System-Level I/O

15-213 / 18-213: Introduction to Computer Systems
15th Lecture, Oct. 16, 2014

Instructors:

Greg Ganger, Greg Kesden, and Dave O'Hallaron

Today

- **Unix I/O**
- Metadata, sharing, and redirection
- Standard I/O
- RIO (robust I/O) package
- Closing remarks

Unix Files

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

- All I/O devices are represented as files:
  - **`/dev/sda2`** (**`/usr`** disk partition)
  - **`/dev/tty2`** (terminal)

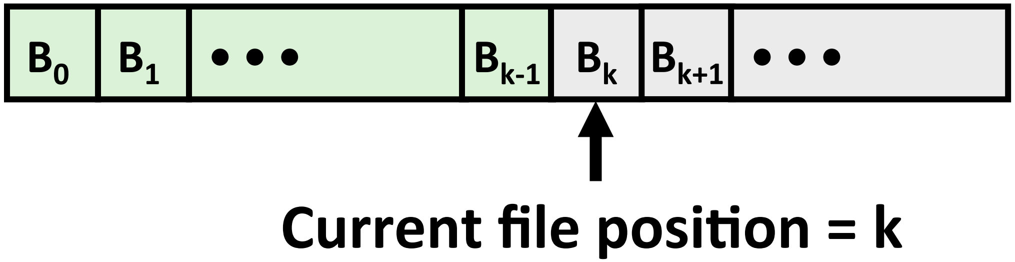
- Even the kernel is represented as a file:
  - **`/dev/kmem`** (kernel memory image)
  - **`/proc`** (kernel data structures)

Unix File Types

- **Regular file**
  - File containing user/app data (binary, text, whatever)
  - OS does not know anything about the format
    - other than "sequence of bytes", akin to main memory
- **Directory file**
  - A file that contains the names and locations of other files
- **Character special and block special files**
  - Terminals (character special) and disks (block special)
- **FIFO (named pipe)**
  - A file type used for inter-process communication
- **Socket**
  - A file type used for network communication between processes

Unix I/O

- **Key Features**
  - Elegant mapping of files to devices allows kernel to export simple interface called Unix I/O
  - Important idea: All input and output is handled in a consistent and uniform way
- **Basic Unix I/O operations (system calls):**
  - 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()`**



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 Unix shell begins life with three open files associated with a terminal:**
  - 0: standard input
  - 1: standard output
  - 2: standard error

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 standard in to standard out, one byte at a time

```
int main(void)
{
    char c;
    int len;

    while ((len = read(0 /*stdin*/, &c, 1)) == 1) {
        if (write(1 /*stdout*/, &c, 1) != 1) {
            exit(20);
        }
    }
    if (len < 0) {
        printf ("read from stdin failed");
        exit (10);
    }
    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 or Unix pipes

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

Today

- Unix I/O
- **Metadata, sharing, and redirection**
- Standard I/O
- RIO (robust I/O) package
- 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

```
/* statcheck.c - Querying and manipulating a file's meta data */
#include "csapp.h"

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

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

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

statcheck.c

```
unix> ./statcheck statcheck.c
type: regular, read: yes
unix> chmod 000 statcheck.c
unix> ./statcheck statcheck.c
type: regular, read: no
unix> ./statcheck ..
type: directory, read: yes
unix> ./statcheck /dev/kmem
type: other, read: yes
```

