

# System-Level I/O

**Computer Systems**

Nov. 20, 2018

Troels Henriksen

**Based on slides by:**

Randal E. Bryant and David R. O'Hallaron

# Today

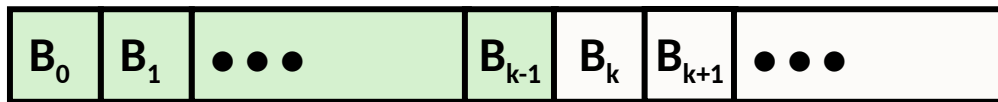
- **Unix I/O**
- RIO (robust I/O) package
- Metadata, sharing, and redirection
- Standard I/O
- Closing remarks

# Unix I/O Overview

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



Current file position =  $k$

# 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, PDFs
  - 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 macOS: '\n' (0xA)
  - Windows and Internet protocols: '\r\n' (0xD 0xA)
    - Carriage return (CR) followed by line feed (LF)
  - C64, Pre-OS X Mac OS, Lisp Machines: '\r'

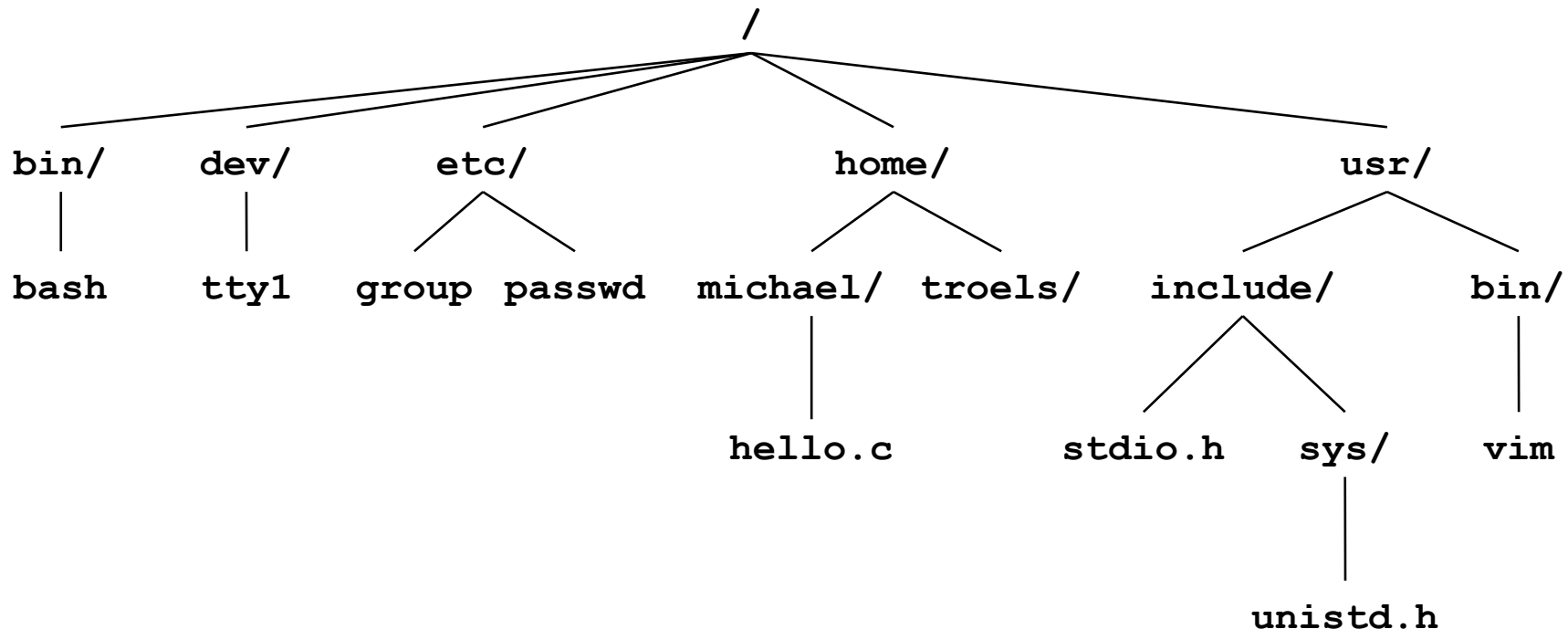


# Directories

- **Directory consists of an array of *links***
  - Each link maps a *filename* to an *inode*
  - An inode contains metadata and disk location of file.
  - Multiple links may point to same 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)



