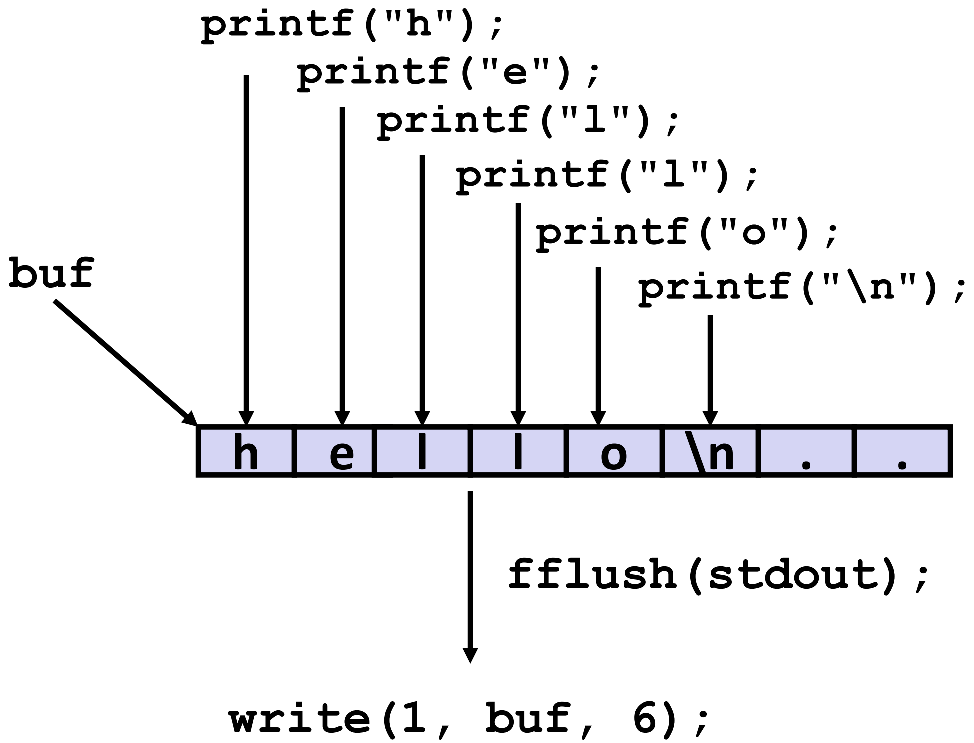
Buffered I/O: Motivation

- **Applications often read/write one character at a time**
  - **`getc, putc, ungetc`**
  - **`gets, fgets`**
    - Read line of text one character at a time, stopping at newline
- **Implementing as Unix I/O calls expensive**
  - **`read`** and **`write`** require Unix kernel calls
    - > 10,000 clock cycles
- **Solution: Buffered read**
  - Use Unix **`read`** to grab block of bytes
  - User input functions take one byte at a time from buffer
    - Refill buffer when empty



Buffering in Standard I/O

- Standard I/O functions use buffered I/O



- Buffer flushed to output fd on "\n", call to `fflush` or `exit`, or return from `main`.

Standard I/O Buffering in Action

- You can see this buffering in action for yourself, using the always fascinating Linux `strace` program:

```
#include <stdio.h>

int main()
{
    printf("h");
    printf("e");
    printf("l");
    printf("l");
    printf("o");
    printf("\n");
    fflush(stdout);
    exit(0);
}
```

```
linux> strace ./hello
execve("./hello", ["hello"], [/* ... */]).
...
write(1, "hello\n", 6)                    = 6
...
exit_group(0)                             = ?
```

Do activity 2 now
(“Standard I/O” and
“Buffering and Performance”)

Today

- Unix I/O
- Standard I/O
- **Which I/O when**
- Metadata, sharing, and redirection

Pros and Cons of Unix I/O

Pros

- Unix I/O is the most general form of I/O
  - All other I/O packages are implemented using Unix I/O functions
- Unix I/O provides functions for accessing file metadata
- Unix I/O functions are async-signal-safe and can be used safely in signal handlers

Cons

- Dealing with short counts is tricky and error prone
- Efficient reading of text lines requires some form of buffering, also tricky and error prone

Pros and Cons of Standard I/O

- **Pros:**
  - Buffering increases efficiency by decreasing the number of **`read`** and **`write`** system calls
  - Short counts are handled automatically
- **Cons:**
  - Provides no function for accessing file metadata
  - Standard I/O functions are not async-signal-safe, and not appropriate for signal handlers
  - Standard I/O is not appropriate for input and output on network sockets
    - There are poorly documented restrictions on streams that interact badly with restrictions on sockets (CS:APP3e, Sec 10.11)

Choosing I/O Functions

- **General rule: use the highest-level I/O functions you can**
  - Many C programmers are able to do all of their work using the standard I/O functions
  - But, be sure to understand the functions you use!

