18-600 Foundations of Computer Systems

Lecture 17: "System Level I/O"

John P. Shen & Zhiyi Yu (with Chris Inacio of SEI)
October 31, 2016

- Required Reading Assignment:
  - **Chapter 10 of CS:APP (3rd edition) by Randy Bryant & Dave O'Hallaron.**

Electrical & Computer ENGINEERING

18-600 Foundations of Computer Systems

Lecture 17: "System Level I/O"

- **Unix I/O**
- RIO (Robust I/O) Package
- Metadata, Sharing, and Redirection
- Standard I/O
- Closing Remarks

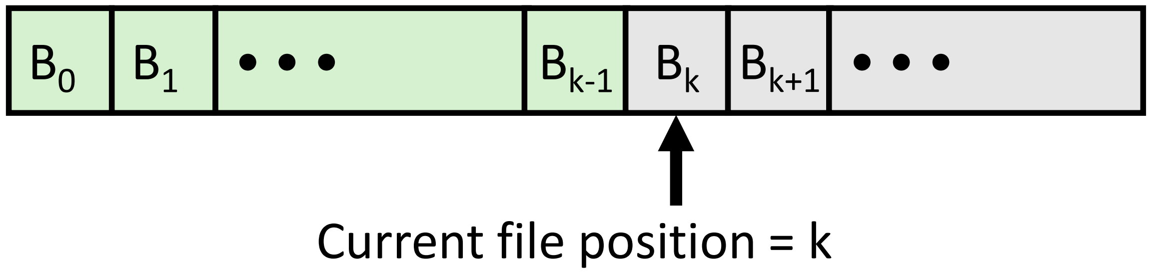
Electrical & Computer ENGINEERING

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)
    - 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
  - *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

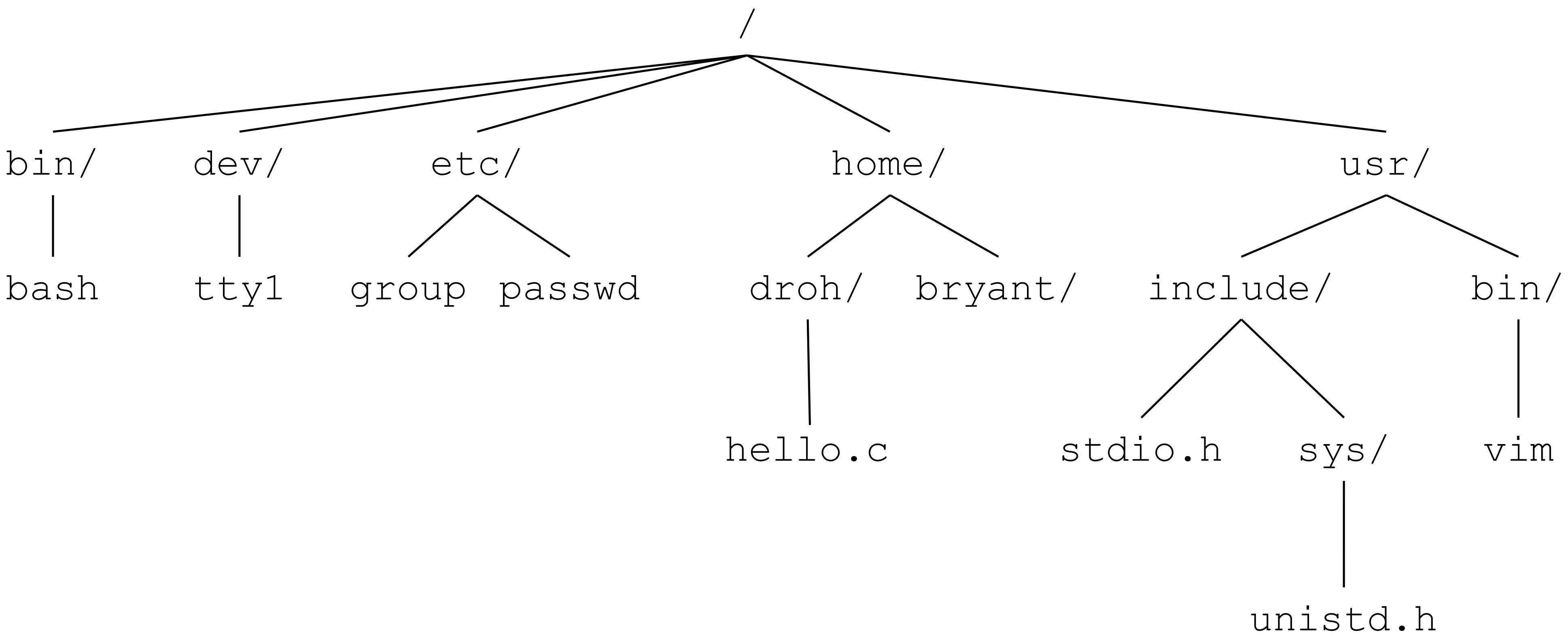
- **A regular file contains arbitrary data**
- **Applications often distinguish between *text files* and *binary files***
  - Text files are regular files with only ASCII or Unicode characters
  - Binary files are everything else
    - e.g., object files, JPEG images
  - Kernel doesn't know the difference!
- **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)
- **Commands for manipulating directories**
  - `mkdir`: create empty directory
  - `ls`: view directory contents
  - `rmdir`: delete empty directory

