System-Level I/O

15-213: Introduction to Computer Systems
21st Lecture, July 21, 2022

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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;
}
```

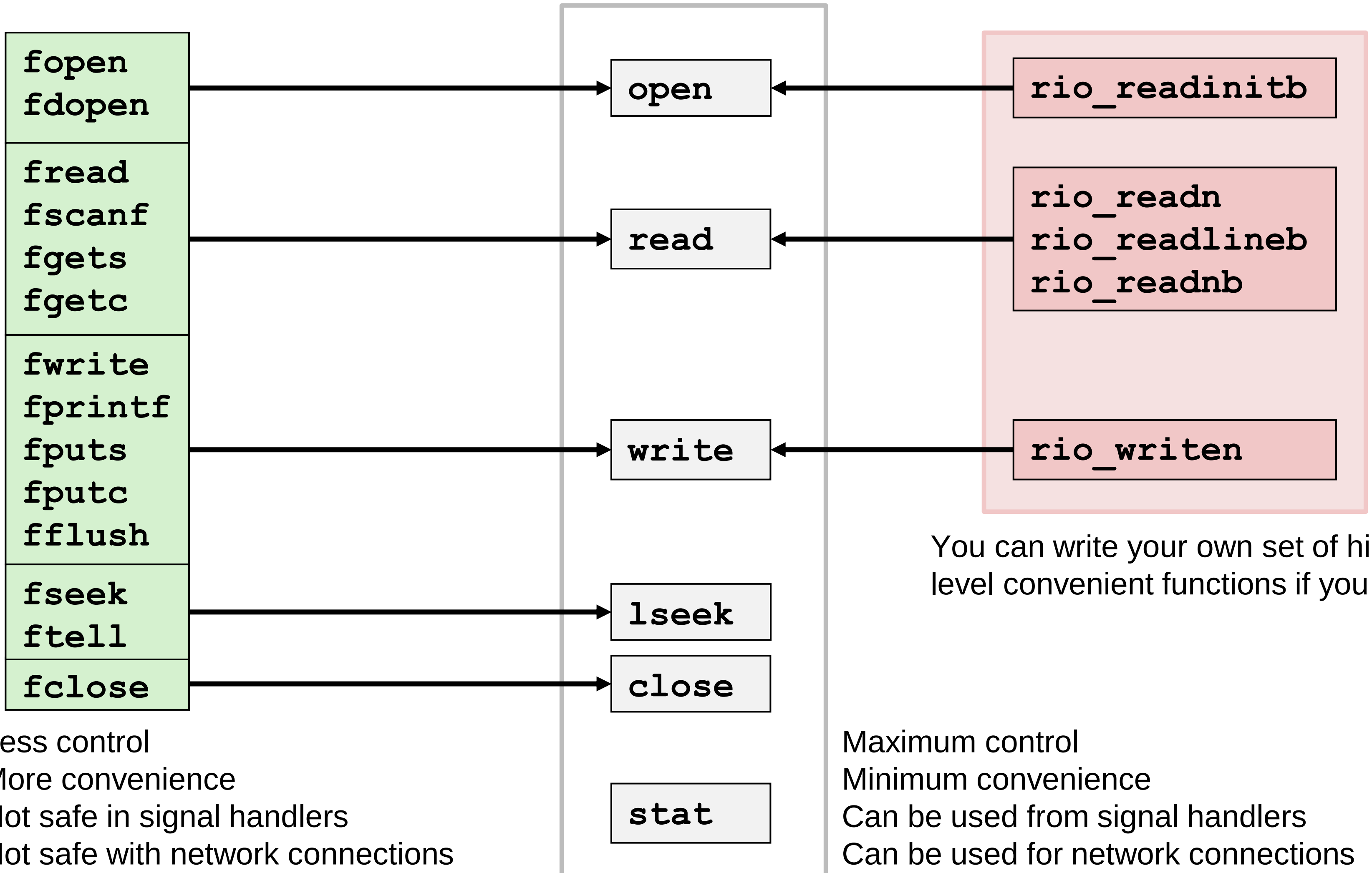
```c
FILE *fopen(const char *fname,
            const char *mode) {
    int fd = open(fname,
                  __mode2flags(mode),
                  DEFFILEPERMS);
    if (fd == -1) {
        return NULL;
    }
    return fdopen(fd, mode);
}
```

```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?



You can write your own set of high-level convenient functions if you want!

Less control
More convenience
Not safe in signal handlers
Not safe with network connections

Maximum control
Minimum convenience
Can be used from signal handlers
Can be used for network connections

