UNM SCHOOL *of* ENGINEERING
Department of Computer Science

Lecture #28
System-Level Input/Ouput
(Chap. 10)

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Today

- Unix I/O (secs. 10.1 to 10.4)
- Metadata, sharing, and redirection
- Standard I/O (part 2)
- Closing remarks

Input/Output

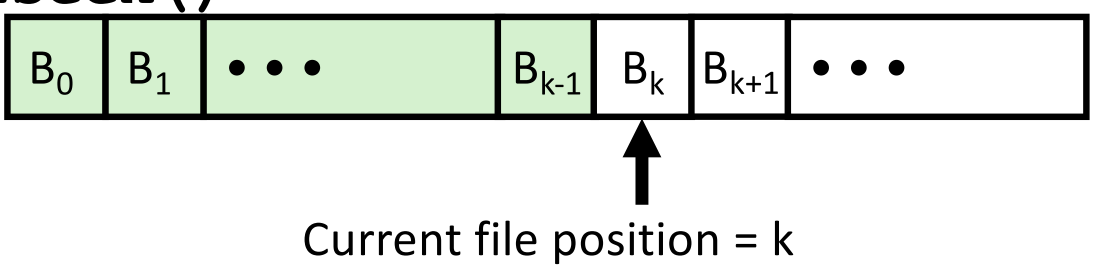
- “Process of copying data between main memory and external devices”
- Examples of external devices: disk drives, terminals, and networks.
- Input operation: copies data from an I/O device to main memory
- Output operation: copies data from memory to a device

Unix I/O Overview

- A Linux *file* is a sequence of *m* bytes:
  - $B_0, B_1, \ldots., B_k, \ldots., B_{m-1}$
- Cool fact: All I/O devices are represented as files:
  - **`/dev/sda2`** (**`/usr`** disk partition)
  - **`/dev/tty2`** (terminal)
- Even the kernel is represented as a file:
  - **`/boot/vmlinuz-3.13.0-55-generic`** (kernel image)
  - **`/proc`** (kernel data structures)

Unix I/O Overview

- Elegant mapping of files to devices allows kernel to export simple interface called *Unix I/O:*
  - Opening and closing files
    - **`open()`** and **`close()`**
  - Reading and writing a file
    - **`read()`** and **`write()`**
  - Changing the ***current file position*** (seek) (beyond our scope)
    - 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:* Contains arbitrary data
  - *Directory:* Index for a related group of files
    - (more on the next two slides)
  - *Socket:* For communicating with a process on another machine (across a network)

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

Regular Files

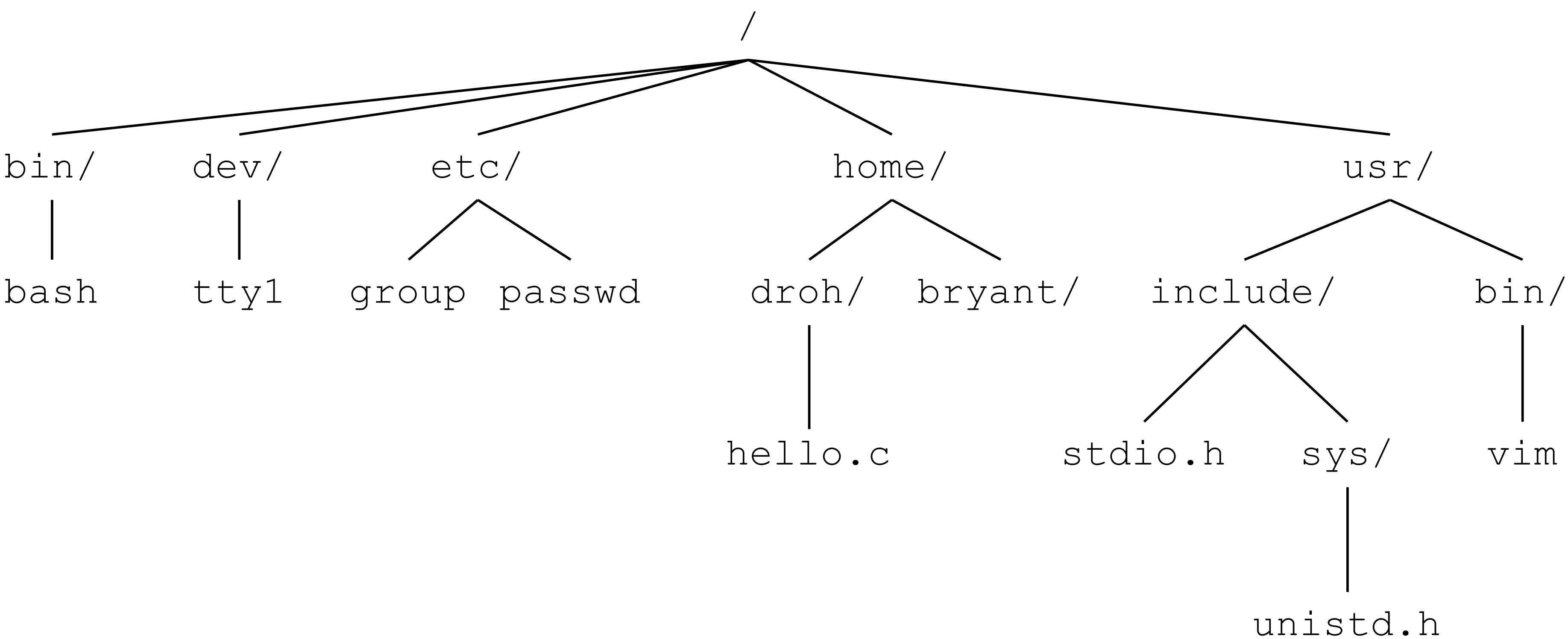
- A regular file contains arbitrary data
- Applications often distinguish between *text files* and *binary files*
  - Text files are regular files with only ASCII or Unicode characters
  - Binary files are everything else
    - e.g., object files, JPEG images
  - Kernel doesn't know the difference!
- Text file is sequence of *text lines*
  - Text line is sequence of chars terminated by *newline char* ('\n')
    - Newline is 0xa, same as ASCII line feed character (LF)
- End of line (EOL) indicators in other systems
  - Linux and Mac OS: '\n' (0xa)
    - line feed (LF)
  - Windows and Internet protocols: '\r\n' (0xd 0xa)
    - Carriage return (CR) followed by line feed (LF)