Directory Hierarchy

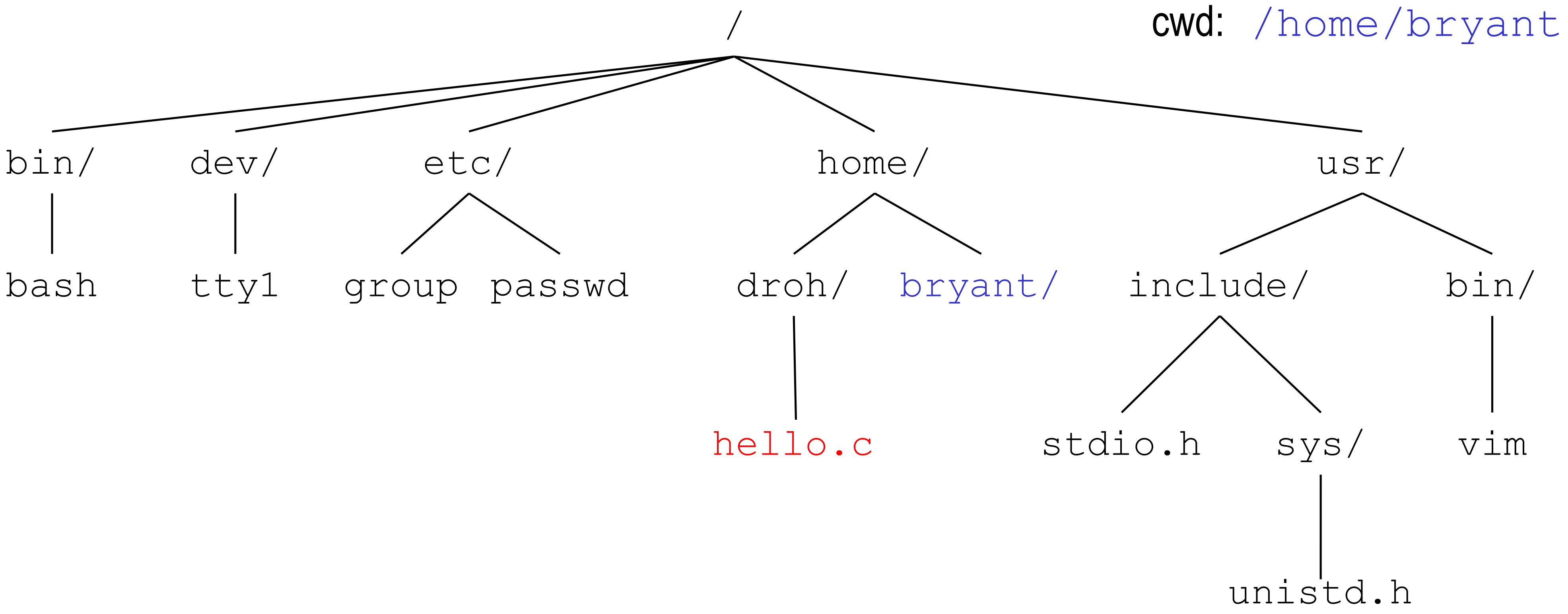
- **All files are organized as a hierarchy anchored by root directory named / (slash)**



- **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
    - `../home/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 created by a Linux shell begins life with three open files associated with a terminal:**
  - 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)`**) 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 "csapp.h"

int main(void)
{
    char c;

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

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

- **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.**

18-600 Foundations of Computer Systems

Lecture 17:
"System Level I/O"

- Unix I/O
- **RIO (Robust I/O) Package**
- Metadata, Sharing, and Redirection
- Standard I/O
- Closing Remarks

The RIO 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

Implementation of **rio_readn**

```
/*
 * rio_readn - Robustly read n bytes (unbuffered)
 */
ssize_t rio_readn(int fd, void *usrbuf, size_t n)
{
    size_t nleft = n;
    ssize_t nread;
    char *bufp = usrbuf;

    while (nleft > 0) {
       if ((nread = read(fd, bufp, nleft)) < 0) {