Today

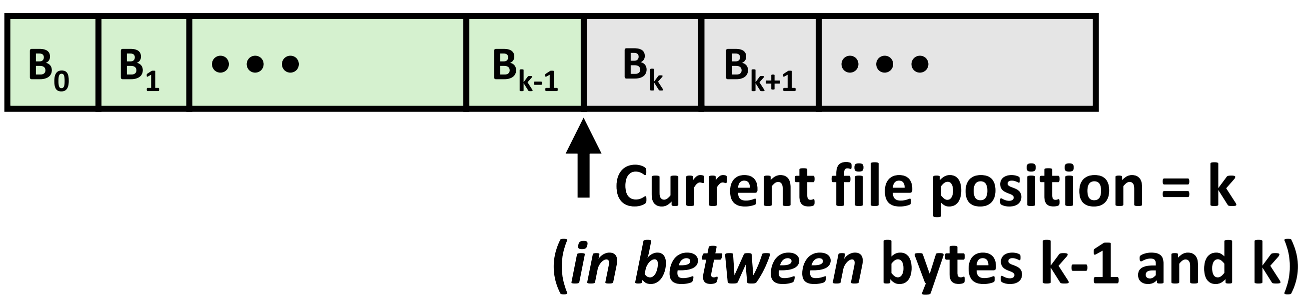
- **Unix I/O**
- Standard I/O
- Which I/O when
- Metadata, sharing, and redirection

Unix I/O Overview

- A *file* is a sequence of bytes:
  - $B_0, B_1, ... , B_k , ... , B_{m-1}$
- 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()`**



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

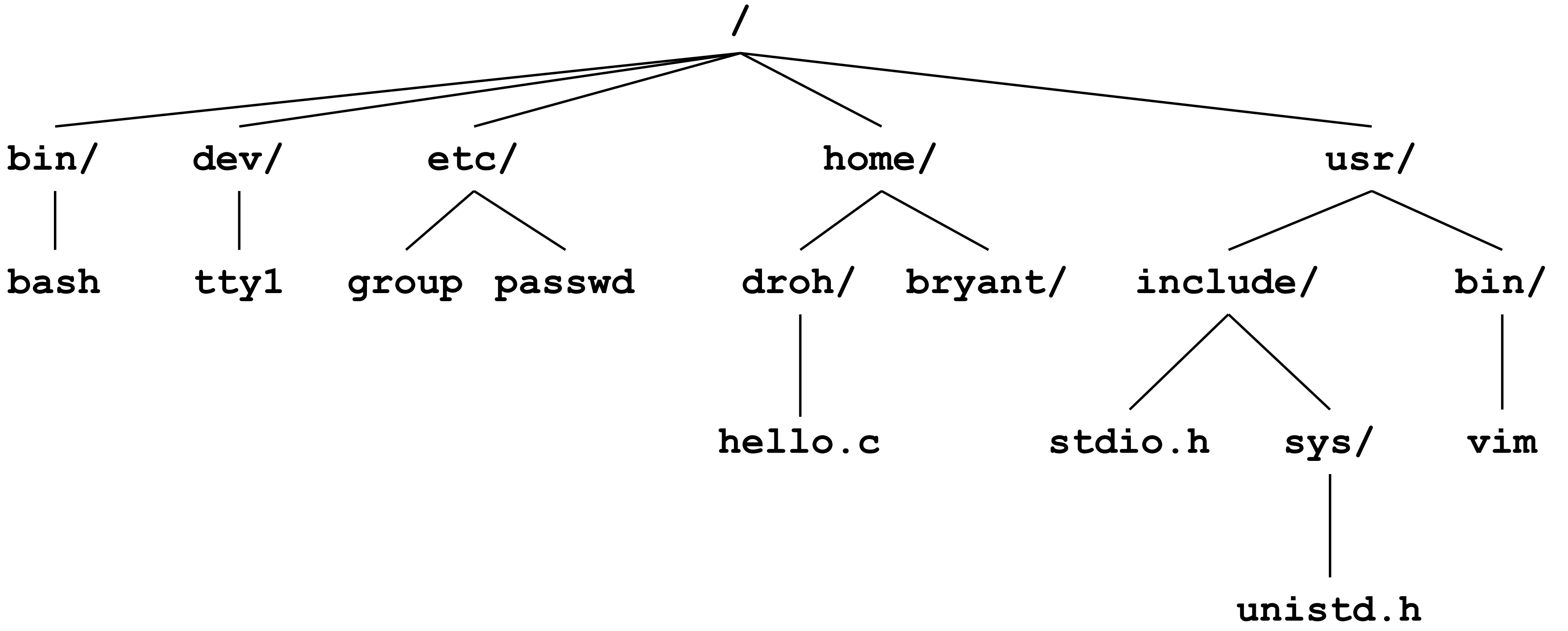
- **A regular file contains arbitrary data**
- **Applications often distinguish between *text* and *binary files***
  - Text files contain human-readable text
  - Binary files are everything else (object files, JPEG images, …)
  - Kernel doesn't care! It's all just bytes!
- **Text file is sequence of *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