Directories

- Directory consists of an array of *links*
  - Each link maps a *filename* to a file
- Each directory contains at least two entries
  - . (dot) is a link to itself
  - .. (dot dot) is a link to *the parent directory* in the *directory hierarchy* (next slide)
  - the command `ls -a` allows you to see both
- 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 the root directory named / (slash)

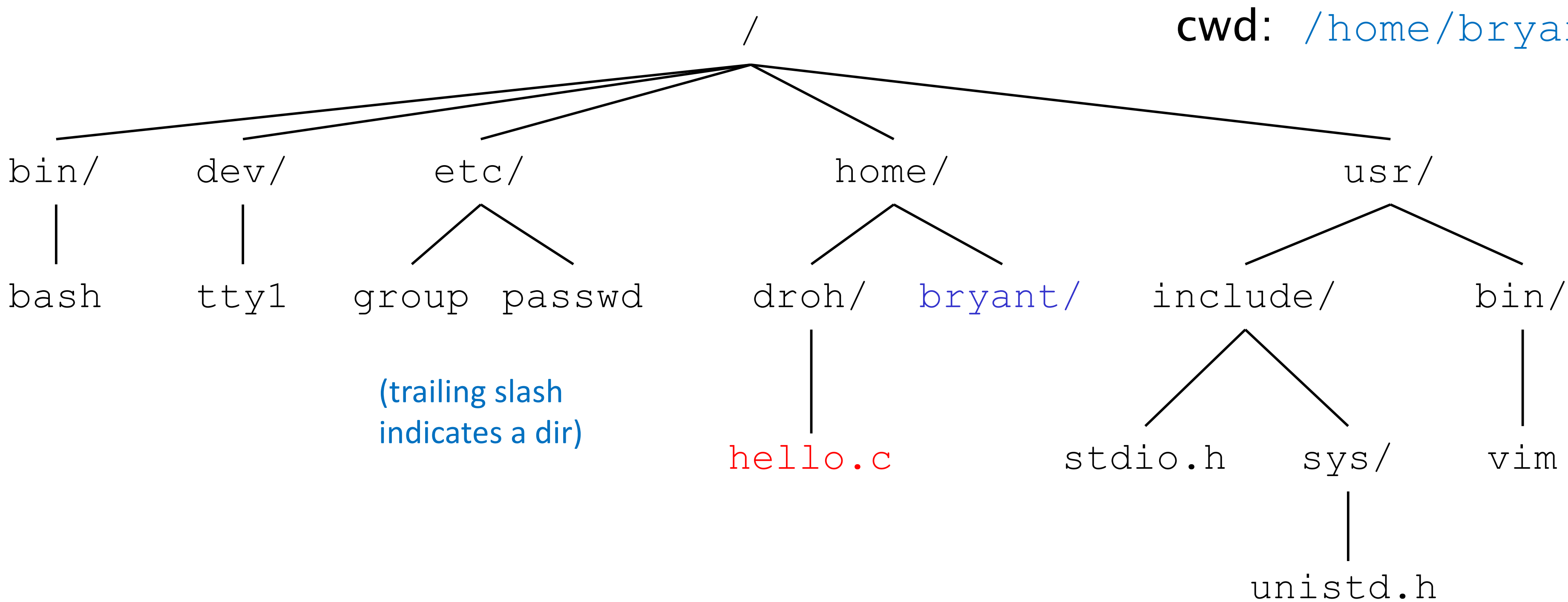


- Kernel maintains *current working directory (cwd)* for each process
  - Modified using the `cd` command; shown by `pwd` command

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`

cwd: `/home/bryant`



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 created by a Linux shell begins life with three open files associated with a terminal: (digit is the file descriptor for each)
  - 0: standard input (stdin)
  - 1: standard output (stdout)
  - 2: standard error (stderr)

Closing Files

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

```
int fd;      /* file descriptor */
int retval; /* return value */

if ((retval = close(fd)) < 0) {
   perror("close");
   exit(1);
}
```

- Closing an already closed file is a recipe for disaster in threaded programs (more on this later)
- Moral: Always check return codes, even for seemingly benign functions such as `close()`