           if (errno == EINTR) /* Interrupted by sig handler return */
              nread = 0;       /* and call read() again */
           else
              return -1;       /* errno set by read() */
       }
       else if (nread == 0)
           break;              /* EOF */
       nleft -= nread;
       bufp += nread;
    }
    return (n - nleft);         /* Return >= 0 */
}
```

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)

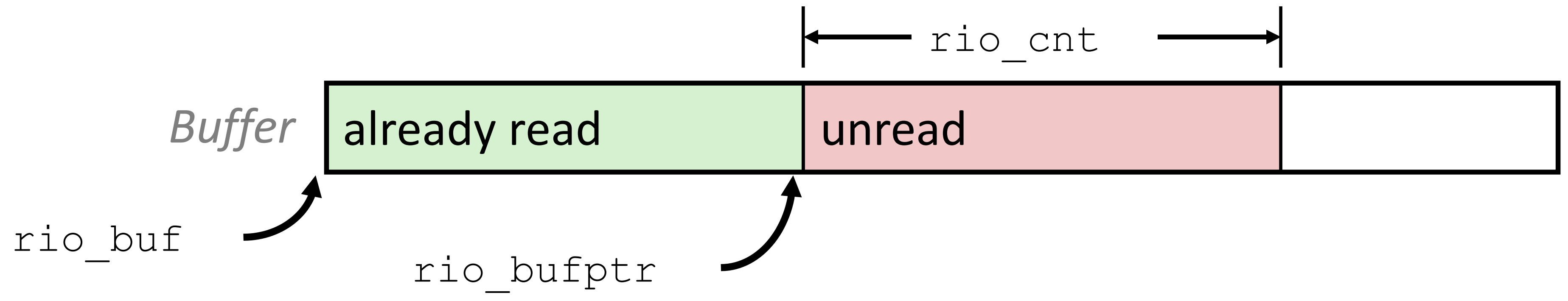
```
#include "csapp.h"

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

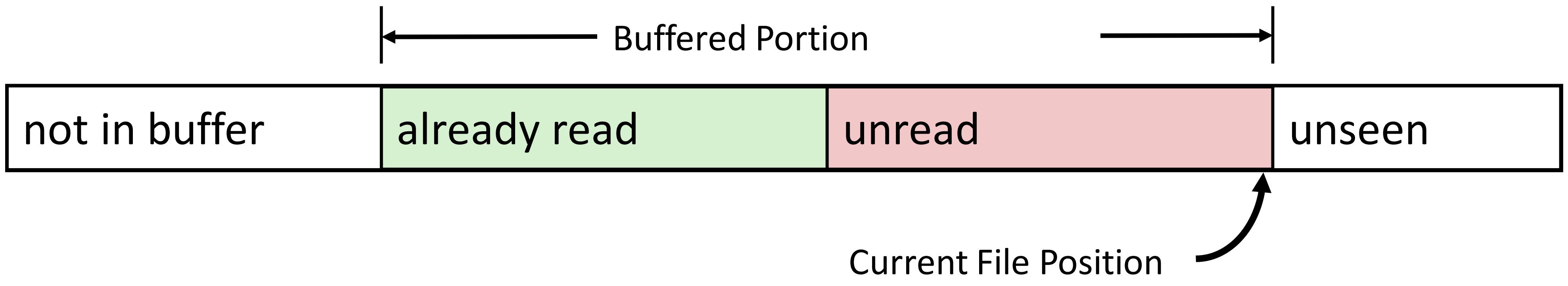
- **`rio_readnb`** reads up to **`n`** bytes from file **`fd`**
- Stopping conditions
  - **`maxlen`** bytes read
  - EOF encountered
- Calls to **`rio_readlineb`** and **`rio_readnb`** can be interleaved arbitrarily on the same descriptor
  - Warning: Don't interleave with calls to **`rio_readn`**

Buffered I/O: Implementation

- **For reading from file**
- **File has associated buffer to hold bytes that have been read from file but not yet read by user code**

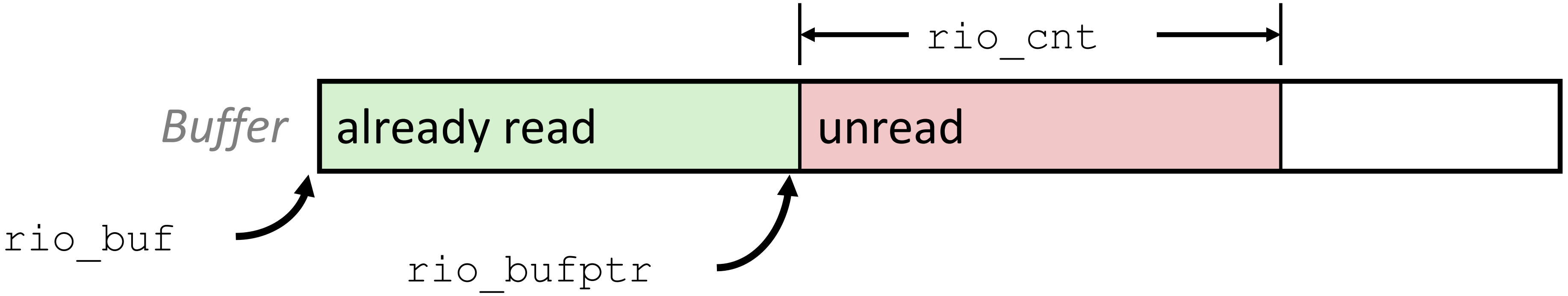


- **Layered on Unix file:**



Buffered I/O: Declaration

- **All information contained in `struct`**