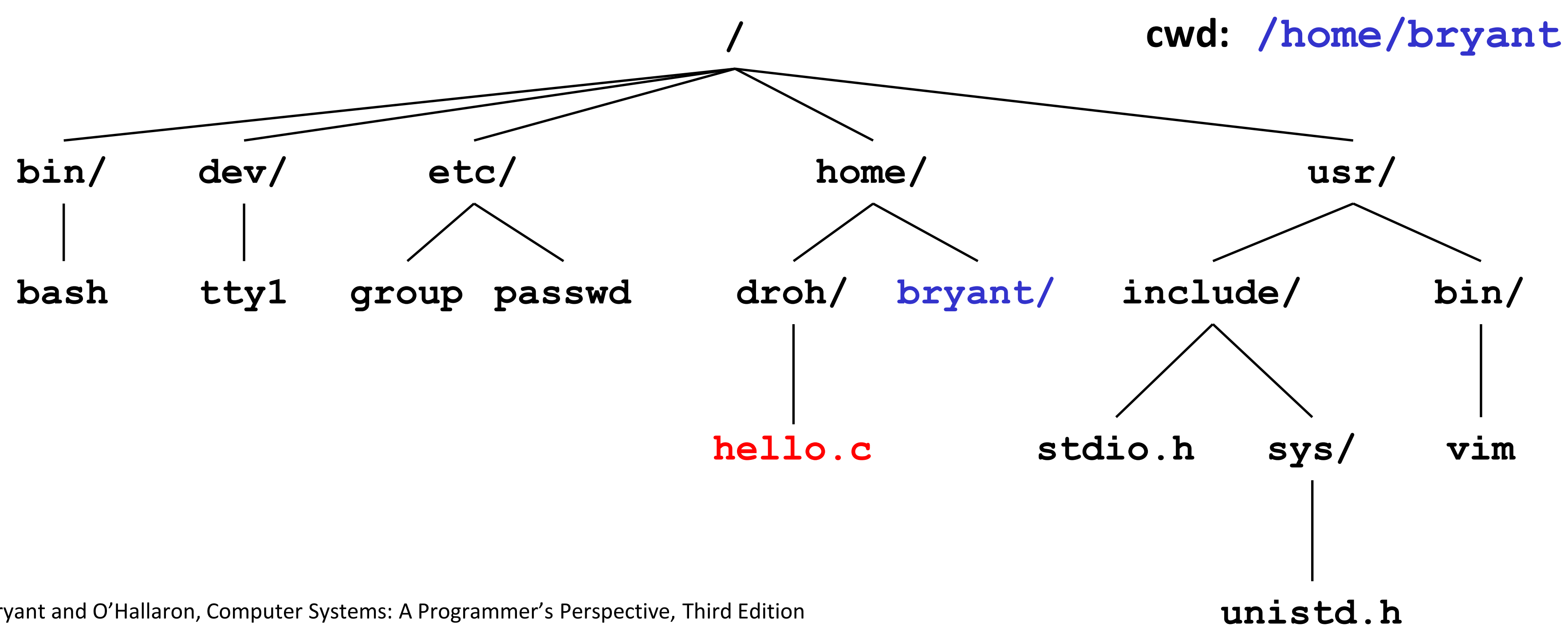
- All files are organized as a hierarchy anchored by root directory named / (slash)



- 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

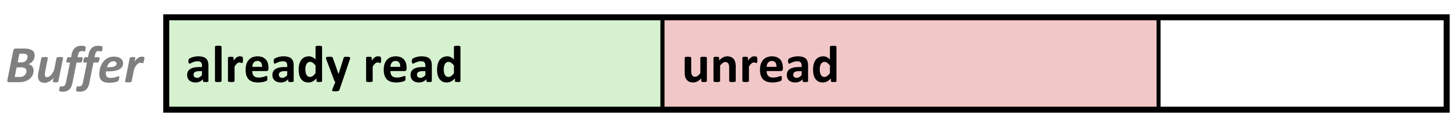
- **C programs begin life with three open streams (defined in `stdio.h`)**
  - `stdin` (standard input)
  - `stdout` (standard output)
  - `stderr` (standard error)

```
#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");
}
```