- **When to use standard I/O**
  - When working with "ordinary" files
- **When to use raw Unix I/O**
  - *Inside signal handlers, because Unix I/O is async-signal-safe*
  - *When you are reading and writing network sockets*
    - Libraries dedicated to buffered network I/O make this easier
    - CS:APP `rio_*` functions; libevent, libuv, …
  - In rare cases when you need absolute highest performance

Aside: Working with Binary Files

- **Functions you should *never* use on binary files**
  - **Text-oriented I/O:** such as **`fgets, scanf, rio_readlineb`**
    - Interpret EOL characters.
    - Use functions like **`rio_readn`** or **`rio_readnb`** instead
  - **String functions**
    - **`strlen, strcpy, strcat`**
    - Interprets byte value 0 (end of string) as special

Today

- Unix I/O
- Standard I/O
- Which I/O when
- **Metadata, sharing, and redirection**

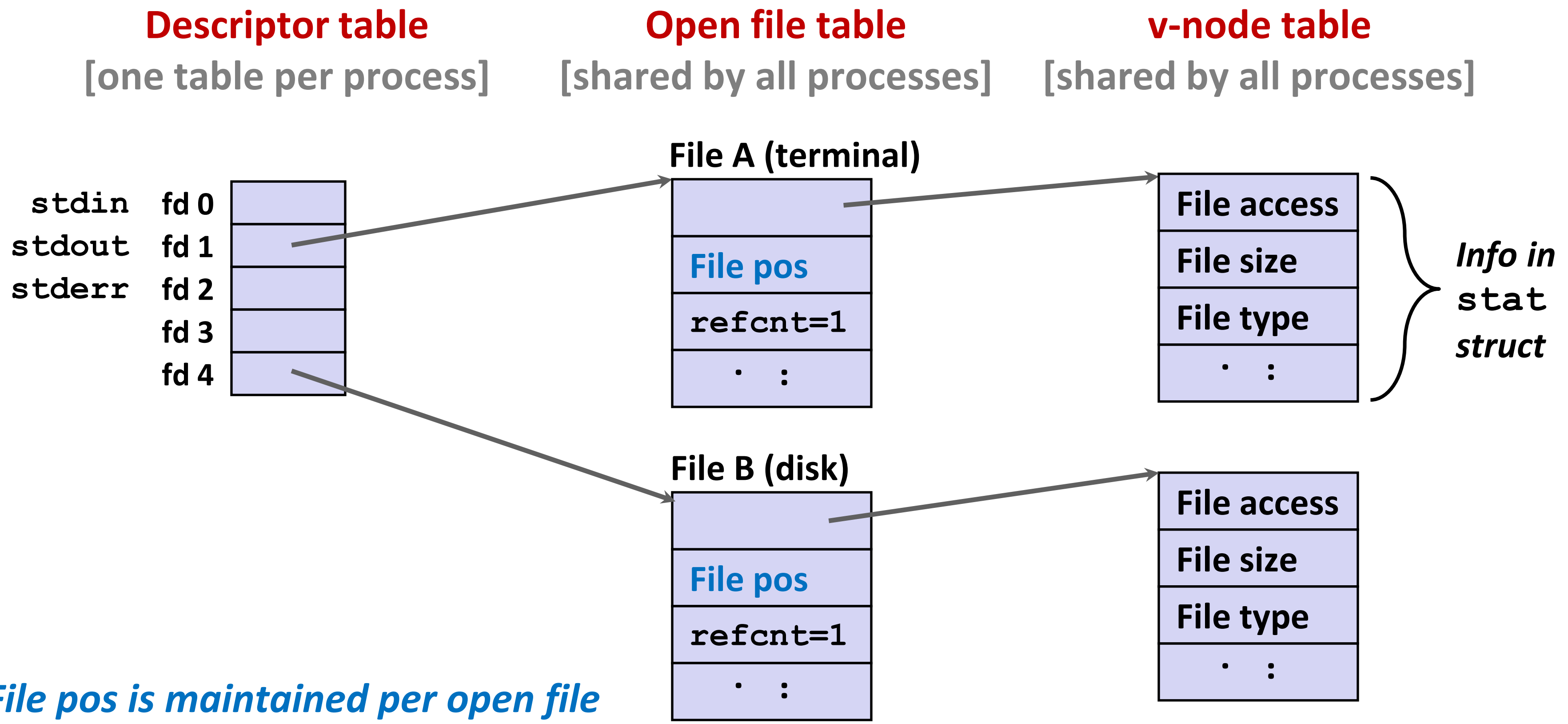
File Metadata

- *Metadata* is data about data, in this case file data
- Per-file metadata maintained by kernel
  - accessed by users with the **stat** and **fstat** functions

```
/* Metadata returned by the stat and fstat functions */
struct stat {
    dev_t         st_dev;      /* Device */
    ino_t         st_ino;      /* inode */
    mode_t        st_mode;     /* Protection and file type */
    nlink_t       st_nlink;    /* Number of hard links */
    uid_t         st_uid;      /* User ID of owner */
    gid_t         st_gid;      /* Group ID of owner */
    dev_t         st_rdev;     /* Device type (if inode device) */
    off_t         st_size;     /* Total size, in bytes */
    unsigned long st_blksize;  /* Blocksize for filesystem I/O */
    unsigned long st_blocks;   /* Number of blocks allocated */
    time_t        st_atime;    /* Time of last access */
    time_t        st_mtime;    /* Time of last modification */
    time_t        st_ctime;    /* Time of last change */
};
```