```
typedef struct {
    int rio_fd;                /* descriptor for this internal buf */
    int rio_cnt;               /* unread bytes in internal buf */
    char *rio_bufptr;          /* next unread byte in internal buf */
    char rio_buf[RIO_BUFSIZE]; /* internal buffer */
} rio_t;
```

RIO Example

- **Copying the lines of a text file from standard input to standard output**

```
#include "csapp.h"

int main(int argc, char **argv)
{
    int n;
    rio_t rio;
    char buf[MAXLINE];

    Rio_readinitb(&rio, STDIN_FILENO);
    while((n = Rio_readlineb(&rio, buf, MAXLINE)) != 0)
       Rio_writen(STDOUT_FILENO, buf, n);
    exit(0);
}
```
cpfile.c

18-600 Foundations of Computer Systems

Lecture 17:
"System Level I/O"

- Unix I/O
- RIO (Robust I/O) Package
- **Metadata, Sharing, and Redirection**
- Standard I/O
- Closing Remarks

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 */
};
```

Example of Accessing File Metadata

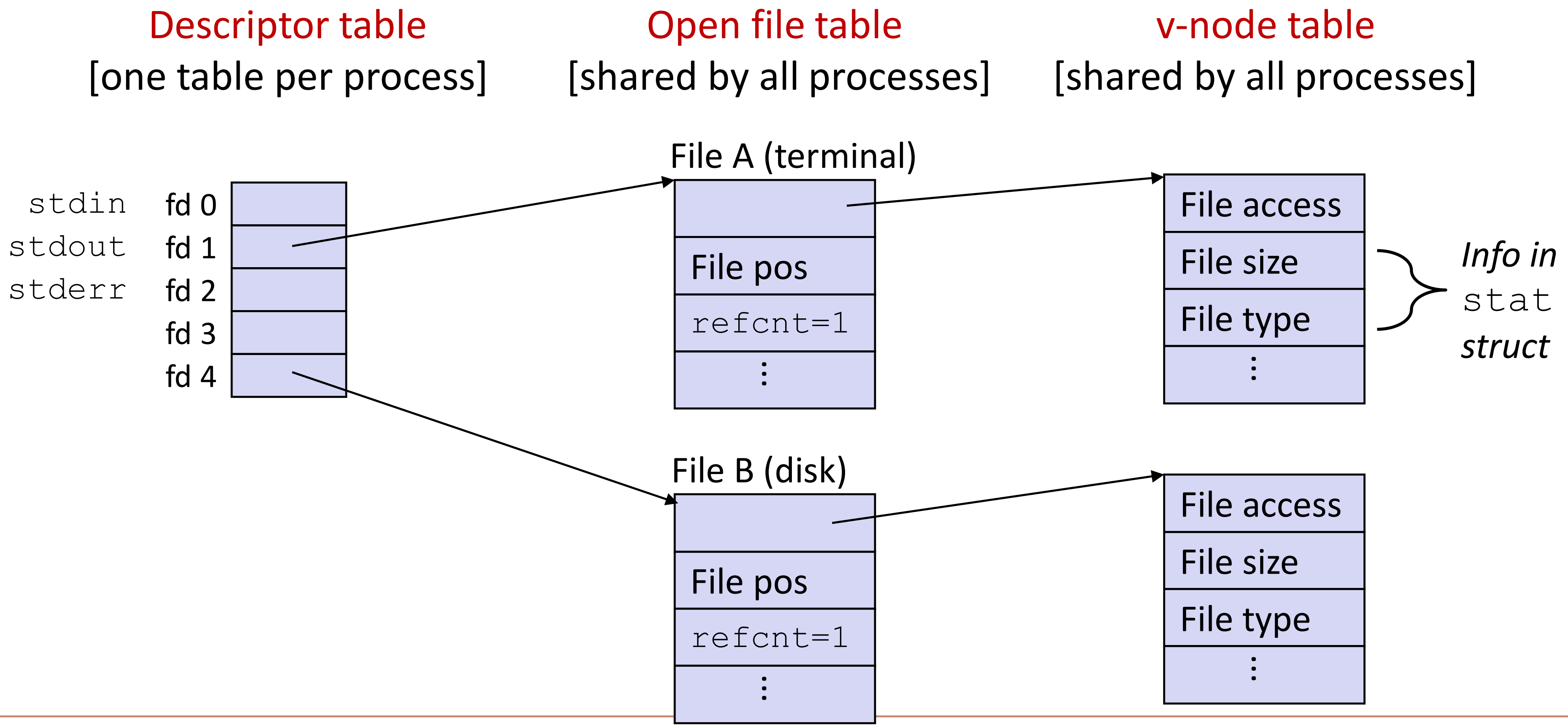
```
linux> ./statcheck statcheck.c
type: regular, read: yes
linux> chmod 000 statcheck.c
linux> ./statcheck statcheck.c
type: regular, read: no
linux> ./statcheck ..
type: directory, read: yes
```

```