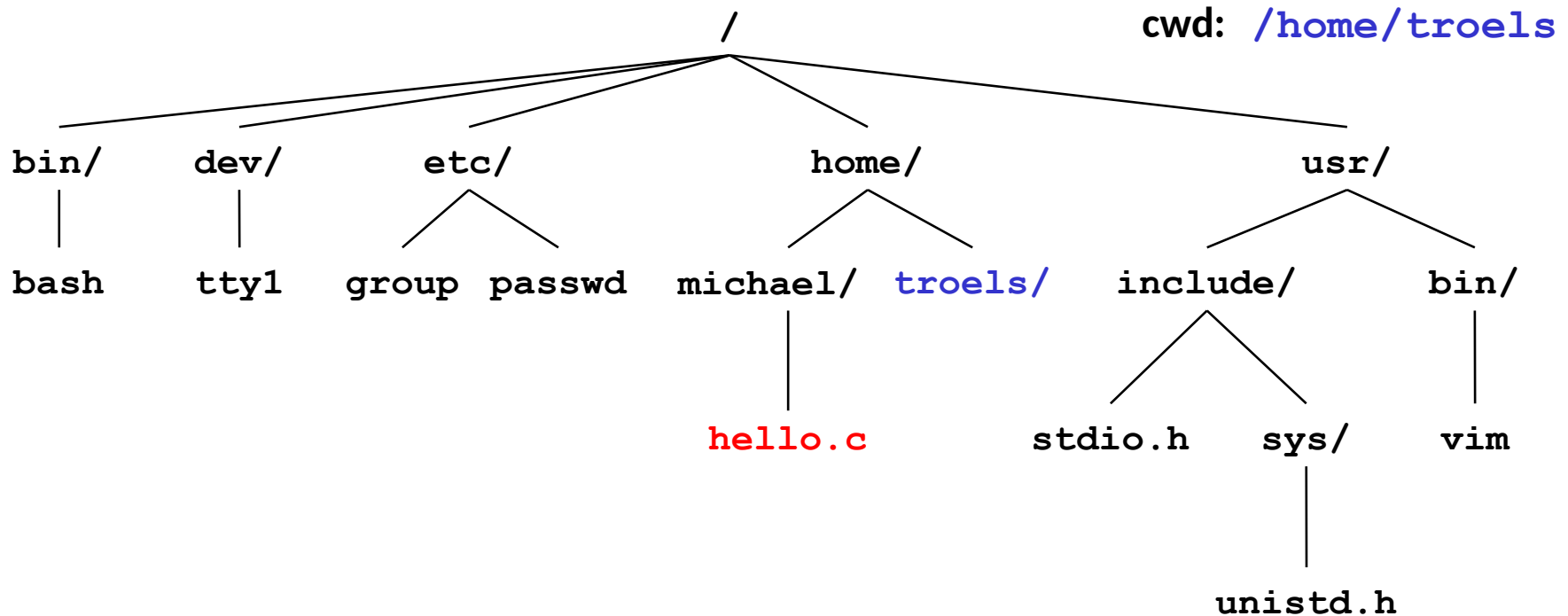
- Kernel maintains *current working directory (cwd)* for each process
  - Modified using the `cd` command or `chdir()` syscall
  - **Question:** is `cd` a normal program run by the shell with `fork+exec`?