Repeated Slide: Opening Files

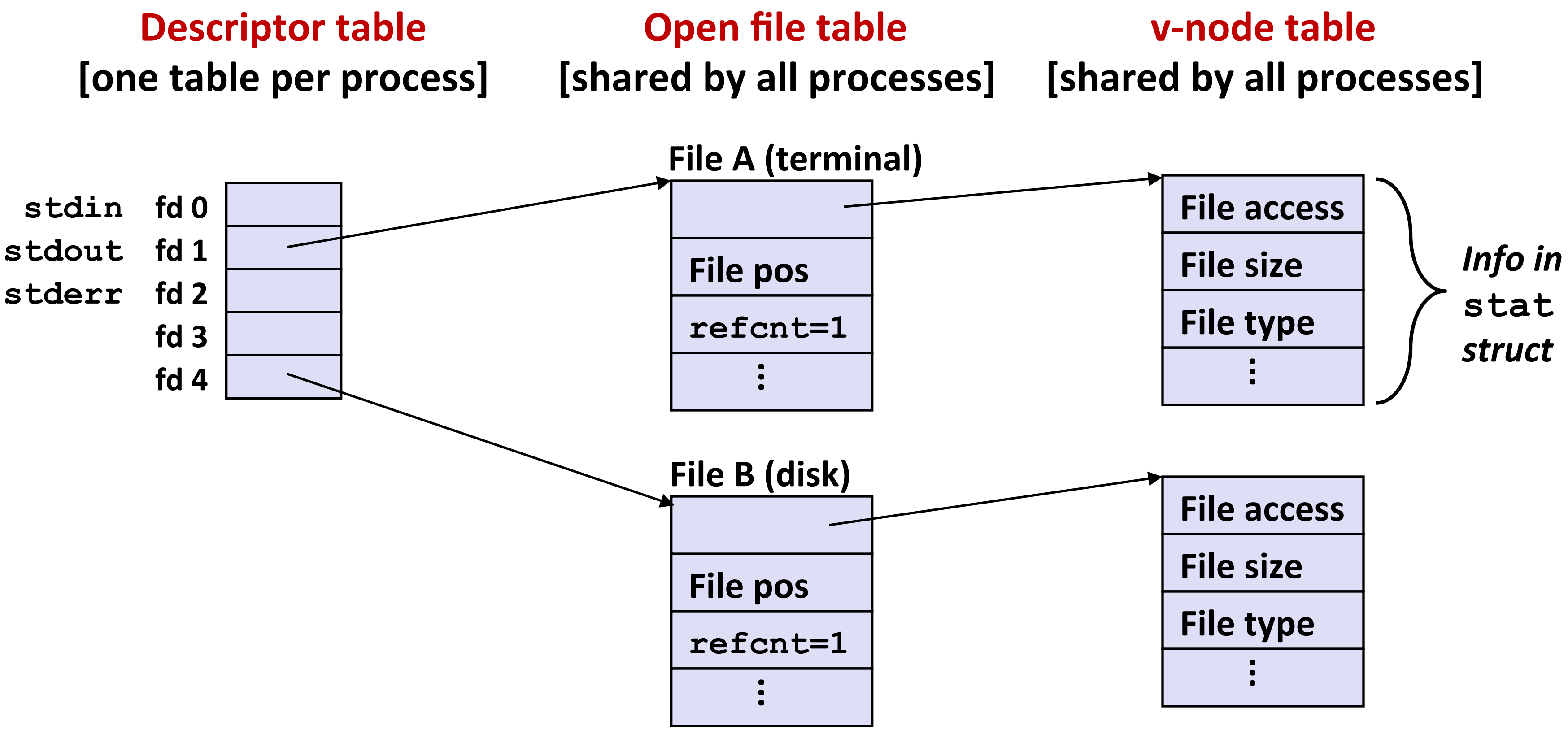
- **Opening a file informs the kernel that you are getting ready to access that file**

```
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

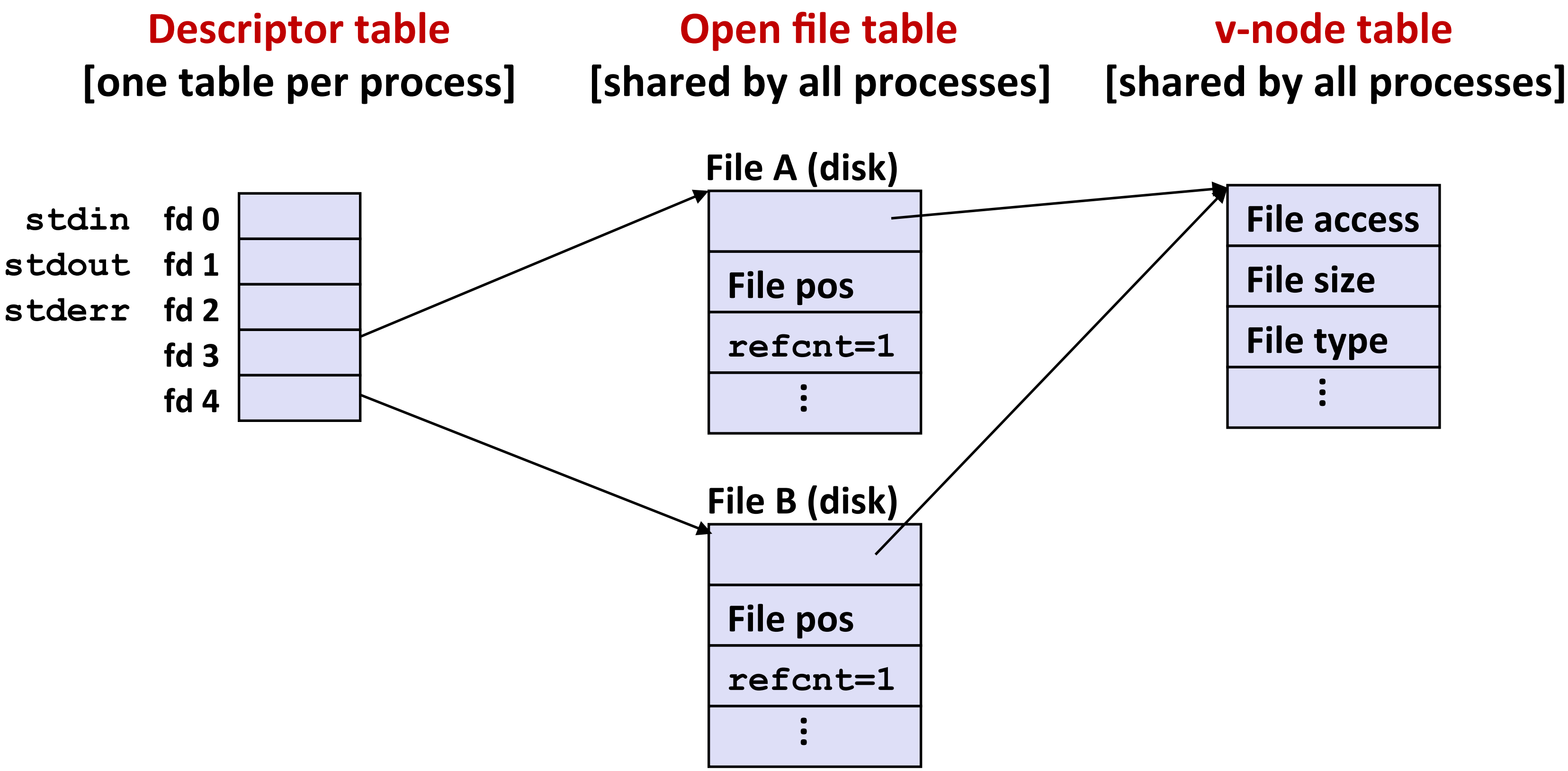