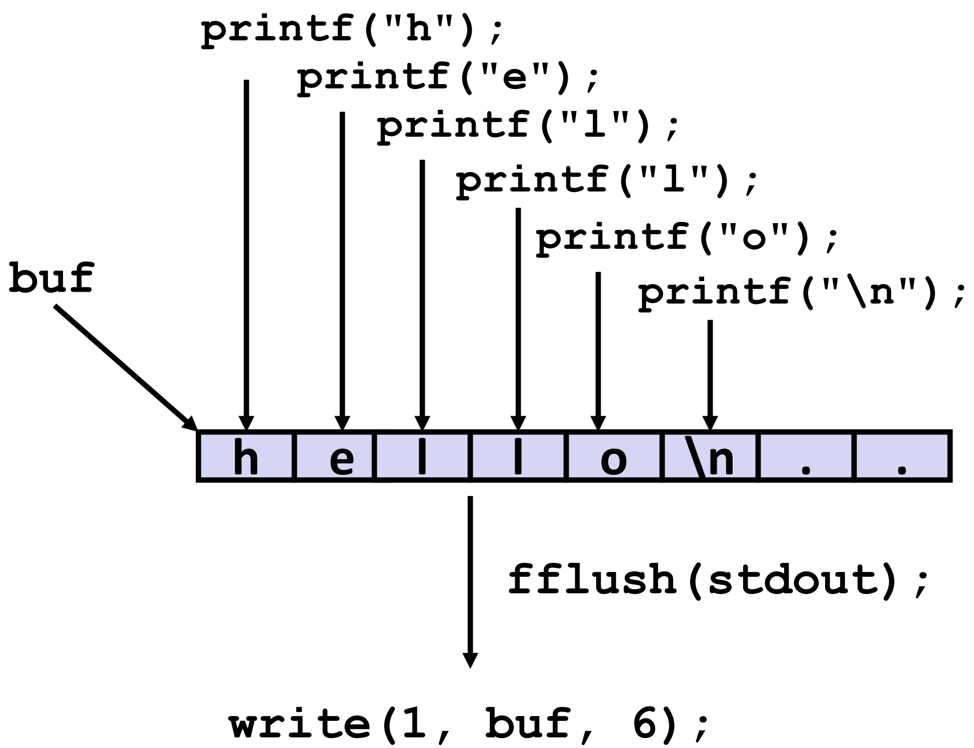
Buffered I/O: Motivation

- **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**

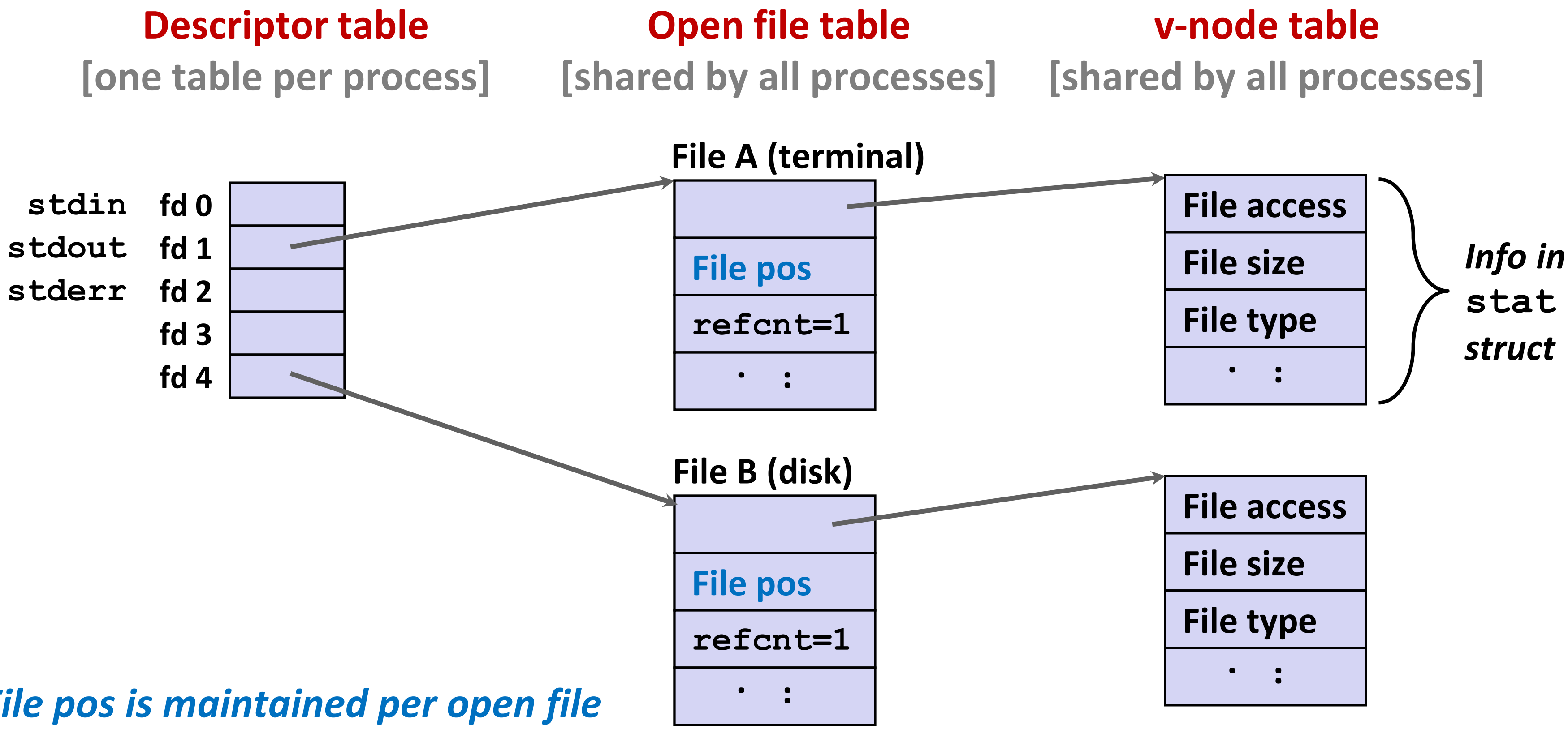
File Metadata

- ***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