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

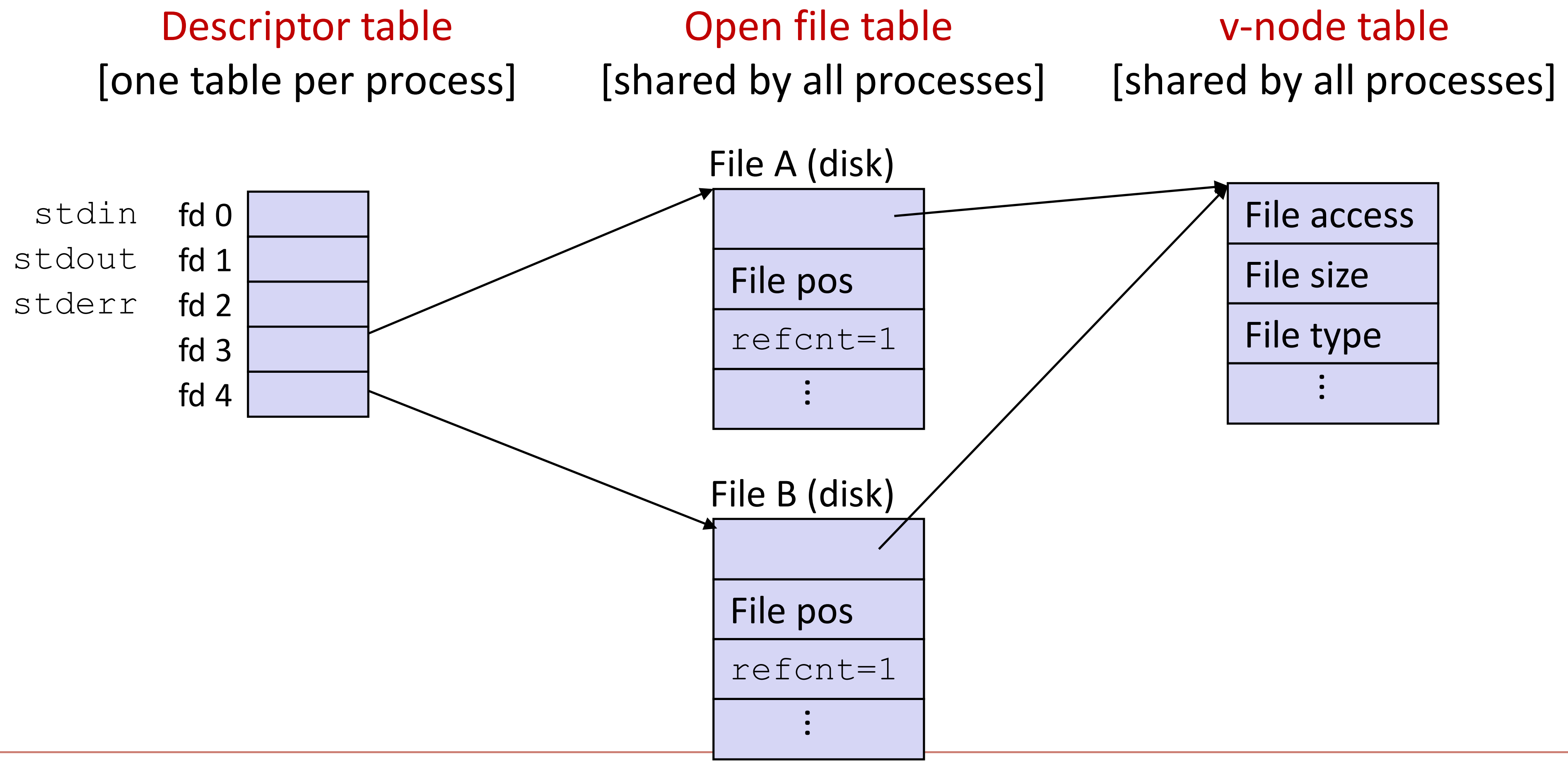
How the Unix Kernel Represents Open Files

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



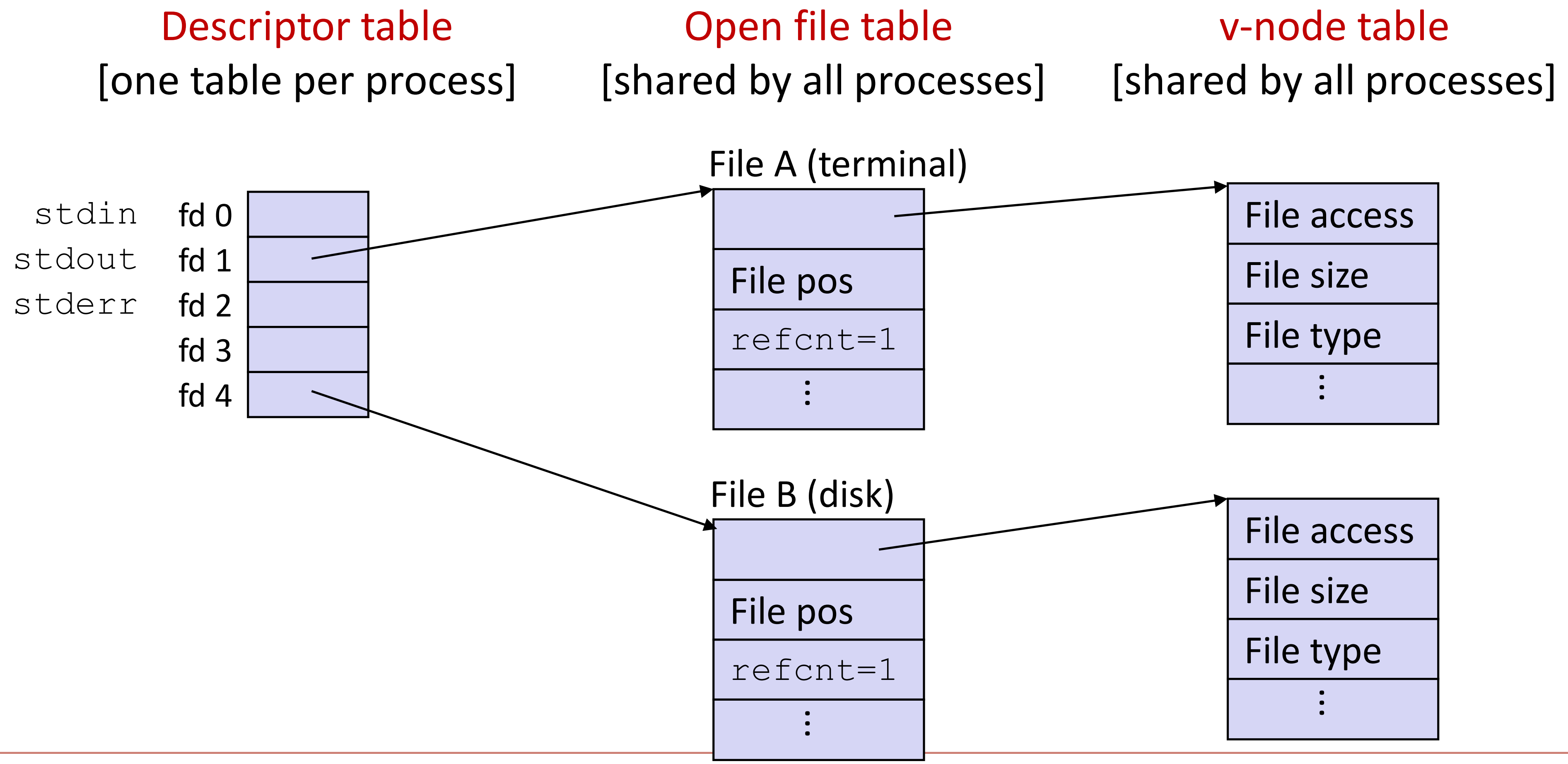
File Sharing

- **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



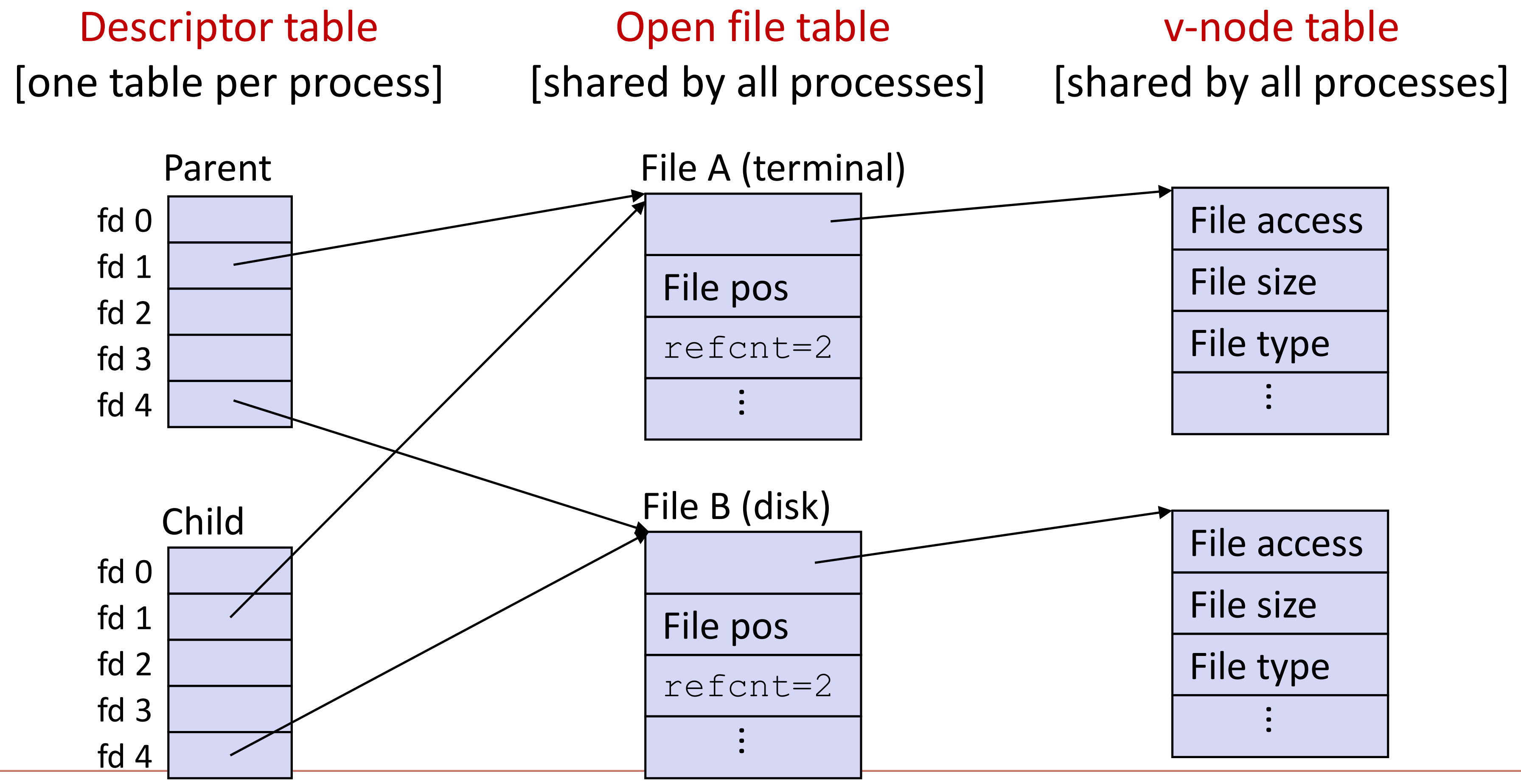
How Processes Share Files: `fork`

- **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)`

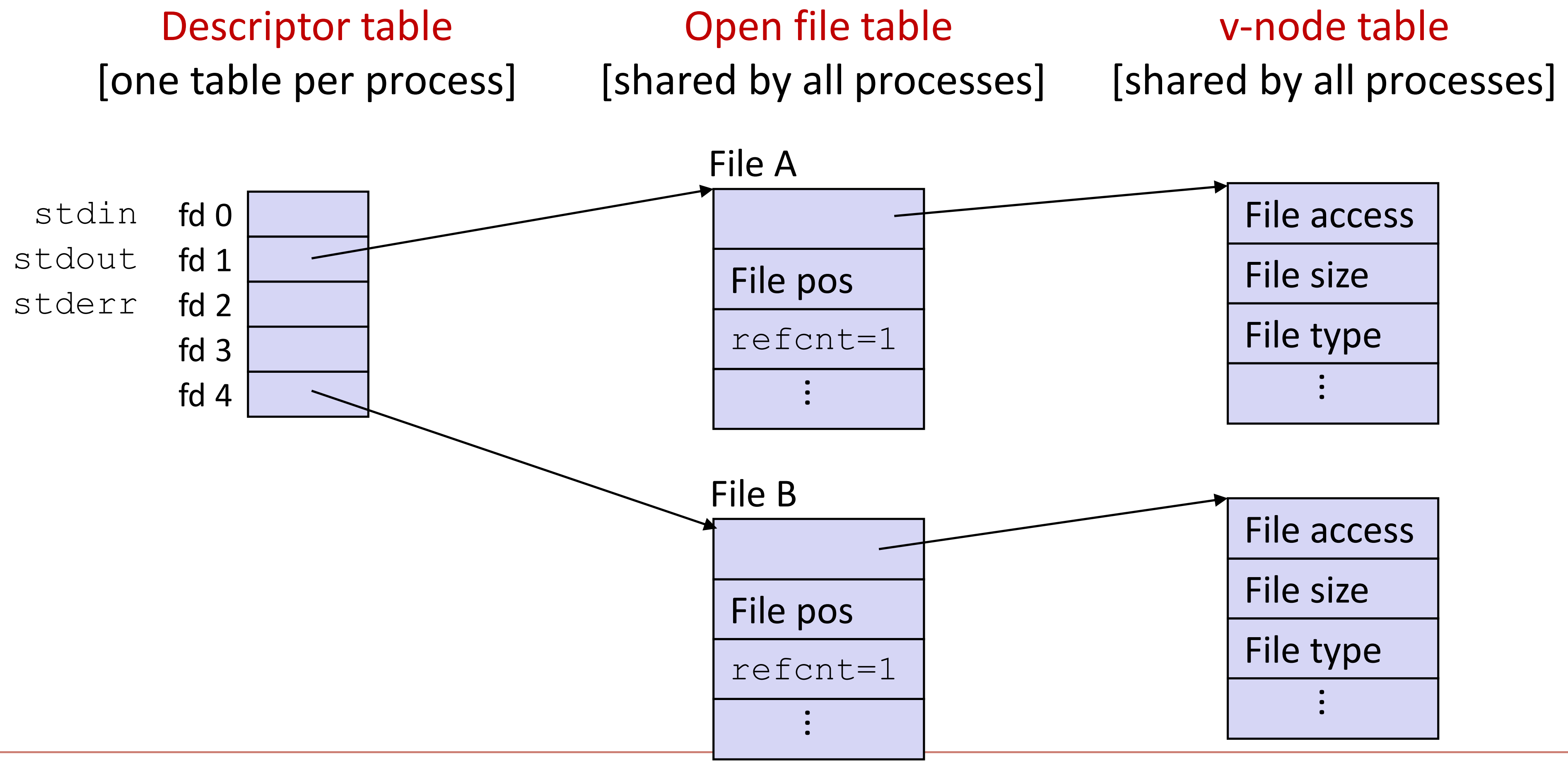
fd 0	
fd 1	a
fd 2	
fd 3	
fd 4	b

Descriptor table
after `dup2(4,1)`

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