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)`**) possible and not errors!
  - nbytes = 0 indicates EOF (end of file)

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 written */

/* 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 "csapp.h"

int main(void)
{
    char c;

    while(Read(STDIN_FILENO, &c, 1) != 0)
        Write(STDOUT_FILENO, &c, 1);
    exit(0);
}
```

On Short Counts (pp. 895-897)

- 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
- 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.

Topics

- Unix I/O
- (skipping sec. 10.5 Robust read/write w/R_{IO} package)
- Metadata, sharing, and redirection (secs. 10.6 to 10.9)
- Standard I/O
- Closing remarks

File Metadata (section 10.6)

- *Metadata* is data about data, in this case file data
- Per-file metadata maintained by kernel: accessed by users with the **stat**(filename) and **fstat** (fd) 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 */
};
```

Example of Accessing File Metadata

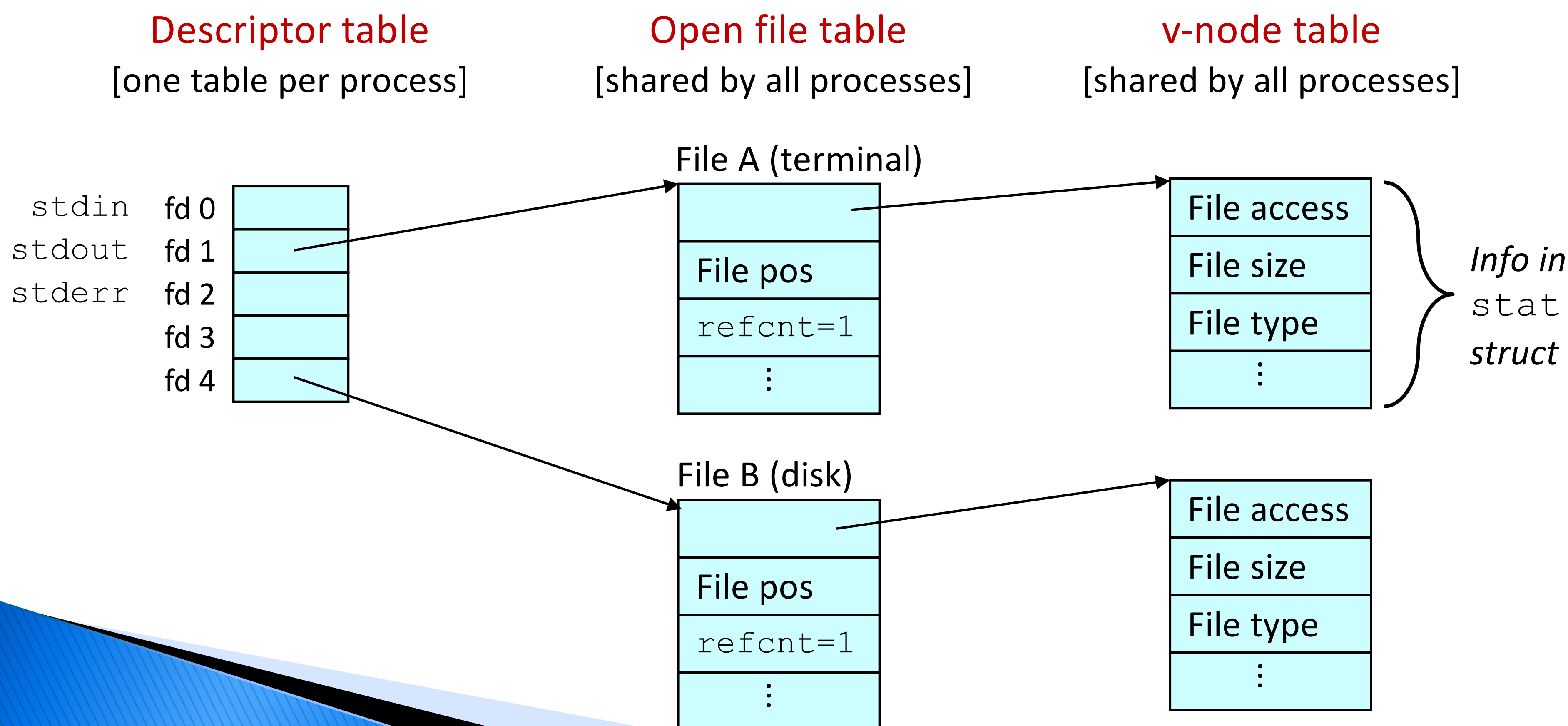
```
linux> ./statcheck statcheck.c
type: regular, read: yes
linux> chmod 000 statcheck.c
linux> ./statcheck statcheck.c
type: regular, read: no
linux> ./statcheck ..
type: directory, read: yes
```

```c
int main (int argc, char **argv)
{
    struct stat stat;
    char *type, *readok;

    Stat(argv[1], &stat);
    if (S_ISREG(stat.st_mode))     /* Determine file type */
    type = "regular";
    else if (S_ISDIR(stat.st_mode))
    type = "directory";
    else
        type = "other";
    if ((stat.st_mode & S_IRUSR)) /* Check read access */
    readok = "yes";
    else
        readok = "no";

    printf("type: %s, read: %s\n", type, readok);
    exit(0);
}
```