How the Unix Kernel Represents Open Files

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



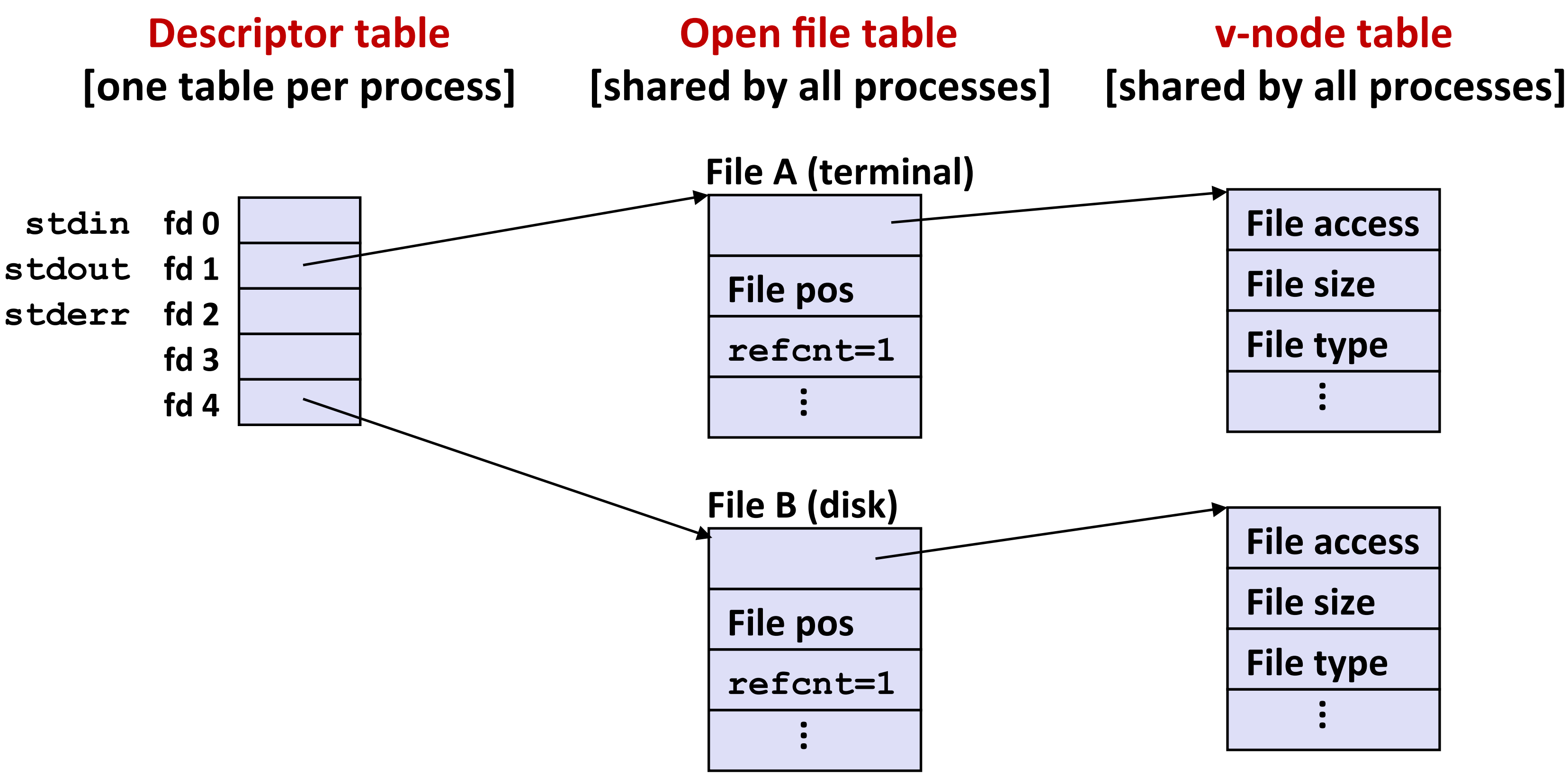
File Sharing

- **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



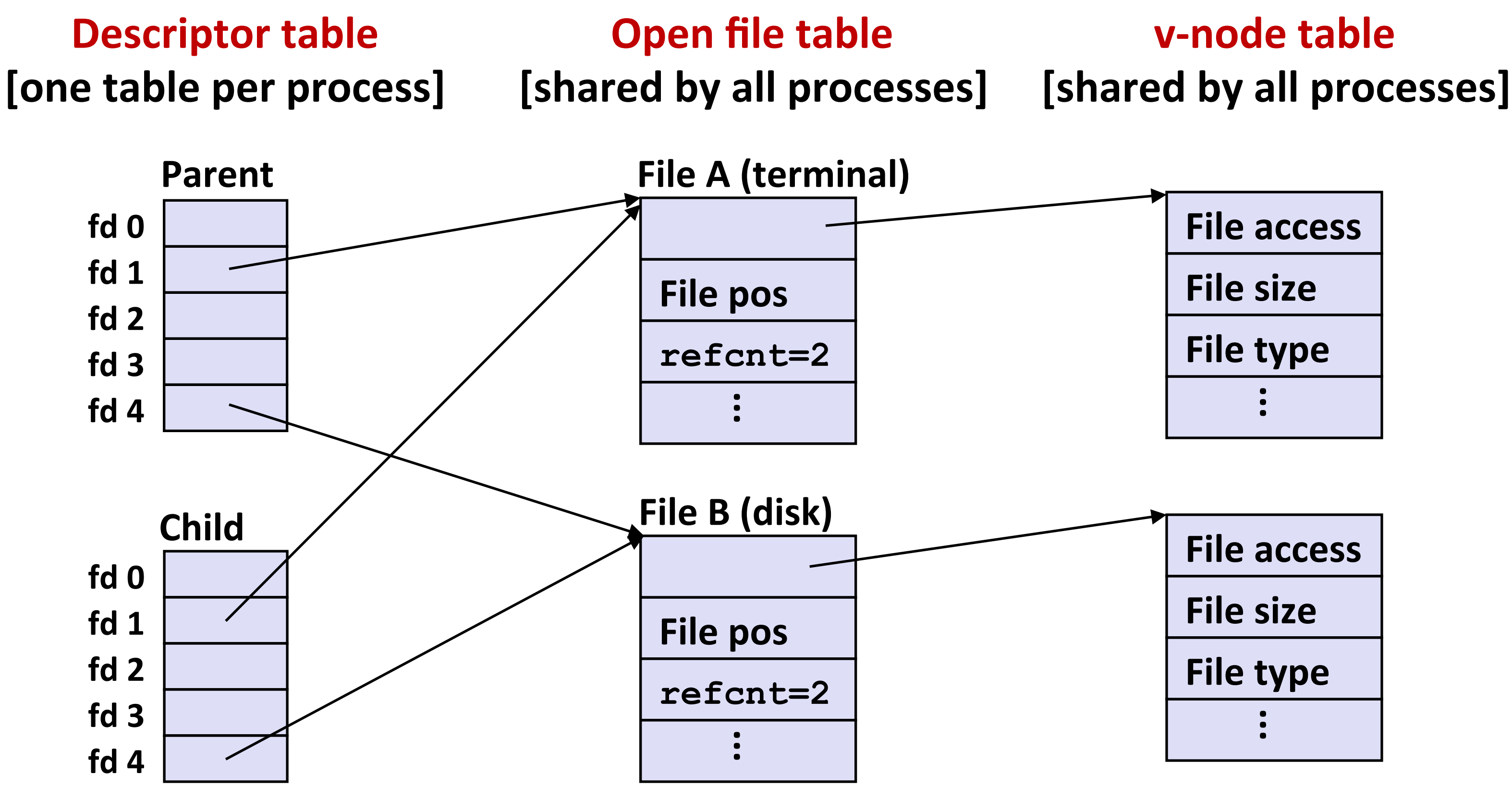
How Processes Share Files: Fork()