# Pathnames

## ■ Locations of files in the hierarchy denoted by *pathnames*

- *Absolute pathname* starts with '/' and denotes path from root
  - `/home/troels/hello.c`
- *Relative pathname* denotes path from current working directory
  - `../home/troels/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 often occurs in these situations:**

- Encountering (end-of-file) EOF on reads
- Reading text lines from a terminal
- Reading and writing network sockets

- **Short counts rarely occurs in these situations:**

- Reading from disk files (except for EOF)
  - ...but may happen for huge reads.
- Writing to disk files
  - ...similarly.

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

- **Distinctly Unix:**

<https://www.dreamsongs.com/RiseOfWorselsBetter.html>

# Today

- 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);
```

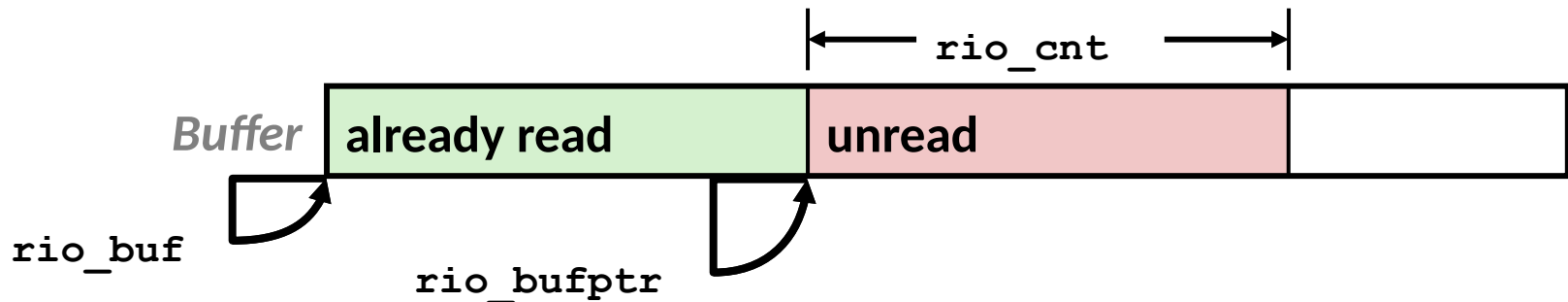
```
ssize_t rio_readnb(rio_t *rp, void *usrbuf, size_t n);
```

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

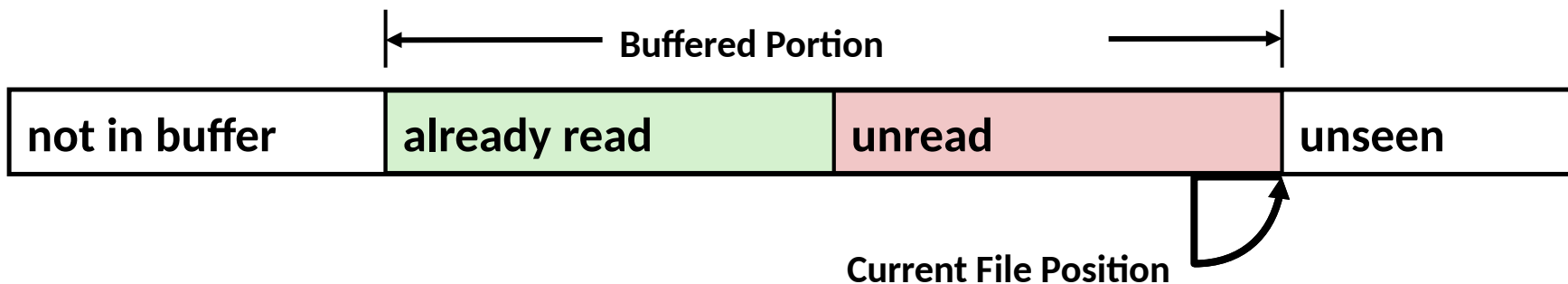
- **rio\_readnb** reads up to **n** bytes from file **fd**
- Stopping conditions
  - **maxlen** bytes read
  - EOF encountered
- Calls to **rio\_readlineb** and **rio\_readnb** can be interleaved arbitrarily on the same descriptor
  - Warning: Don't interleave with calls to **rio\_readn**

# 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

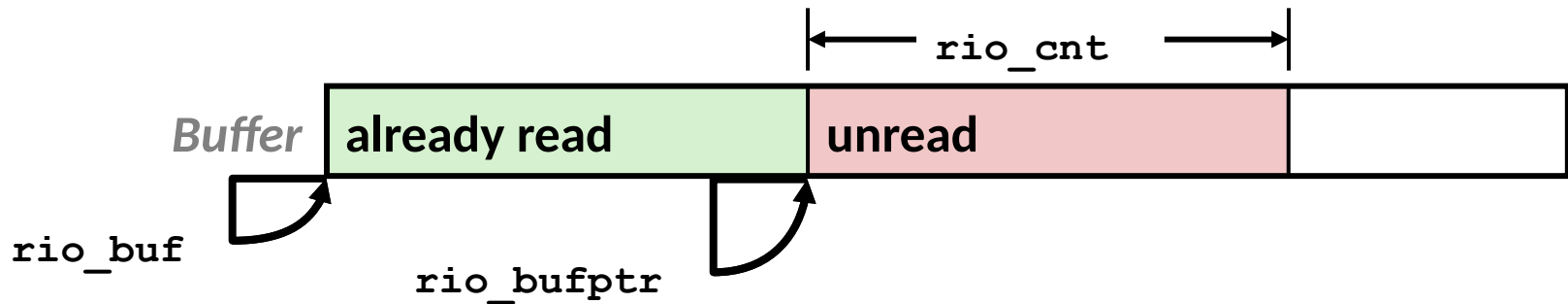


- Layered on Unix file:



# 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;
```