statcheck.c

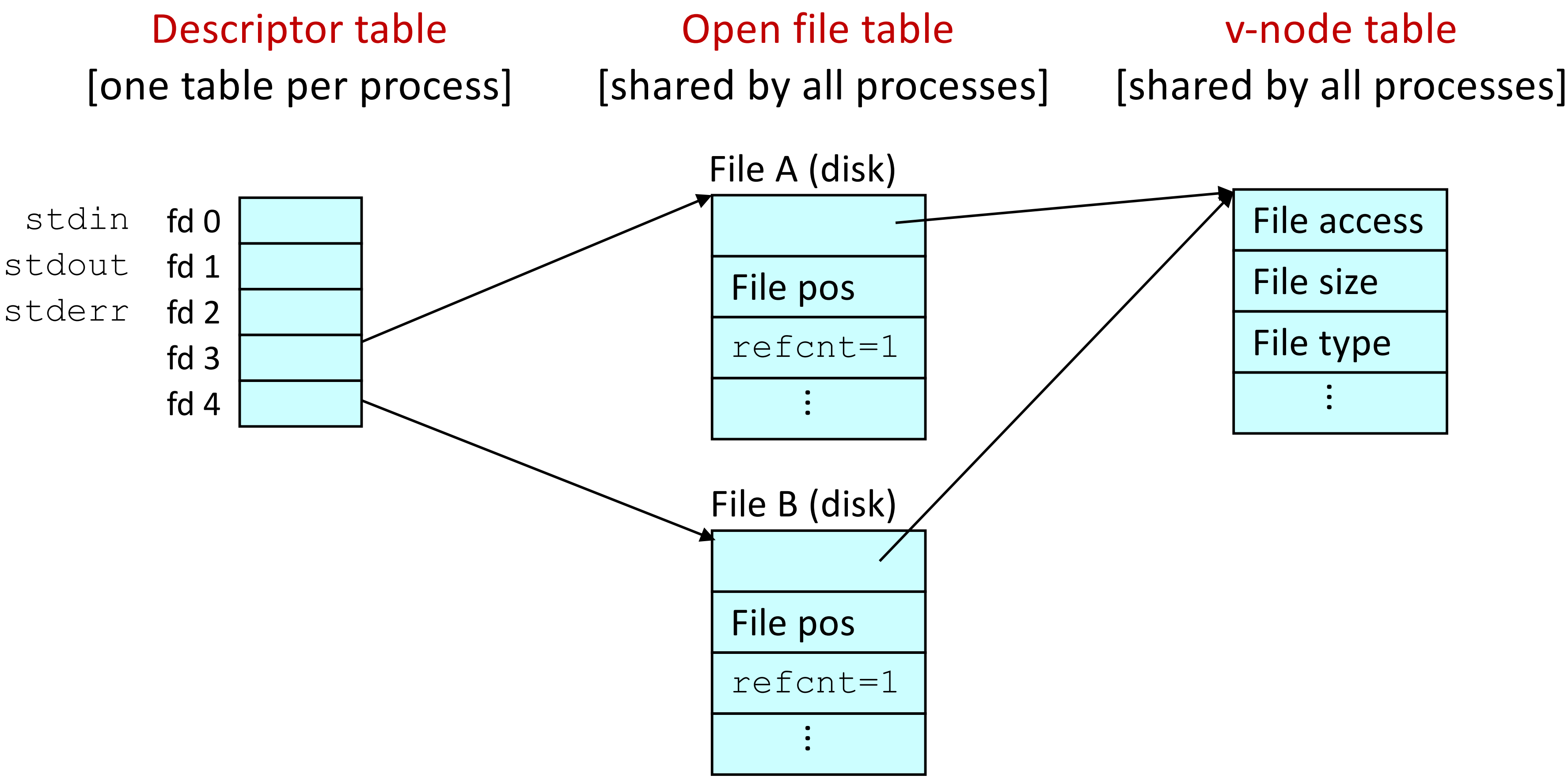
How the Unix Kernel Represents Open Files

- Two descriptors referencing two distinct open files. Descriptor 1 (stdout) points to terminal, and descriptor 4 points to open disk file (fig. 10.12)