How the Unix Kernel Represents Open Files

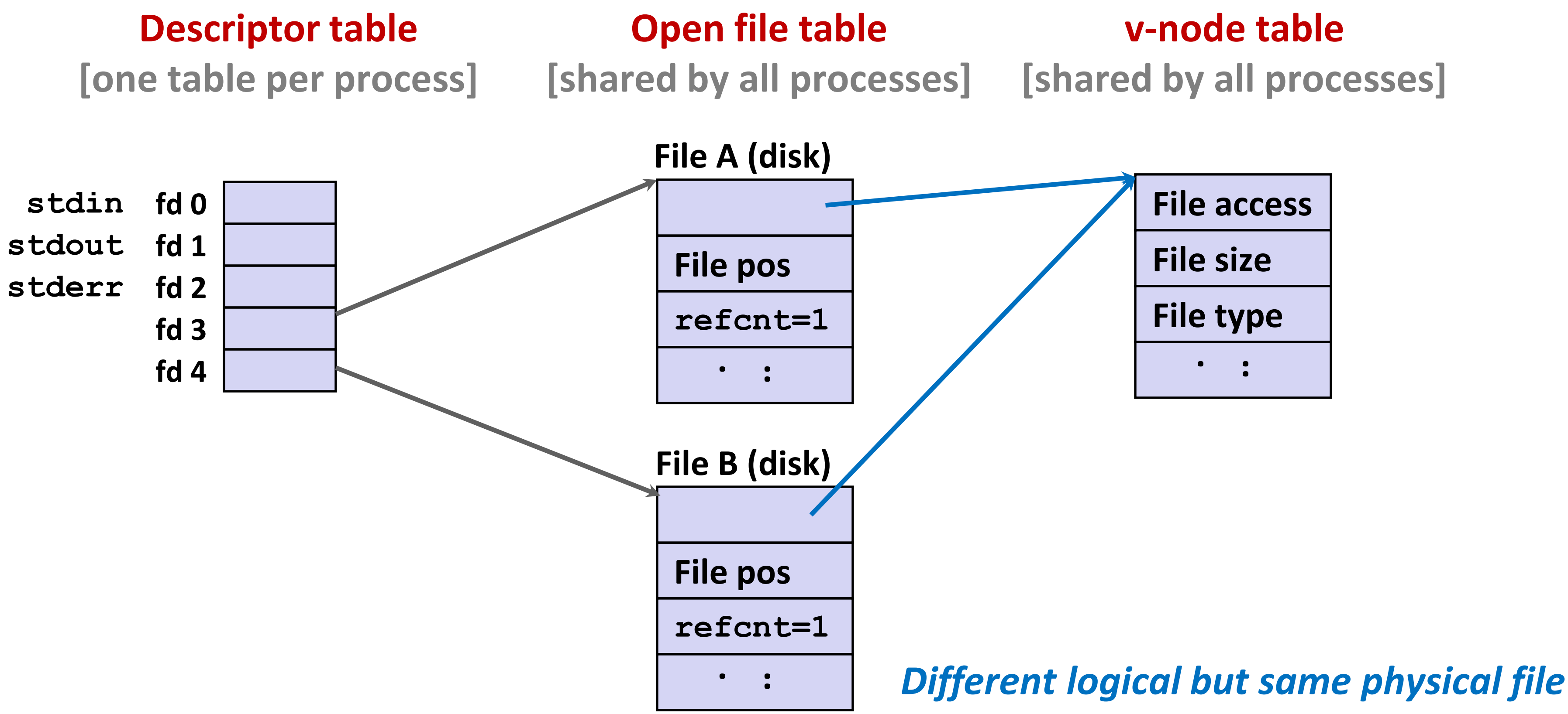
- Two descriptors referencing two distinct open files. Descriptor 1 (stdout) points to terminal, and descriptor 4 points to open disk file