# Buffered I/O: Read some bytes

```
static ssize_t rio_read(rio_t *rp, char *usrbuf, size_t n)
{
    int cnt;

    while (rp->rio_cnt <= 0) { /* Refill if buf is empty */
        rp->rio_cnt = read(rp->rio_fd, rp->rio_buf,
                           sizeof(rp->rio_buf));
        if (rp->rio_cnt < 0) {
            if (errno != EINTR) /* Interrupted by sig handler return */
                return -1;
        }
        else if (rp->rio_cnt == 0) /* EOF */
            return 0;
        else
            rp->rio_bufptr = rp->rio_buf; /* Reset buffer ptr */
    }

    /* Copy min(n, rp->rio_cnt) bytes from internal buf to user buf */
    cnt = n;
    if (rp->rio_cnt < n)
        cnt = rp->rio_cnt;
    memcpy(usrbuf, rp->rio_bufptr, cnt);
    rp->rio_bufptr += cnt;
    rp->rio_cnt -= cnt;
    return cnt;
}
```

csapp.c



# Buffered I/O: Read $n$ bytes robustly

```
ssize_t rio_readnb(rio_t *rp, void *usrbuf, size_t n)
{
    size_t nleft = n;
    ssize_t nread;
    char *bufp = usrbuf;

    while (nleft > 0) {
        if ((nread = rio_read(rp, bufp, nleft)) < 0)
            return -1;          /* errno set by read() */
        else if (nread == 0)
            break;              /* EOF */
        nleft -= nread;
        bufp += nread;
    }
    return (n - nleft);          /* return >= 0 */
}
```