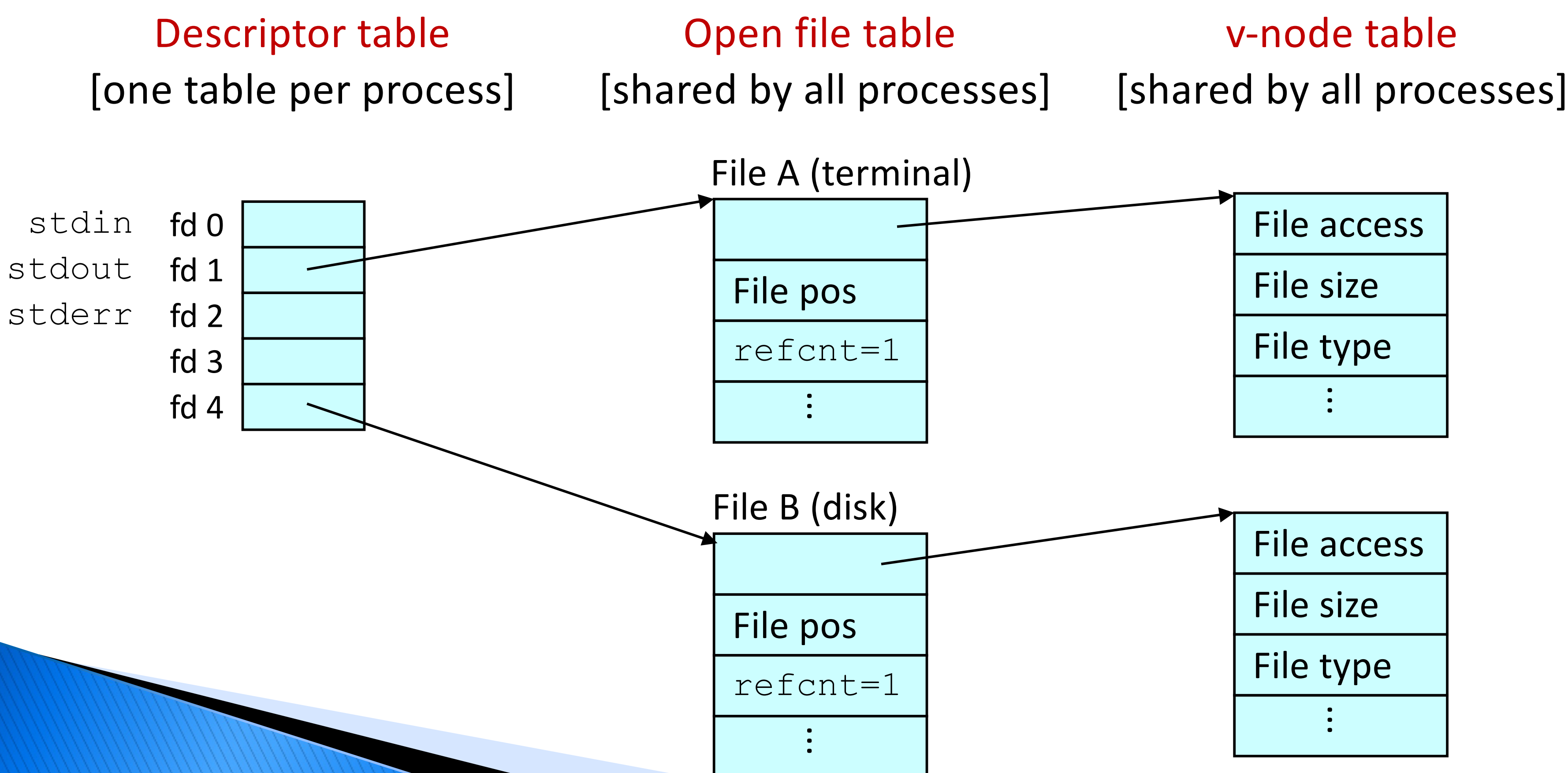
File Sharing

- Two distinct descriptors sharing the same disk file through two distinct open file table entries (fig. 10.13)
  - E.g. Calling **`open`** twice with the same **`filename`** argument