File pos is maintained per open file

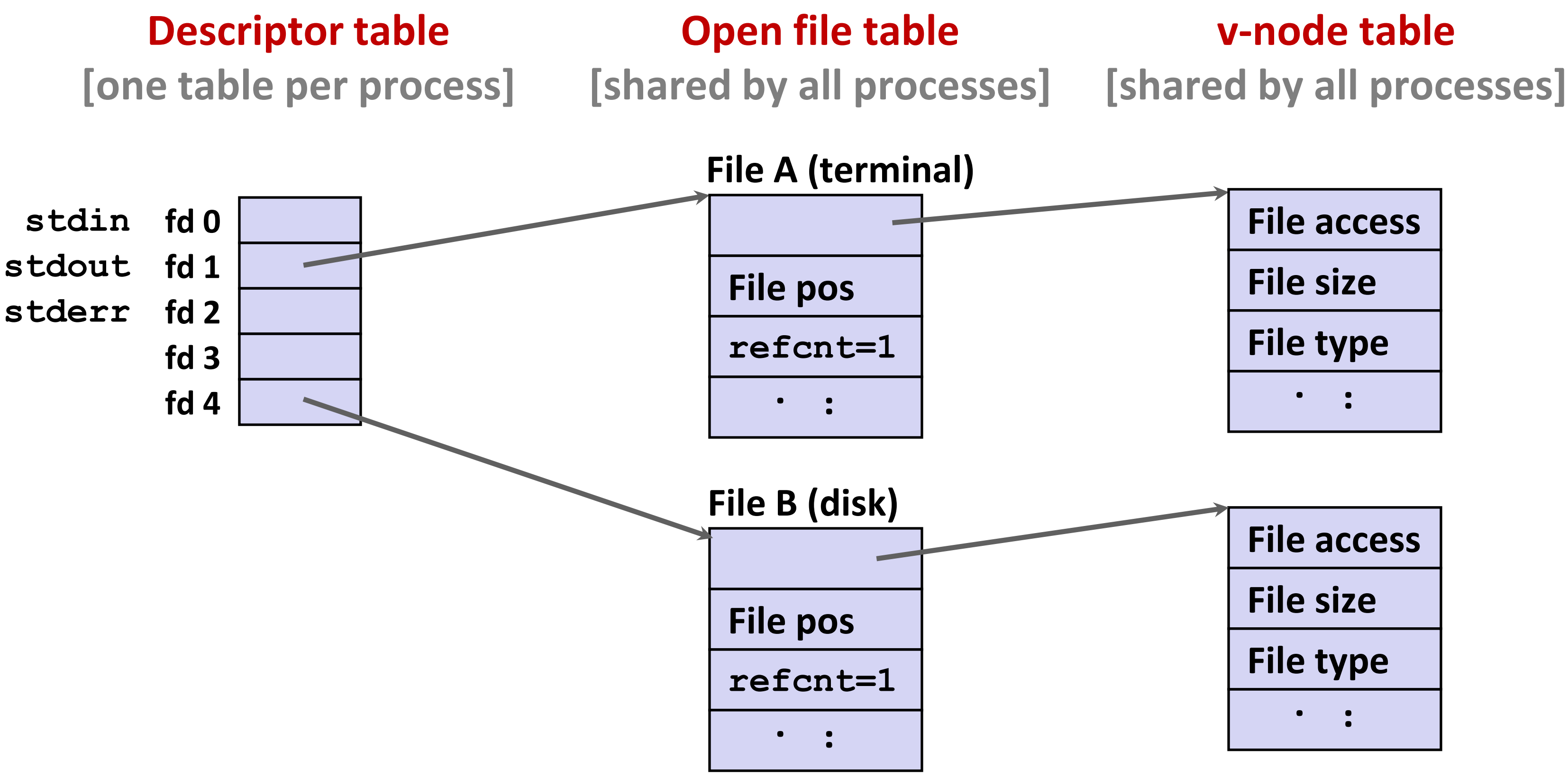
File Sharing

- **Two distinct descriptors sharing the same disk file through two distinct open file table entries**
  - E.g., Calling **`open`** twice with the same **`filename`** argument