- 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?**

  `unix> 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)`**

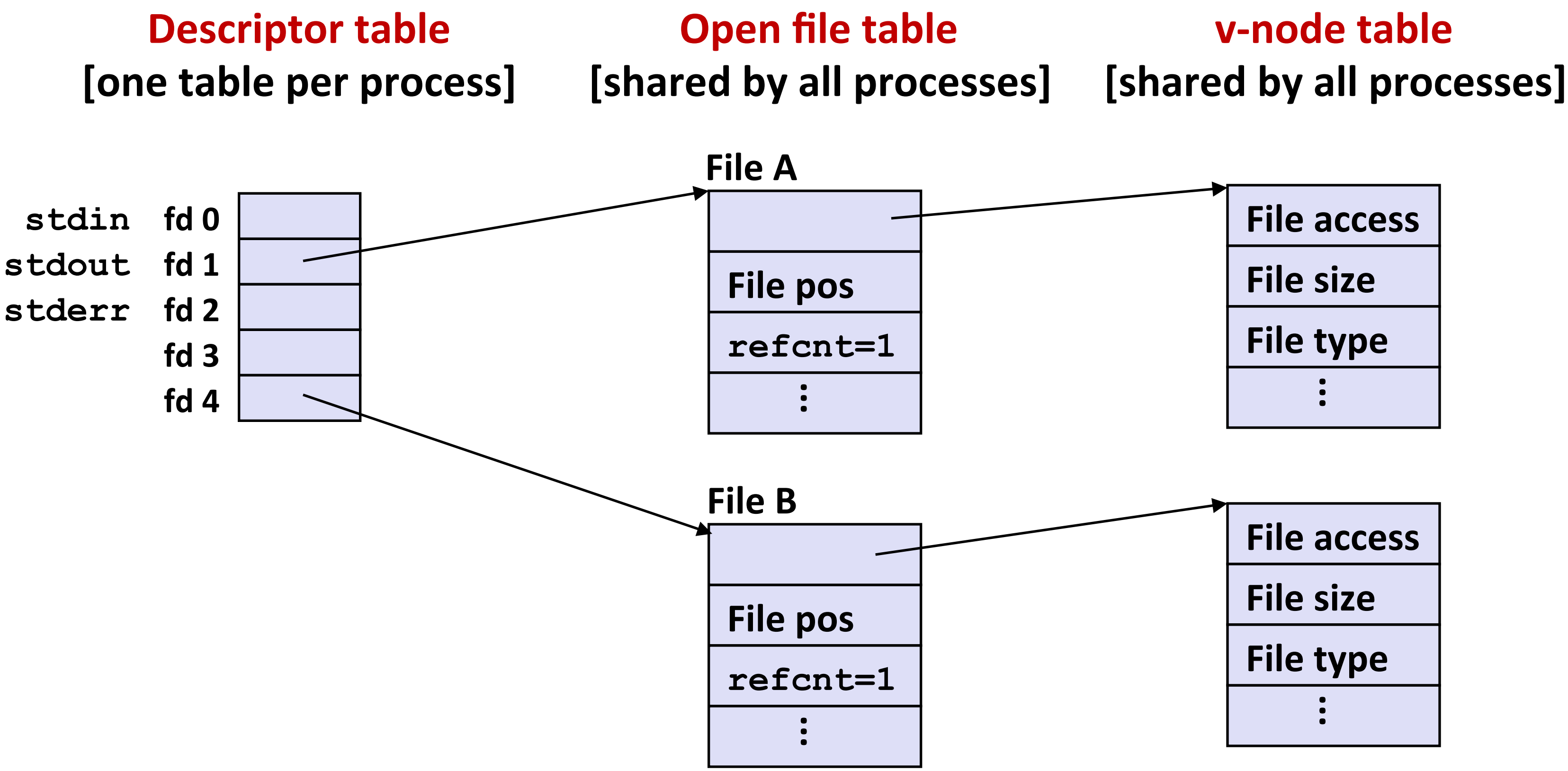
fd 0	
fd 1	a
fd 2	
fd 3	
fd 4	b

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