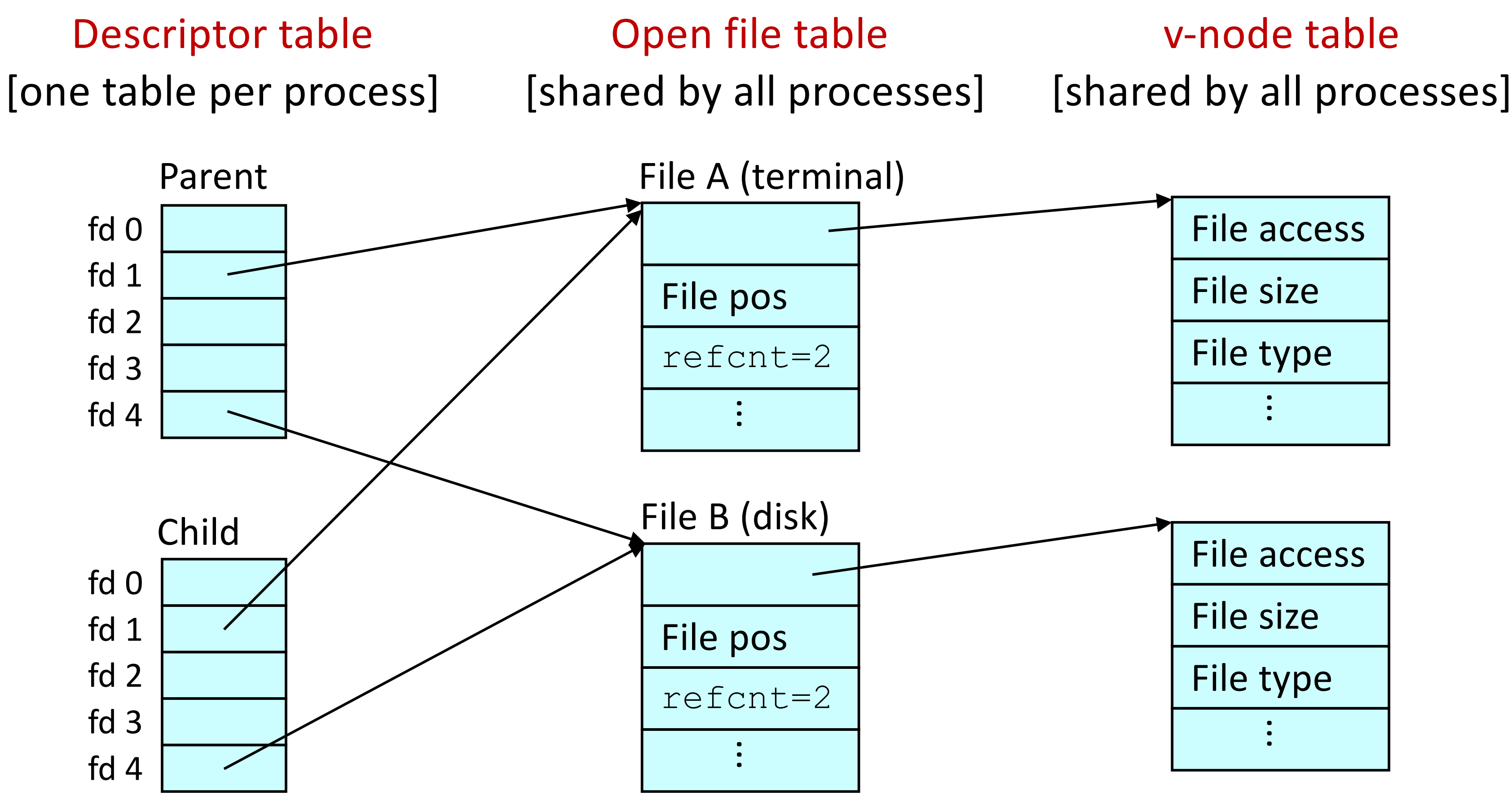
How Processes Share Files: `fork`

- A child process inherits its parent's open files
  - Note: situation unchanged by **`exec`** functions (use **`fcntl`** to change)
- *Before* `fork` call: (fig. 10.12)



How Processes Share Files: `fork` (2)

- A child process inherits its parent's open files
- *After* `fork`: (fig. 10.14)
  - 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)`