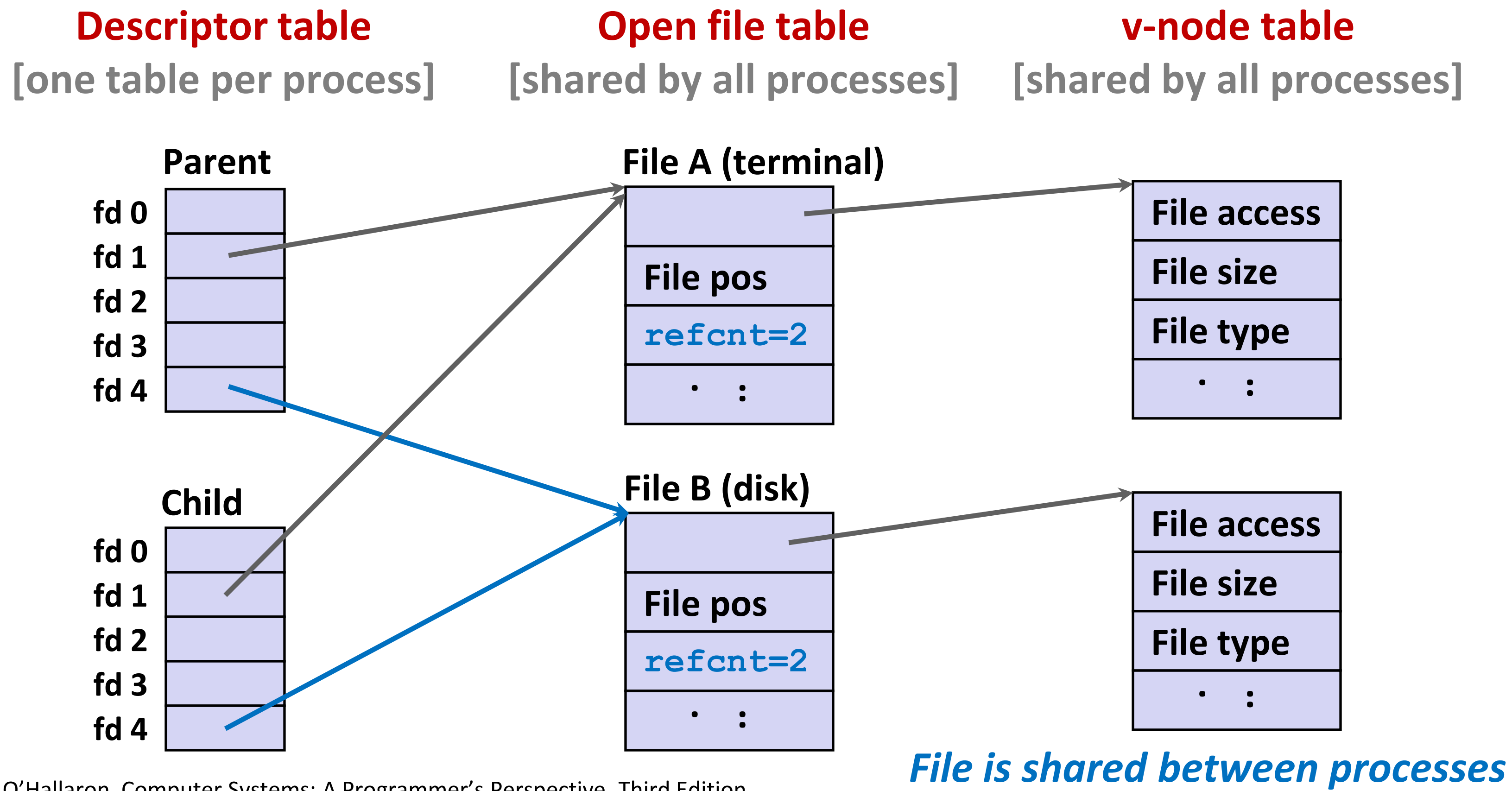
How Processes Share Files: `fork`

- A child process inherits its parent's open files
  - Note: situation unchanged by **`exec`** functions (use **`fcntl`** to change)
- *Before* **`fork`** call:



How Processes Share Files: `fork`

- **A child process inherits its parent's open files**
- ***After*** **`fork`:**
  - Child's table same as parent's, and +1 to each refcnt



I/O Redirection

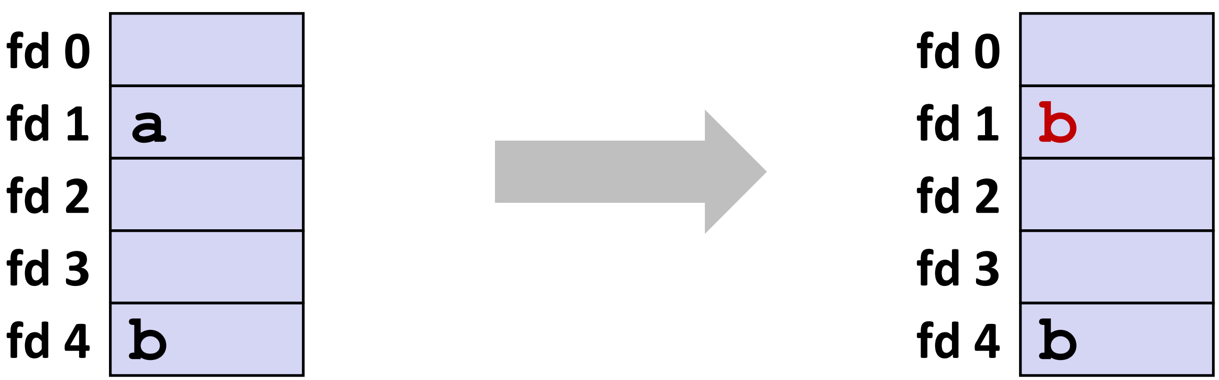
- **Question: How does a shell implement I/O redirection?**

```
linux> ls > foo.txt
```