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

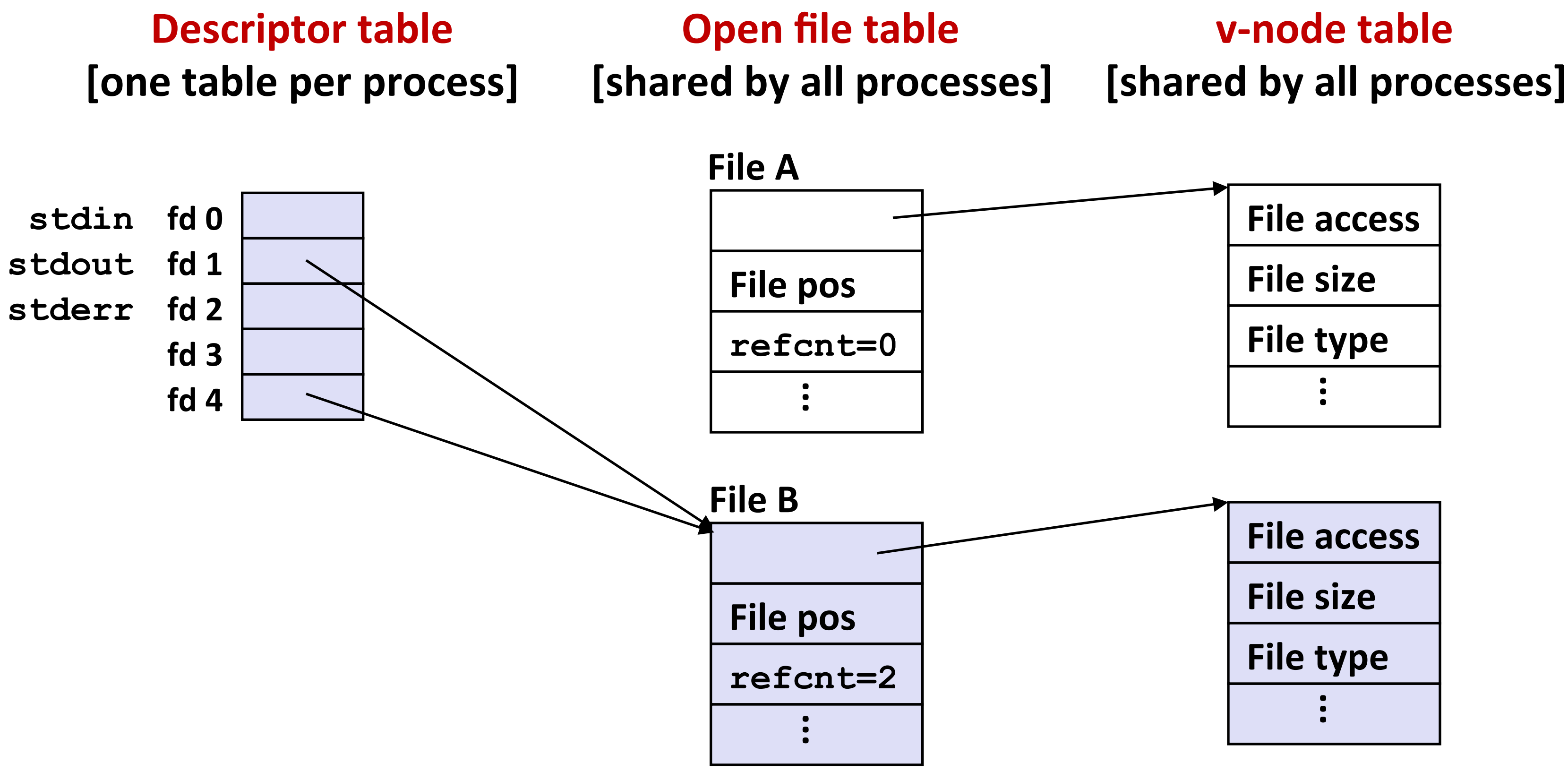
I/O Redirection Example

- **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



Today

- Unix I/O
- Metadata, sharing, and redirection
- **Standard I/O**
- RIO (robust I/O) package
- 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

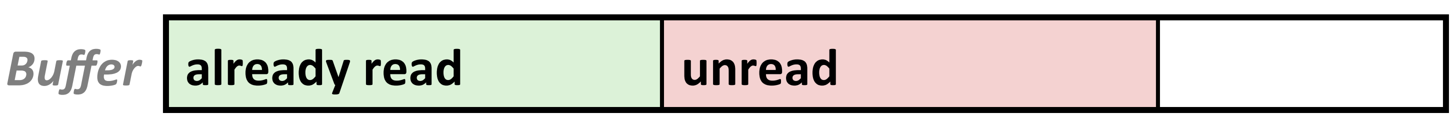
- **Standard I/O models open files as *streams***
  - Abstraction for a file descriptor and a buffer in memory

- **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");
}
```