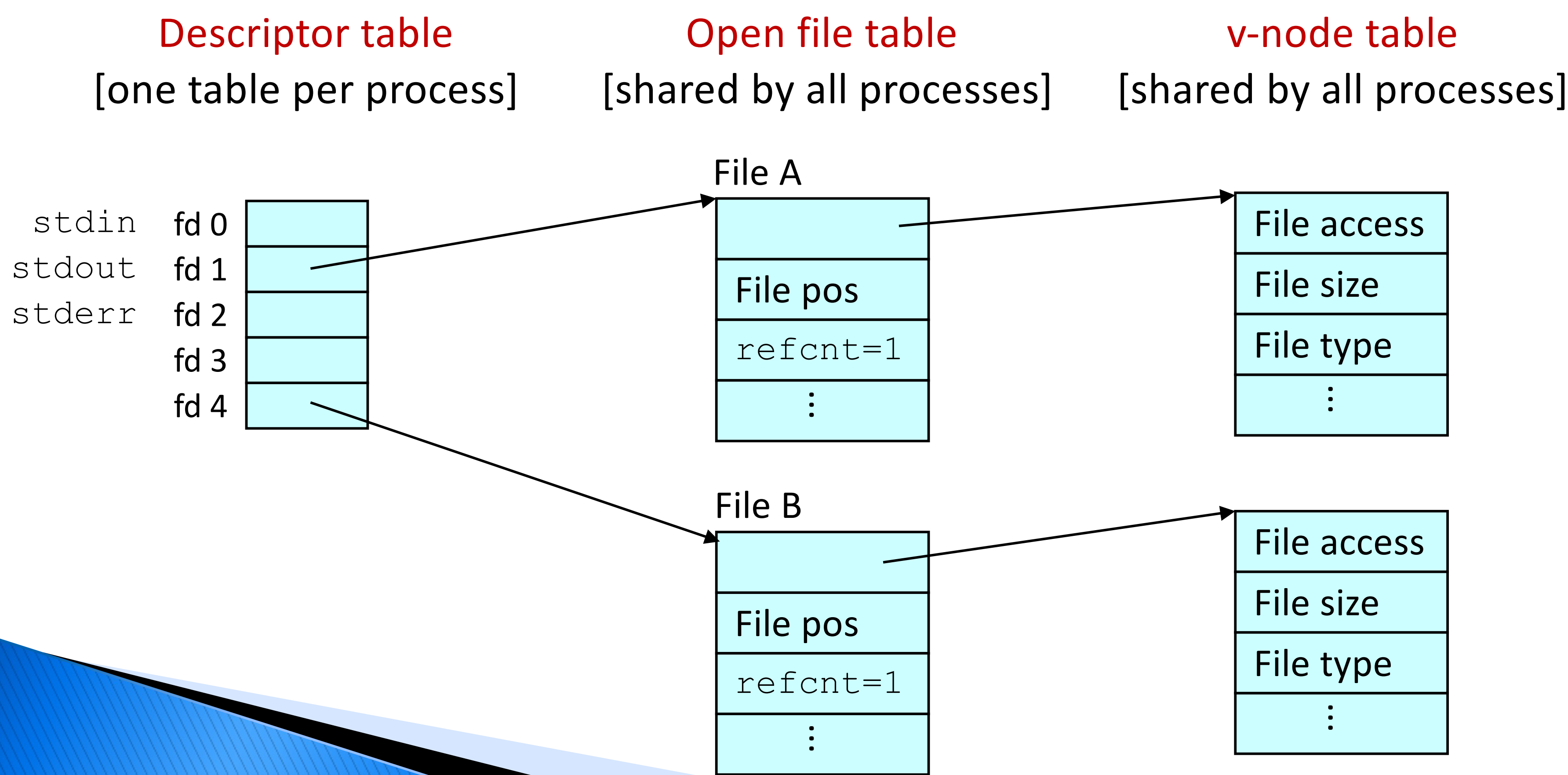
fd 0	
fd 1	a
fd 2	
fd 3	
fd 4	b

Descriptor table
after `dup2(4,1)`

fd 0	
fd 1	b
fd 2	
fd 3	
fd 4	b

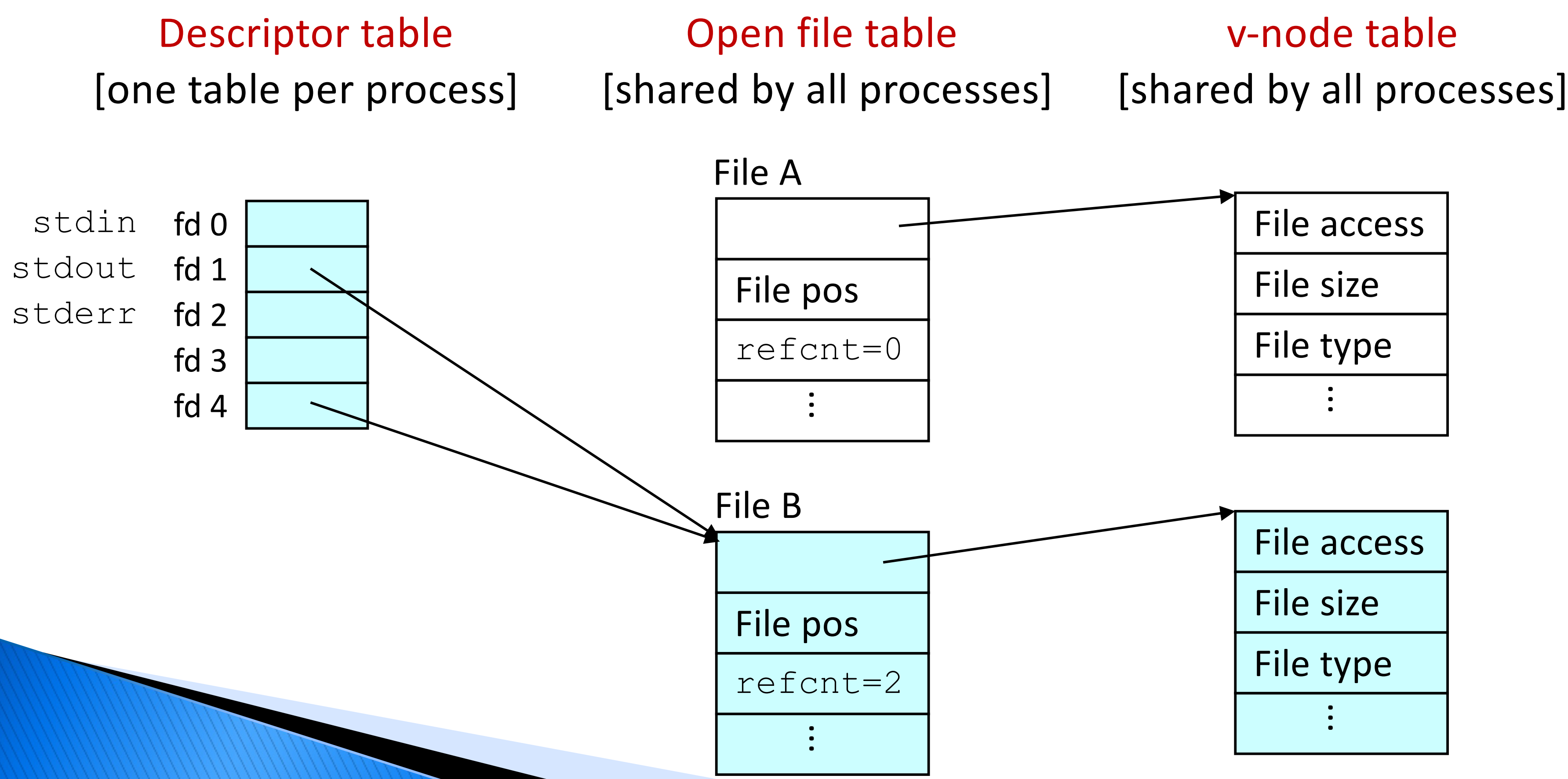
I/O Redirection Example

- 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 exercises

- Problem 10.2
- Problem 10.3 (careful with the answer given in the book, there is a subtlety here)
- Both use file foobar.txt which contains:

  `foobar`

  Only those 6 characters and the eof char

Problem 10.2 (with minor changes)

```
#include "csapp.h"

int main()
{
  int fd1, fd2;
  char c;

  fd1 = open("foobar.txt", O_RDONLY, 0);
  fd2 = open("foobar.txt", O_RDONLY, 0);
  read(fd1, &c, 1);
  printf("c1 = %c\n", c);
  read(fd2, &c, 1);
  printf("c1 = %c\n", c);
  exit(0);
}
```

What is the output?
Build the 3 data structures.