- **Answer: By calling the `dup2(oldfd, newfd)` function**
  - Copies (per-process) descriptor table entry **`oldfd`** to entry **`newfd`**

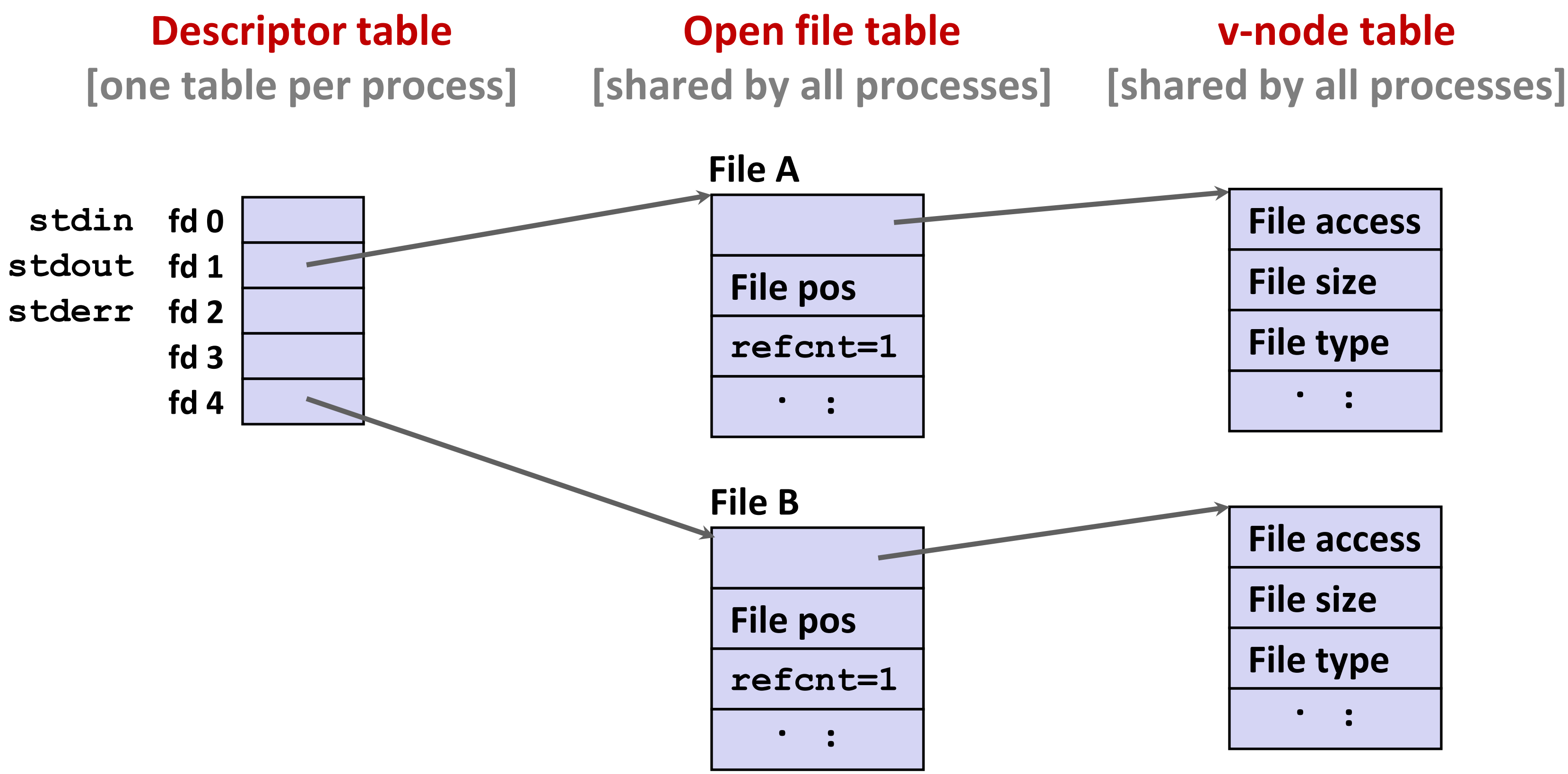
Descriptor table
before **`dup2(4,1)`**

Descriptor table
after **`dup2(4,1)`**



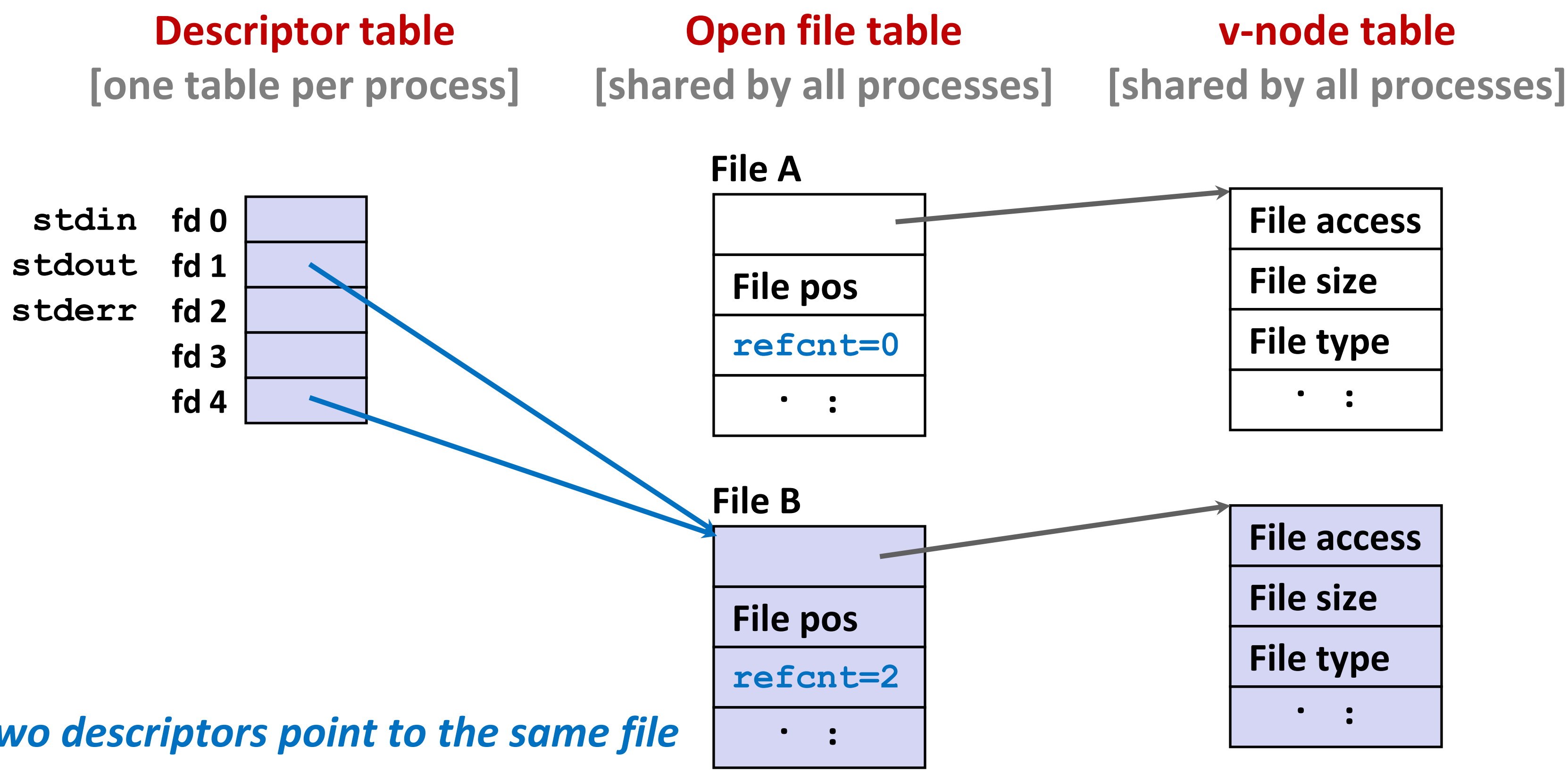
I/O Redirection Example

- **Step #1: open file to which stdout should be redirected**
  - Happens in child executing shell code, before **`exec`**



I/O Redirection Example (cont.)

- **Step #2: call `dup2(4,1)`**
  - cause fd=1 (stdout) to refer to disk file pointed at by fd=4



Two descriptors point to the same file

Warm-Up: I/O and Redirection Example

```
#include "csapp.h"
int main(int argc, char *argv[])
{
    int fd1, fd2, fd3;
    char c1, c2, c3;
    char *fname = argv[1];
    fd1 = open(fname, O_RDONLY, 0);
    fd2 = open(fname, O_RDONLY, 0);
    fd3 = open(fname, O_RDONLY, 0);
    dup2(fd2, fd3);
    read(fd1, &c1, 1);
    read(fd2, &c2, 1);
    read(fd3, &c3, 1);
    printf("c1 = %c, c2 = %c, c3 = %c\n", c1, c2, c3);
    return 0;
}                                              ffiles1.c
```

- **What would this program print for file containing "`abcde`"?**

Warm-Up: I/O and Redirection Example

```
#include "csapp.h"
int main(int argc, char *argv[])
{
    int fd1, fd2, fd3;
    char c1, c2, c3;
    char *fname = argv[1];
    fd1 = open(fname, O_RDONLY, 0);
    fd2 = open(fname, O_RDONLY, 0);
    fd3 = open(fname, O_RDONLY, 0);
    dup2(fd2, fd3);
    read(fd1, &c1, 1);
    read(fd2, &c2, 1);
    read(fd3, &c3, 1);
    printf("c1 = %c, c2 = %c, c3 = %c\n", c1, c2, c3);
    return 0;
}
```

ffiles1.c

```
c1 = a, c2 = a, c3 = b
```

```
dup2(oldfd, newfd)
```

- What would this program print for file containing “abcde”?