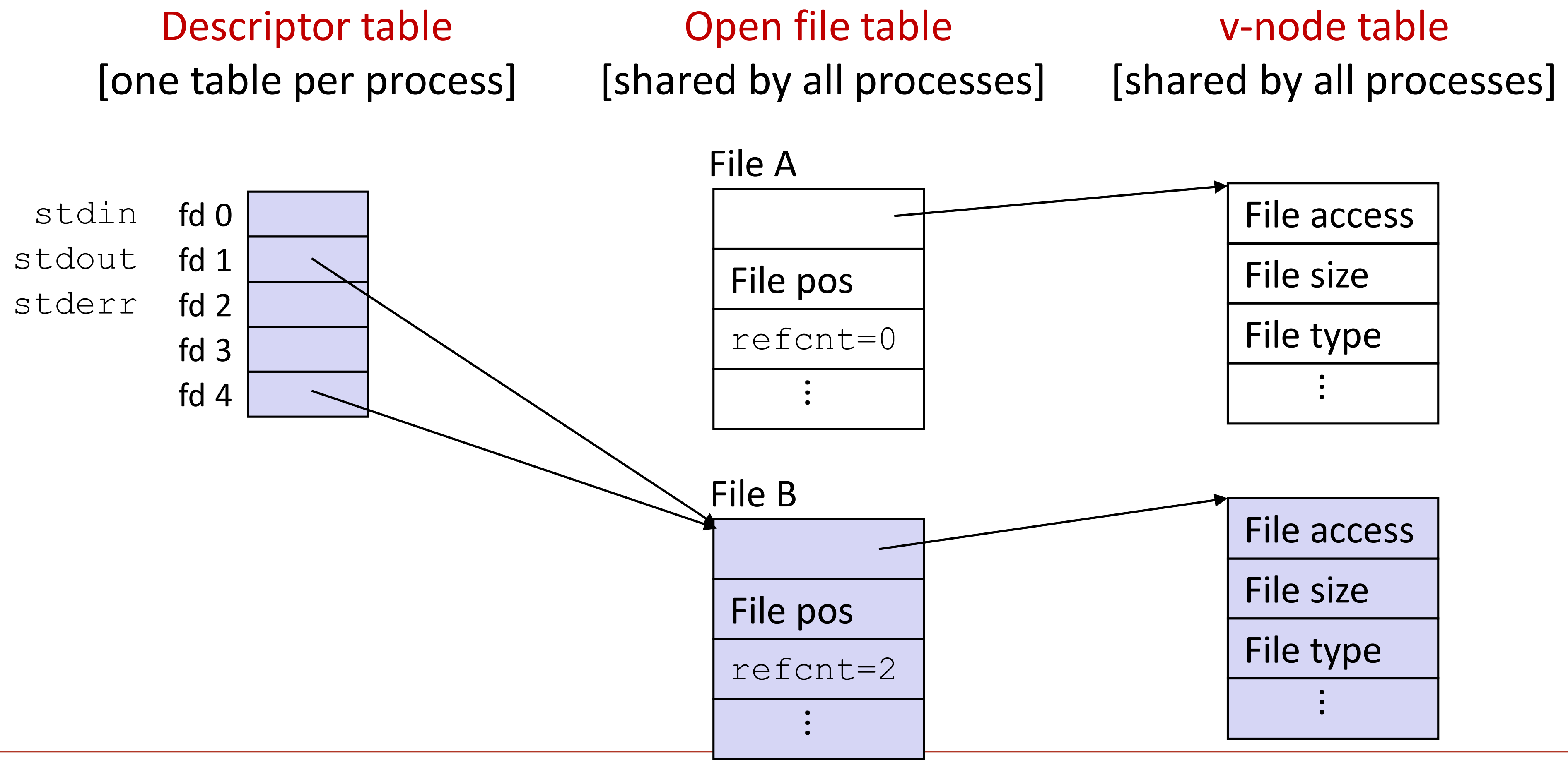
I/O Redirection Example

- **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



18-600 Foundations of Computer Systems

Lecture 17: "System Level I/O"

- Unix I/O
- RIO (Robust I/O) Package
- Metadata, Sharing, and Redirection
- **Standard I/O**
- Closing Remarks

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

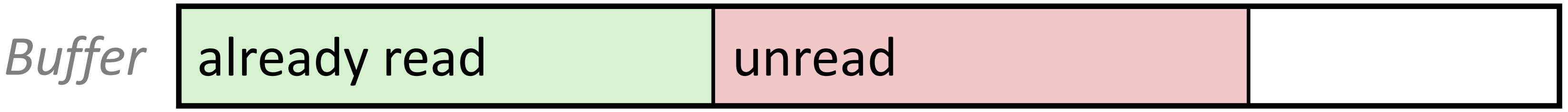
- **Standard I/O models open files as *streams***
  - Abstraction for a file descriptor and a buffer in memory

- **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");
}
```