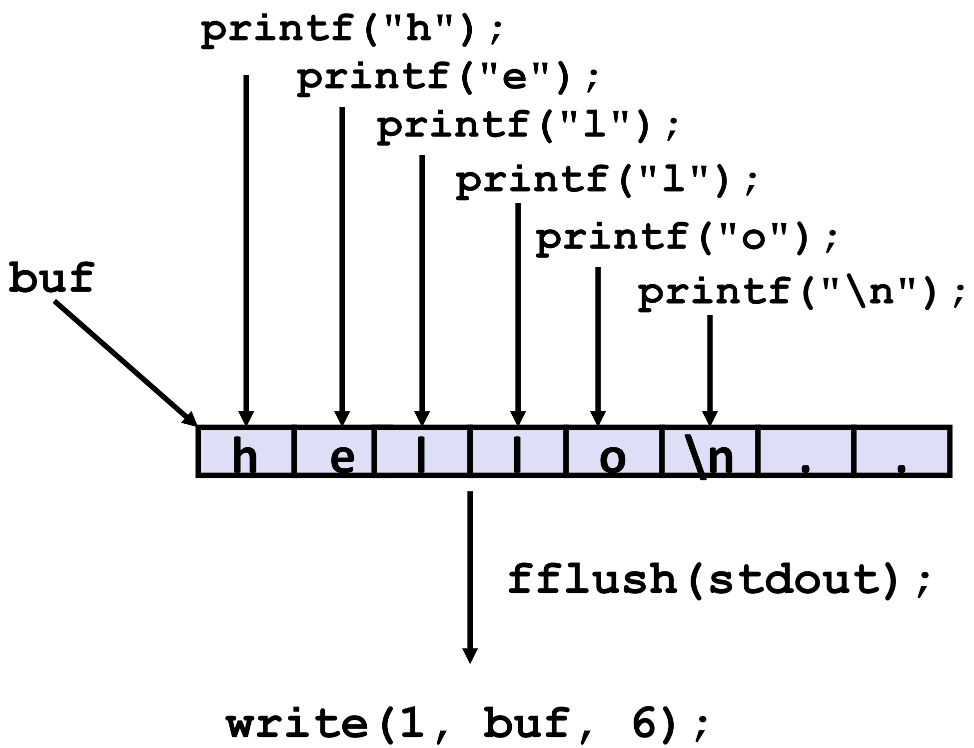
Buffered I/O: Motivation

- **Applications often read/write one character at a time**
  - `getc, putc, ungetc`
  - `gets, fgets`
    - Read line of text on 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" or `fflush()` call

Standard I/O Buffering in Action

- You can see this buffering in action for yourself, using the always fascinating Unix `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)                             = ?
```

Today

- Unix I/O
- Metadata, sharing, and redirection
- Standard I/O
- **RIO (robust I/O) package**
- 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 binary data and text lines
    - **`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/public/code.html**

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

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 */
}
```

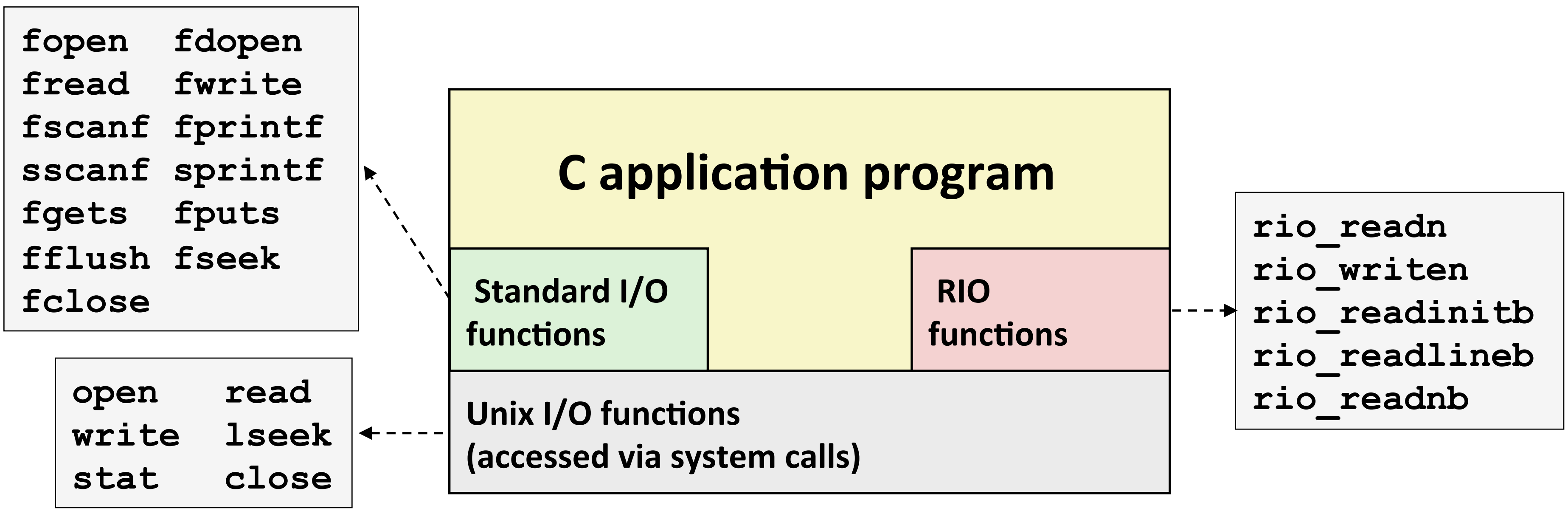
csapp.c

Today

- Unix I/O
- Metadata, sharing, and redirection
- Standard I/O
- RIO (robust I/O) package
- **Closing comments**

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:APP2e, Sec 10.9)

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: Working with Binary Files

- **Binary File Examples**
  - Object code, Images (JPEG, GIF),
- **Functions you shouldn't use on binary files**
  - Line-oriented I/O such as **`fgets, scanf, printf, rio_readlineb`**
    - Different systems interpret **`0x0A ('\n')`** (newline) differently:
      - Linux and Mac OS X: **`LF(0x0a) ['\n']`**
      - HTTP servers & Windoes: **`CR+LF(0x0d 0x0a) ['\r\n']`**
    - Use things like **`rio_readn`** or **`rio_readnb`** instead
  - String functions
    - **`strlen, strcpy`**
    - 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

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);
}
```

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);
```

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)