Master Class: Process Control and I/O

```
#include "csapp.h"
int main(int argc, char *argv[])
{
    int fd1;
    int s = getpid() & 0x1;
    char c1, c2;
    char *fname = argv[1];
    fd1 = open(fname, O_RDONLY, 0);
    read(fd1, &c1, 1);
    if (fork()) { /* Parent */
        sleep(s);
        read(fd1, &c2, 1);
        printf("Parent: c1 = %c, c2 = %c\n", c1, c2);
    } else { /* Child */
        sleep(1-s);
        read(fd1, &c2, 1);
        printf("Child: c1 = %c, c2 = %c\n", c1, c2);
    }
    return 0;
}
```

ffiles2.c

- **What would this program print for file containing "abcde"?**

Master Class: Process Control and I/O

```
#include "csapp.h"
int main(int argc, char *argv[])
{
    int fd1;
    int s = getpid() & 0x1;
    char c1, c2;
    char *fname = argv[1];
    fd1 = open(fname, O_RDONLY, 0);
    read(fd1, &c1, 1);
    if (fork()) { /* Parent */
        sleep(s);
        read(fd1, &c2, 1);
        printf("Parent: c1 = %c, c2 = %c\n", c1, c2);
    } else { /* Child */
        sleep(1-s);
        read(fd1, &c2, 1);
        printf("Child: c1 = %c, c2 = %c\n", c1, c2);
    }
    return 0;
}
```

ffiles2.c

```
Child: c1 = a, c2 = b
Parent: c1 = a, c2 = c
```

```
Parent: c1 = a, c2 = b
Child: c1 = a, c2 = c
```

Bonus: Which way does it go?

- What would this program print for file containing “abcde”?

Do activities
3 and 4 now
(and then we're done)

Supplementary slides

The RIO Package (213/CS:APP Package)

- **RIO is a set of wrappers that provide efficient and robust I/O in apps, such as network programs that are subject to short counts**
- **RIO provides two different kinds of functions**
  - Unbuffered input and output of binary data
    - `rio_readn` and `rio_writen`
  - Buffered input of text lines and binary data
    - `rio_readlineb` and `rio_readnb`
    - Buffered RIO routines are thread-safe and can be interleaved arbitrarily on the same descriptor
- **Download from http://csapp.cs.cmu.edu/3e/code.html**

  → `src/csapp.c` and `include/csapp.h`

Unbuffered RIO Input and Output

- Same interface as Unix **`read`** and **`write`**
- Especially useful for transferring data on network sockets

```
#include "csapp.h"

ssize_t rio_readn(int fd, void *usrbuf, size_t n);
ssize_t rio_writen(int fd, void *usrbuf, size_t n);
```

Return: num. bytes transferred if OK, 0 on EOF (`rio_readn` only), -1 on error

- **`rio_readn`** returns short count only if it encounters EOF
  - Only use it when you know how many bytes to read
- **`rio_writen`** never returns a short count
- Calls to **`rio_readn`** and **`rio_writen`** can be interleaved arbitrarily on the same descriptor

Buffered RIO Input Functions

- **Efficiently read text lines and binary data from a file partially cached in an internal memory buffer**

```
#include "csapp.h"

void rio_readinitb(rio_t *rp, int fd);

ssize_t rio_readlineb(rio_t *rp, void *usrbuf, size_t maxlen);
ssize_t rio_readnb(rio_t *rp, void *usrbuf, size_t n);
```

Return: num. bytes read if OK, 0 on EOF, -1 on error

- **`rio_readlineb`** reads a ***text line*** of up to **`maxlen`** bytes from file **`fd`** and stores the line in **`usrbuf`**
  - Especially useful for reading text lines from network sockets
- Stopping conditions
  - **`maxlen`** bytes read
  - EOF encountered
  - Newline (‘**`\n`**’) encountered

Buffered RIO Input Functions (cont.)

```
#include "csapp.h"

void rio_readinitb(rio_t *rp, int fd);

ssize_t rio_readlineb(rio_t *rp, void *usrbuf, size_t maxlen);
ssize_t rio_readnb(rio_t *rp, void *usrbuf, size_t n);
```

Return: num. bytes read if OK, 0 on EOF, -1 on error

- **`rio_readnb`** reads up to **`n`** ***bytes*** from file **`fd`**
- Stopping conditions
  - **`maxlen`** bytes read
  - EOF encountered
- Calls to **`rio_readlineb`** and **`rio_readnb`** can be interleaved arbitrarily on the same descriptor
  - **Warning:** Don't interleave with calls to **`rio_readn`**