csapp.c

# 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

# Today

- 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

```
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)) /* Check read access */
        readok = "yes";
    else
        readok = "no";

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

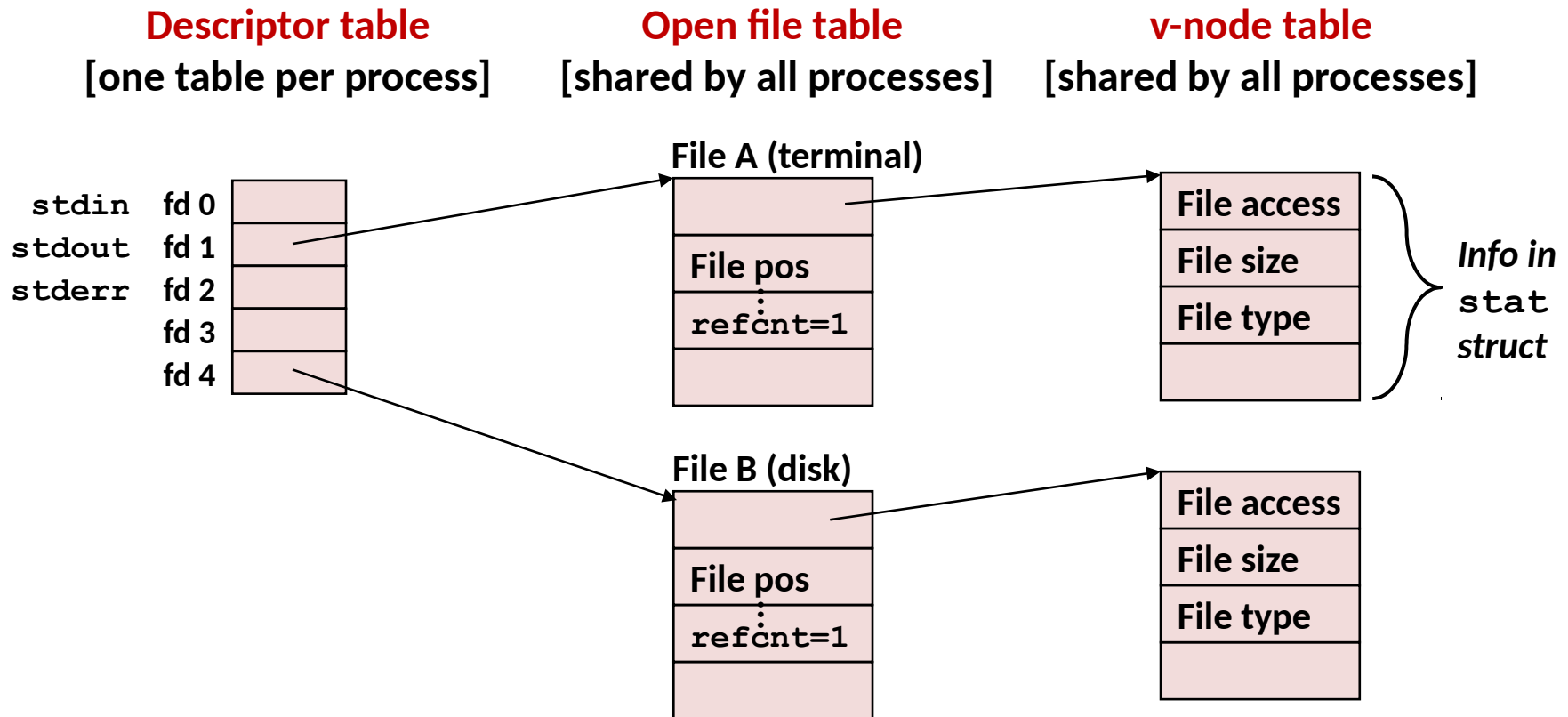
```
linux> ./statcheck statcheck.c
type: regular, read: yes
linux> chmod 000 statcheck.c
linux> ./statcheck statcheck.c
type: regular, read: no
linux> ./statcheck ..
type: directory, read: yes
```