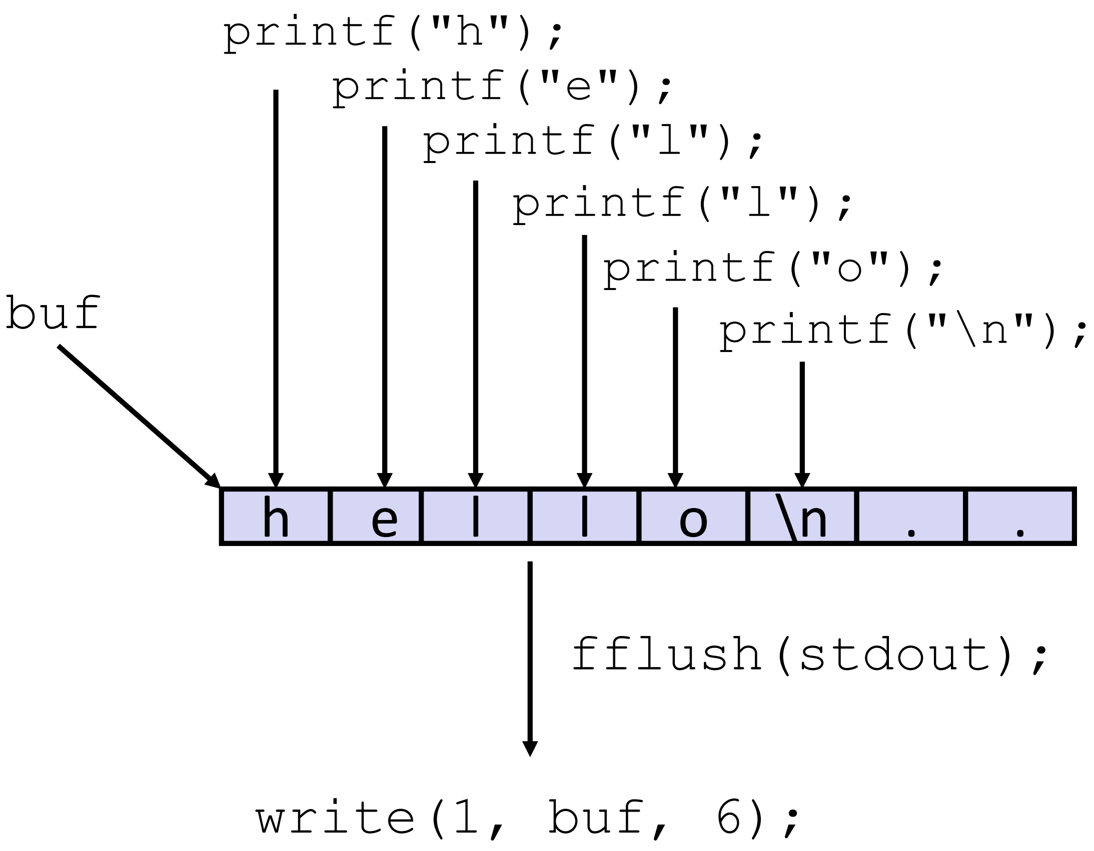
Buffered I/O: Motivation

- **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)                          = ?
```

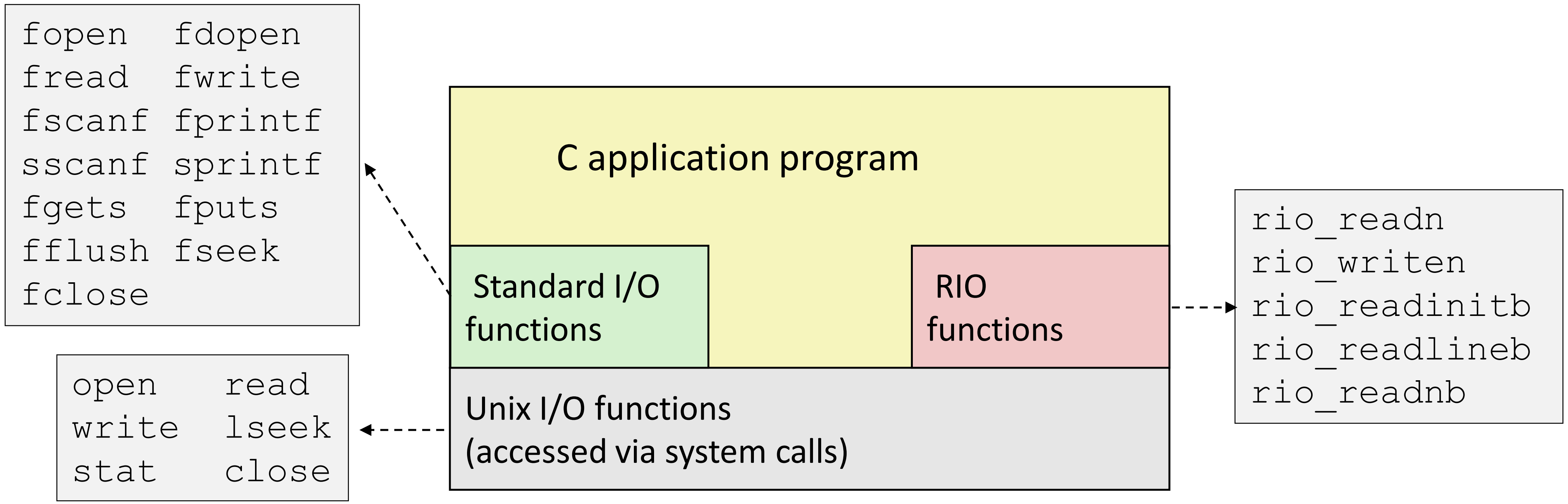
18-600 Foundations of Computer Systems

Lecture 17: "System Level I/O"

- Unix I/O
- RIO (Robust I/O) Package
- Metadata, Sharing, and Redirection
- Standard I/O
- **Closing Remarks**

Unix I/O vs. Standard I/O vs. RIO

- **Standard I/O and RIO are implemented using low-level Unix I/O**



- **Which ones should you use in your programs?**

Pros and Cons of Unix 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 and RIO packages

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 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
- **When to use RIO**
  - When you are reading and writing network sockets
  - Avoid using standard I/O on sockets

Aside: What's wrong with this snippet?

```
void incorrect_password(const char *user) {
  int ret;
  /* User names are restricted to 256 or fewer characters */
  static const char msg_format[] = "%s cannot be
authenticated.\n";
  size_t len = strlen(user) + sizeof(msg_format);
  char *msg = (char *)malloc(len);
  if (msg == NULL) {
    /* Handle error */
  }
  ret = snprintf(msg, len, msg_format, user);
  if (ret < 0) {
    /* Handle error */
  } else if (ret >= len) {
    /* Handle truncated output */
  }
  fprintf(stderr, msg);
  free(msg);
}
```

Security Violation

- **NEVER use a USER input string as the format for a *printf**
  - The user can create an exploit against your program this way
  - Check the "%n" format string
- **Acceptable solutions**
  - `fprintf(stream, "%s: cannot be authenicated", user); /* won't get evaluated again by *printf */`
  - -OR-
  - `fputs(msg, stream); /* fputs doesn't evaluate msg again */`
- **NEVER use `gets`**
  - There is absolutely no safe way to use that function

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

For Further Information

- **The Unix bible:**
  - W. Richard Stevens & Stephen A. Rago, ***Advanced Programming in the Unix Environment***, 2nd Edition, Addison Wesley, 2005
    - Updated from Stevens's 1993 classic text

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

Extra Slides

Fun with File Descriptors (1)

```
#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"?**

Fun with File Descriptors (2)

```
#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"?**

Fun with File Descriptors (3)

```
#include "csapp.h"
int main(int argc, char *argv[])
{
    int fd1, fd2, fd3;
    char *fname = argv[1];
    fd1 = Open(fname, O_CREAT|O_TRUNC|O_RDWR, S_IRUSR|S_IWUSR);
    Write(fd1, "pqrs", 4);
    fd3 = Open(fname, O_APPEND|O_WRONLY, 0);
    Write(fd3, "jklmn", 5);
    fd2 = dup(fd1);  /* Allocates descriptor */
    Write(fd2, "wxyz", 4);
    Write(fd3, "ef", 2);
    return 0;
}                                                    ffiles3.c
```

- **What would be the contents of the resulting file?**

Accessing Directories

- **Only recommended operation on a directory: read its entries**
  - **`dirent`** structure contains information about a directory entry
  - DIR structure contains information about directory while stepping through its entries

```
#include <sys/types.h>
#include <dirent.h>

{
  DIR *directory;
  struct dirent *de;
  ...
  if (!(directory = opendir(dir_name)))
      error("Failed to open directory");
  ...
  while (0 != (de = readdir(directory))) {
      printf("Found file: %s\n", de->d_name);
  }
  ...
  closedir(directory);
}
```

18-600 Foundations of Computer Systems

Lecture 18:
"Virtual Memory Concepts and Systems"

John P. Shen & Zhiyi Yu
November 2, 2016

Next Time …

- Required Reading Assignment:
  - **Chapter 9 of CS:APP (3rd edition) by Randy Bryant & Dave O'Hallaron.**

Electrical & Computer ENGINEERING