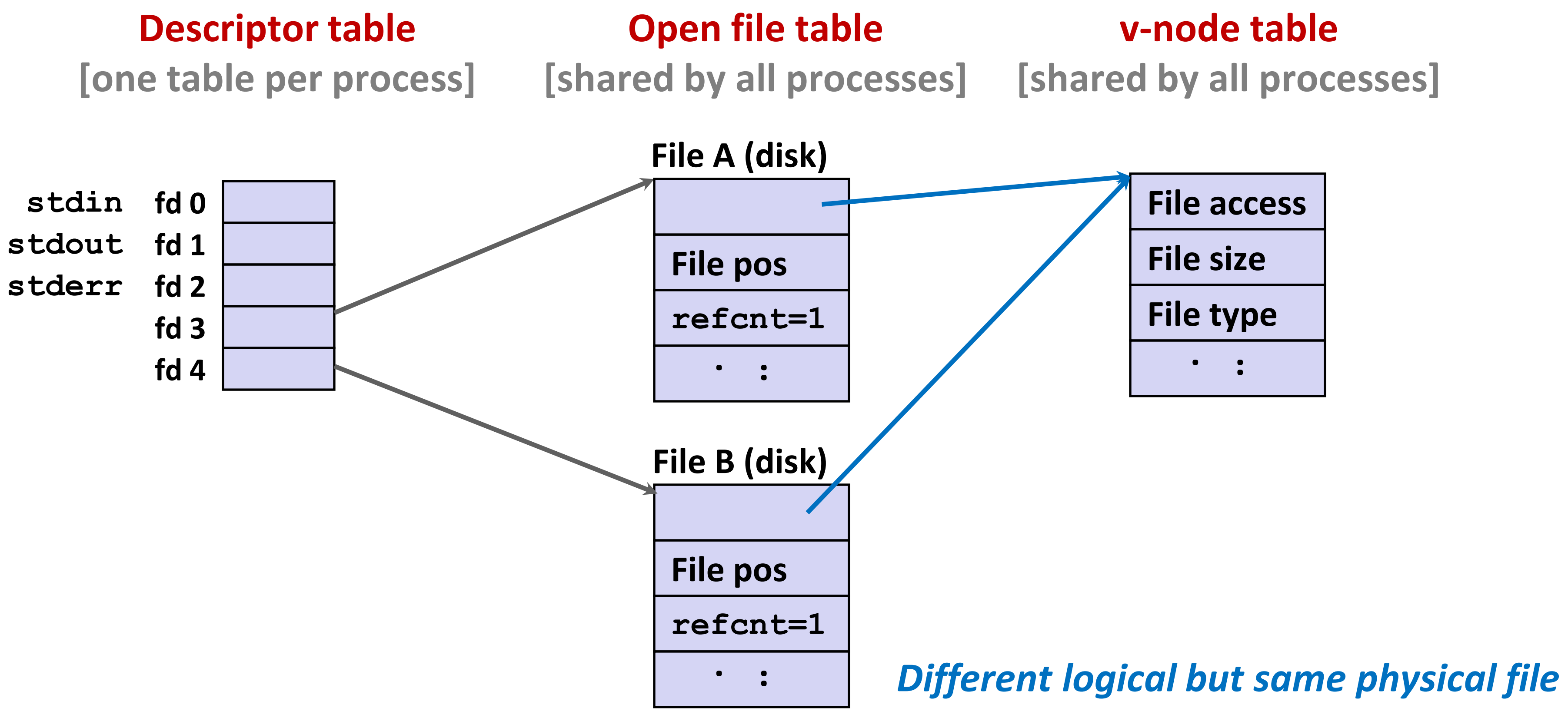
- **Two descriptors referencing two distinct open files. Descriptor 1 (stdout) points to terminal, and descriptor 4 points to open disk file**