Problem 10.3

```
#include "csapp.h"
int main()
{
  int fd;
  char c;
  fd1 = Open("foobar.txt", O_RDONLY, 0);
  if (Fork() == 0){
     Read(fd, &c, 1);
     exit(0):
  }
  Wait(NULL);
  Read(fd, &c, 1);
  printf("c1 = %c\n", c);
  exit(0);
}
```

What is the output?
Build the 3 data structures.

Topics

- Unix I/O
- (skipping sec. 10.5 Robust read/write w/R_{IO} package)
- Metadata, sharing, and redirection (secs. 10.6 to 10.9)
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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 [KRC book]

- 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");
}
```

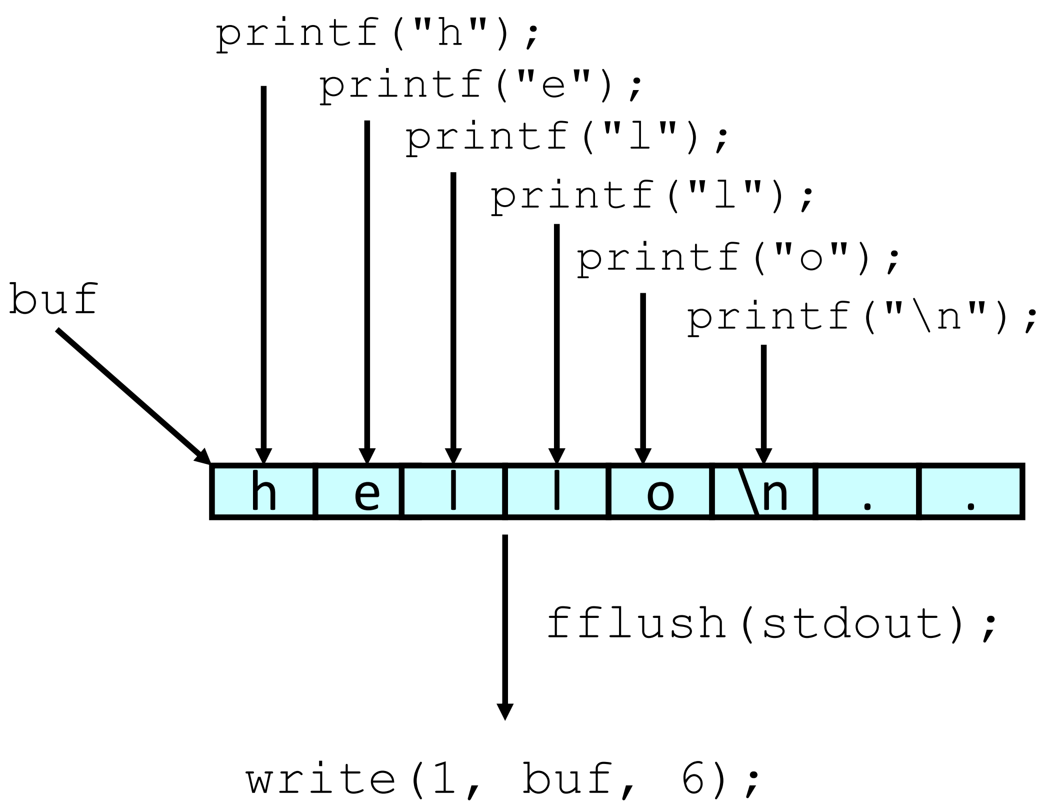
Buffered I/O: Motivation

- 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

Buffer	already read	unread	

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)                         = ?
```

Topics

- Unix I/O
- (skipping sec. 10.5 Robust read/write w/R_{IO} package)
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Pros and Cons of Unix I/O (compared to std I/O)

- Pros
  - Unix I/O is the most general and lowest overhead 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
  - Both of these issues are addressed by the standard I/O packages

Pros and Cons of Standard I/O (over Unix 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 disk or terminal files
- When to use raw Unix I/O
  - Inside signal handlers, because Unix I/O is async-signal-safe
  - 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`**
    - Interpret EOL characters.
  - String functions
    - **`strlen, strcpy, strcat`**
    - Interprets byte value 0 (end of string) as special

For Further Information (important resources)

- The Unix bible:
  - W. Richard Stevens & Stephen A. Rago, ***Advanced Programming in the Unix Environment***, 3rd Edition, Pearson Education Inc., 2013
    - Updated from Stevens's 1993 classic text and from 2nd Ed. 2005
  - http://www.apuebook.com/code3e.html has code and relevant info about the 3rd ed. of this book

- The Linux bible:
  - Michael Kerrisk, The Linux Programming Interface, No Starch Press, 2010
    - Encyclopedic and authoritative

Continue with last topic

- Ch. 12: Concurrency (next pptx file)