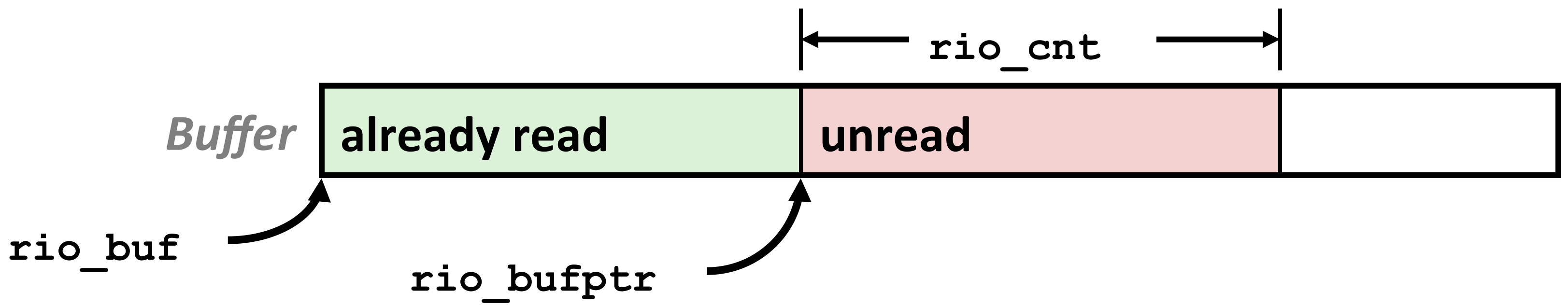
```
#include "csapp.h"

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

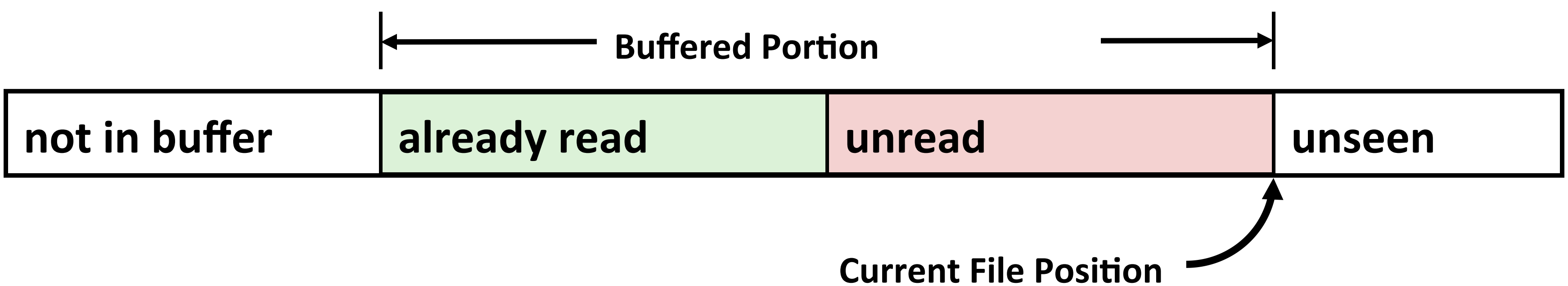
- **`rio_readnb`** reads up to **`n`** bytes from file **`fd`**
- Stopping conditions
  - **`maxlen`** bytes read
  - EOF encountered
- Calls to **`rio_readlineb`** and **`rio_readnb`** can be interleaved arbitrarily on the same descriptor
  - Warning: Don't interleave with calls to **`rio_readn`**

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

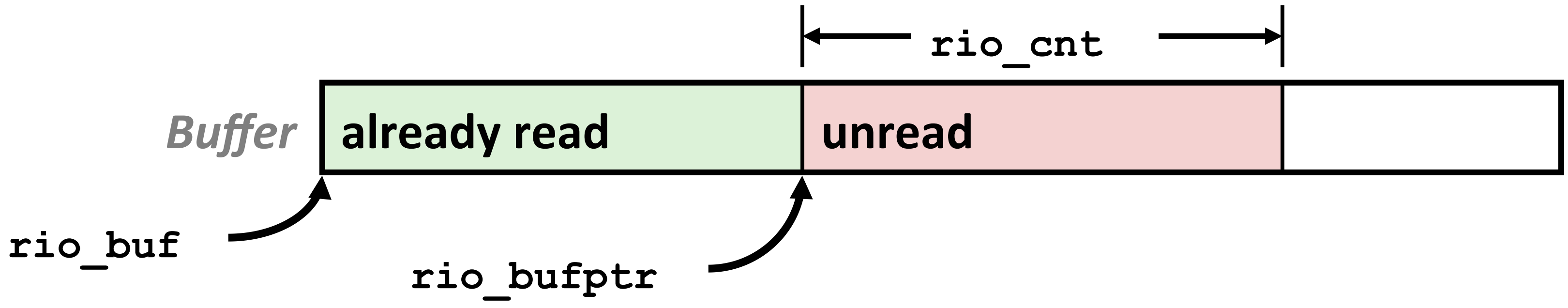


- Layered on Unix file:



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