File pos is maintained per open file

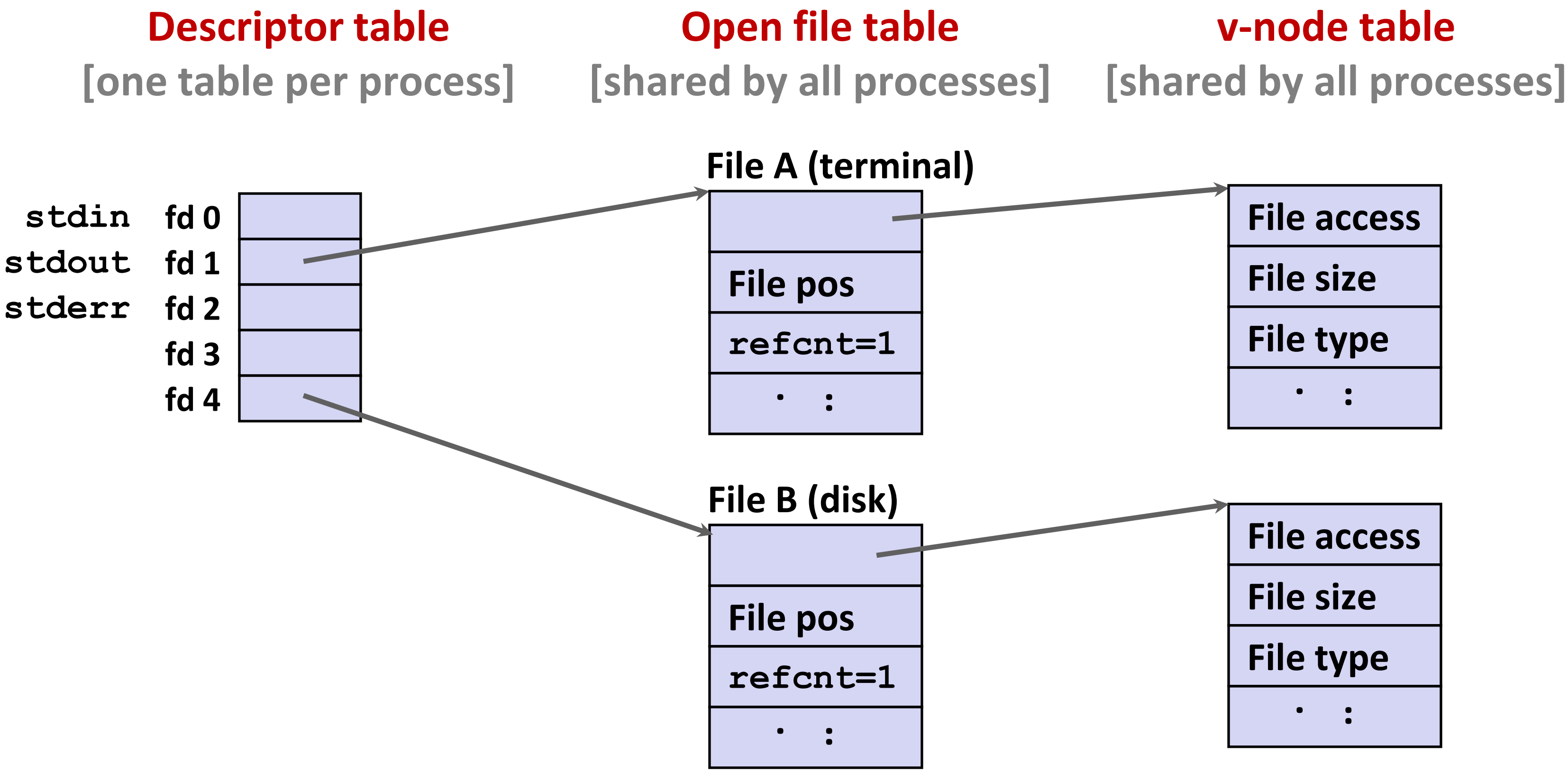
File Sharing

- **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



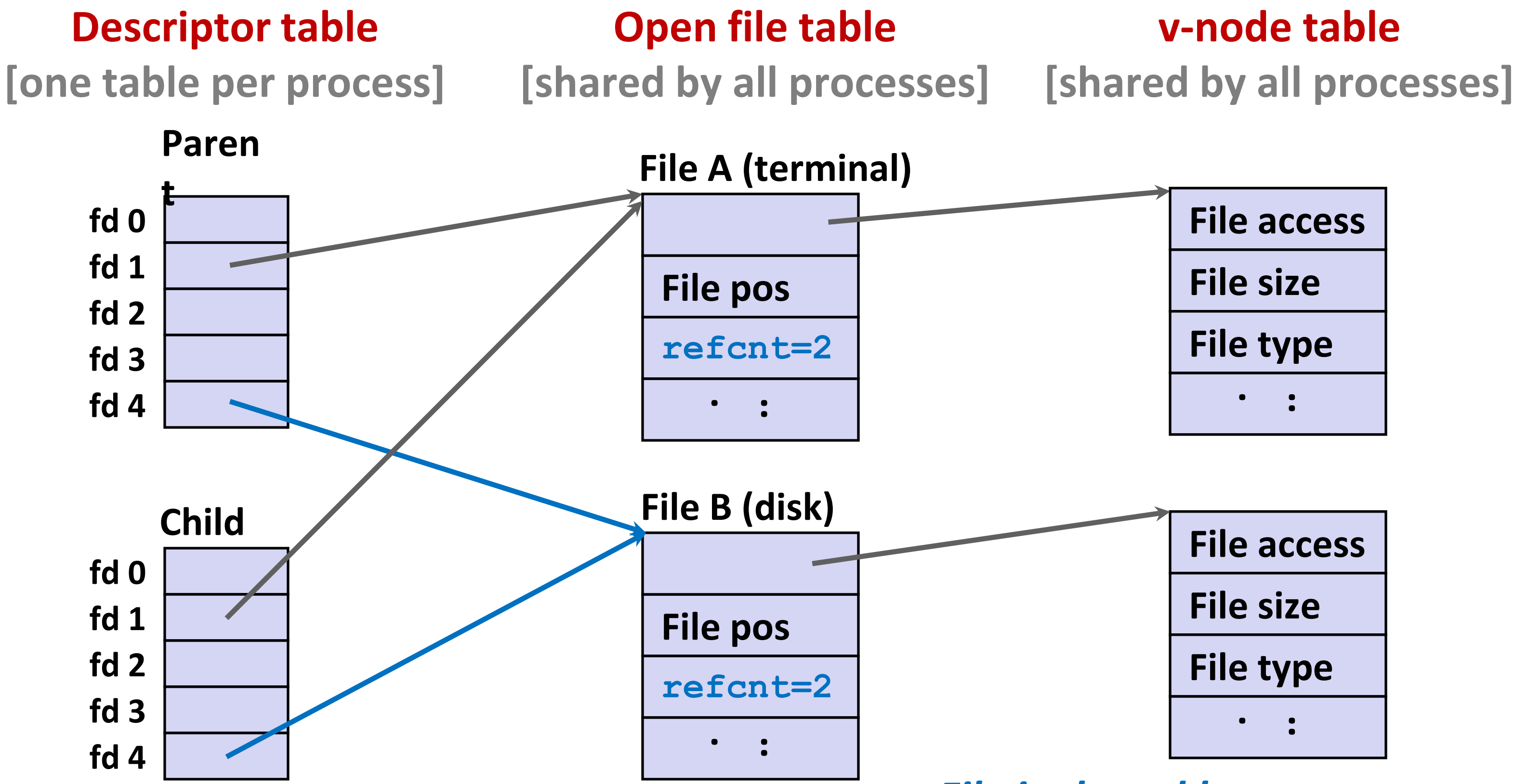
How Processes Share Files: `fork`

- **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



File is shared between processes

I/O Redirection

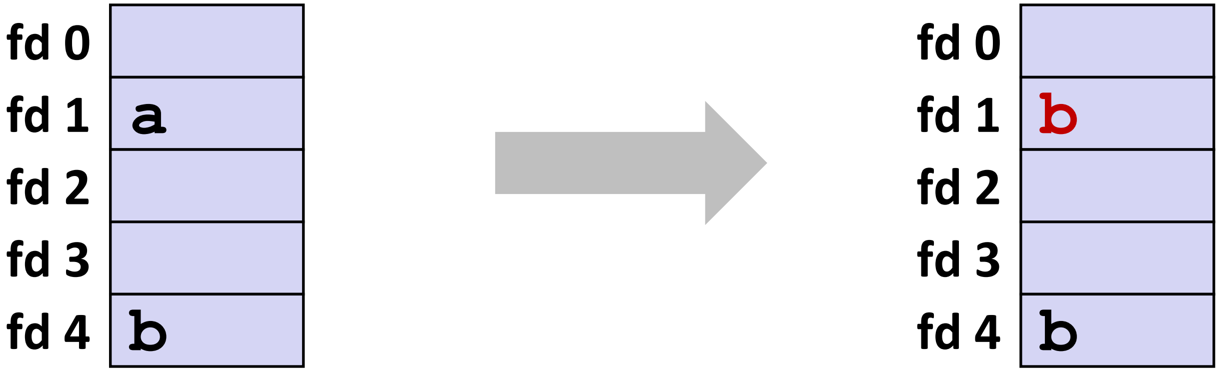
- **Question: How does a shell implement I/O redirection?**

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

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

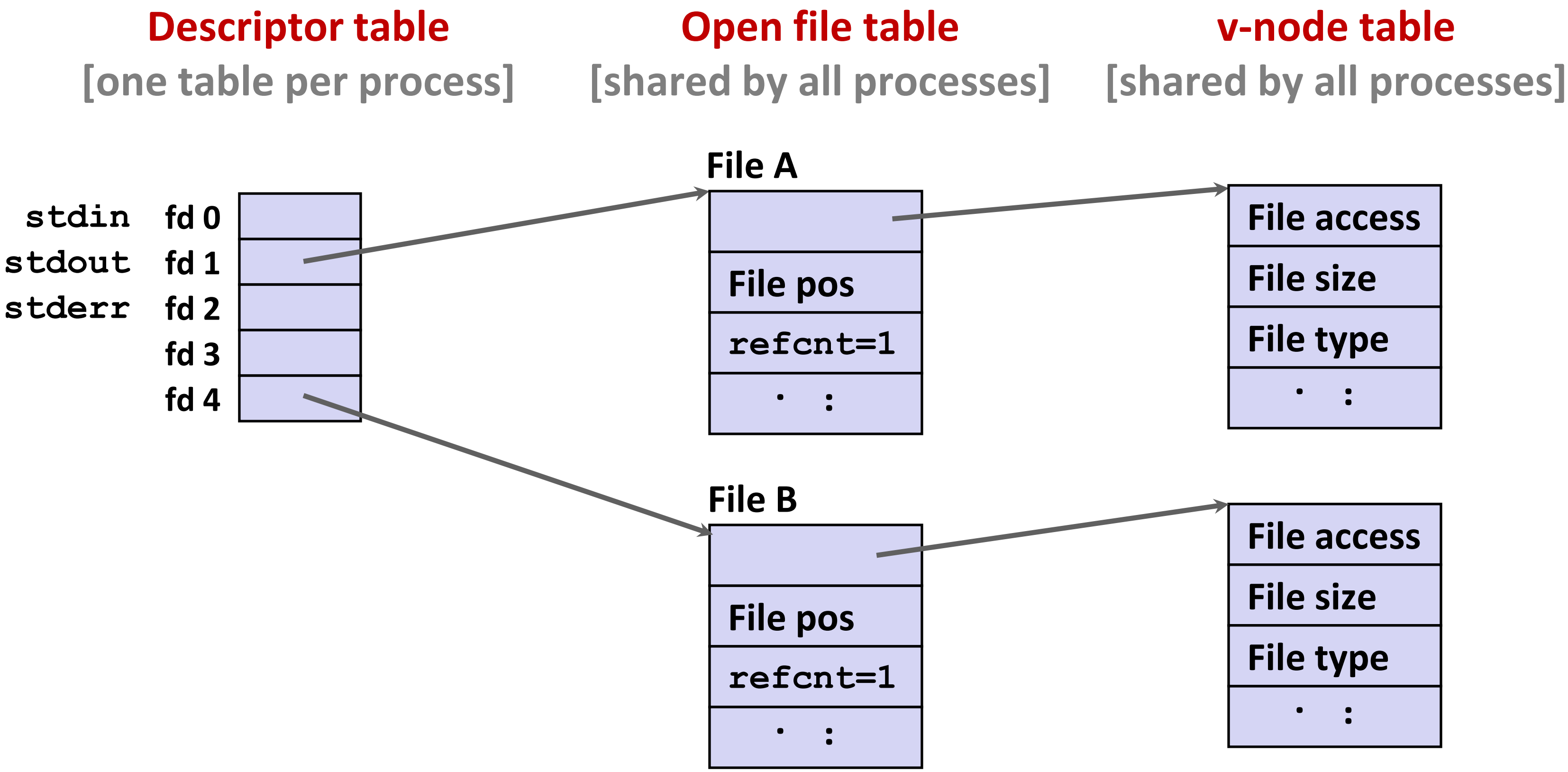
Descriptor table *before* `dup2(4,1)`

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



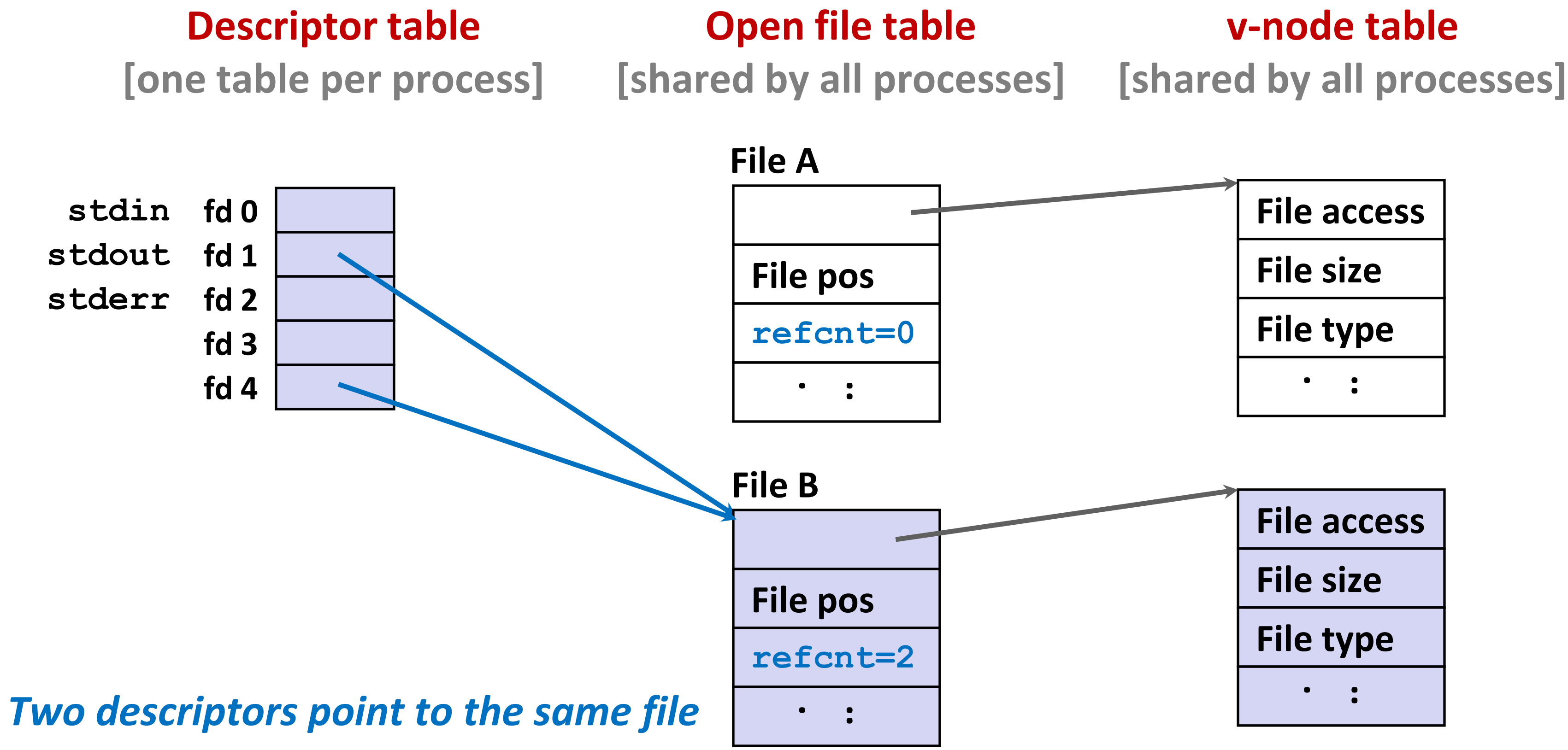
I/O Redirection Example

- **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



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