/\* Determine file type \*/

statcheck.c

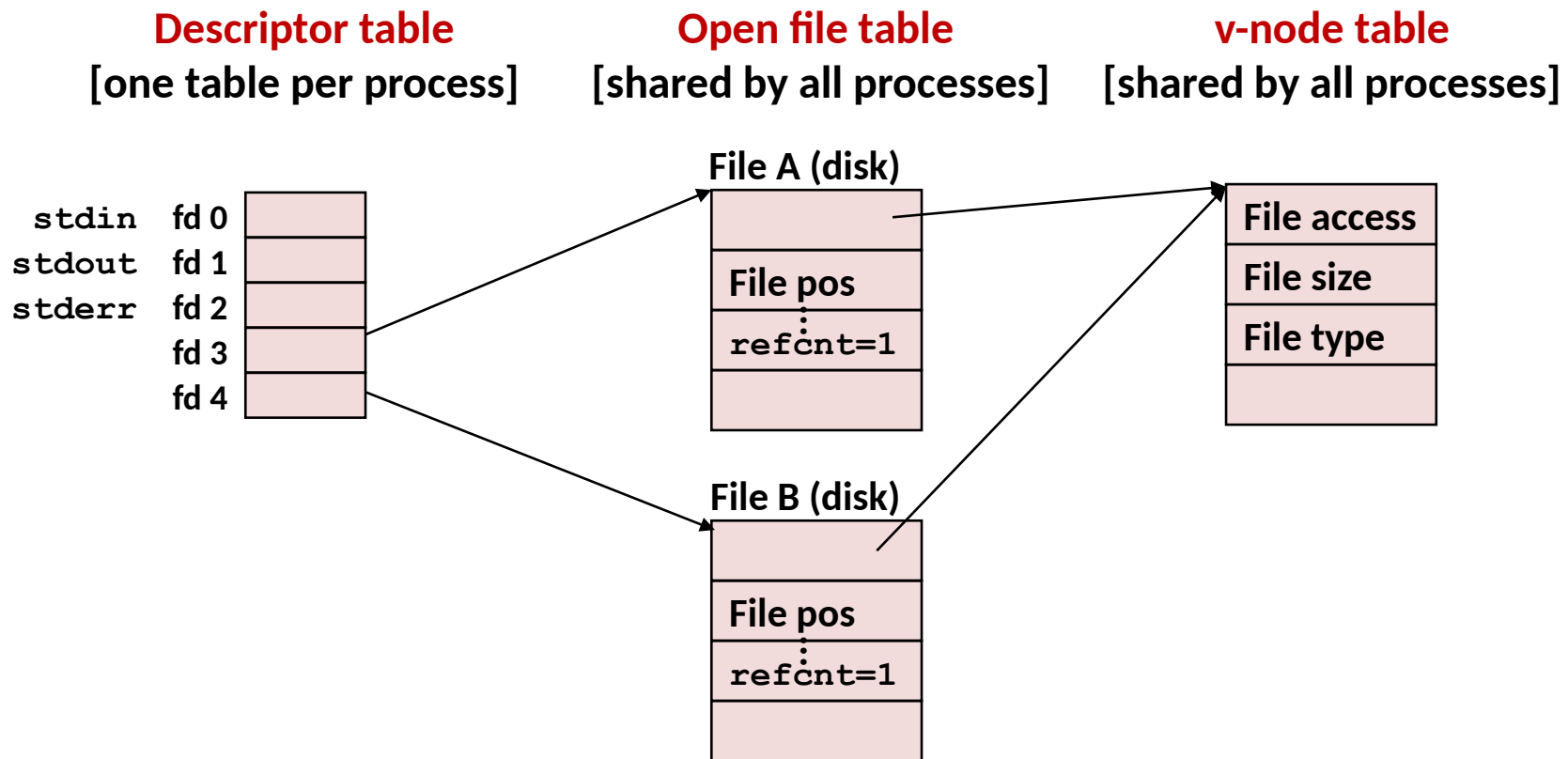
# How the Unix Kernel Represents Open Files

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



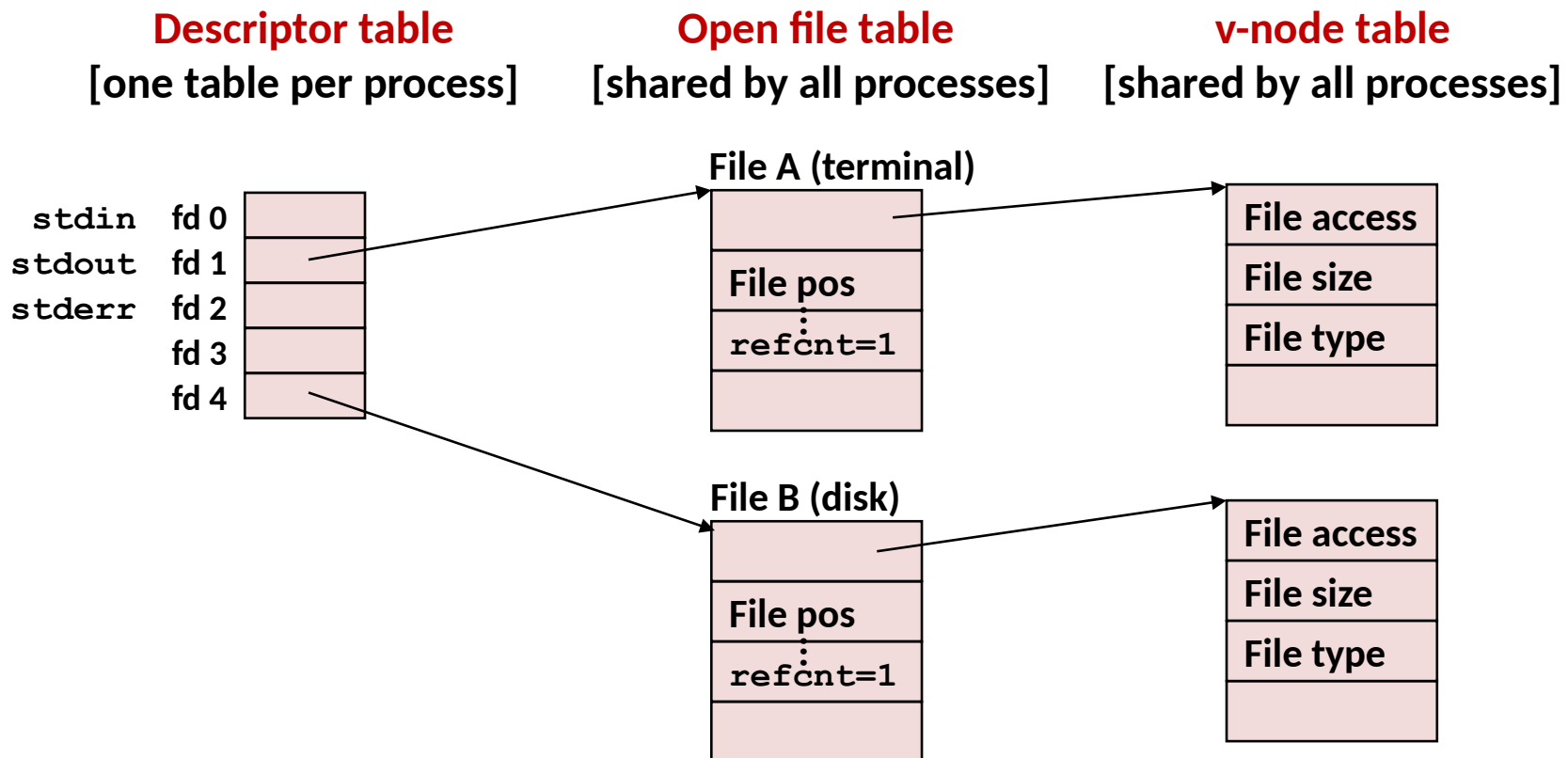
# File Sharing

- 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:**

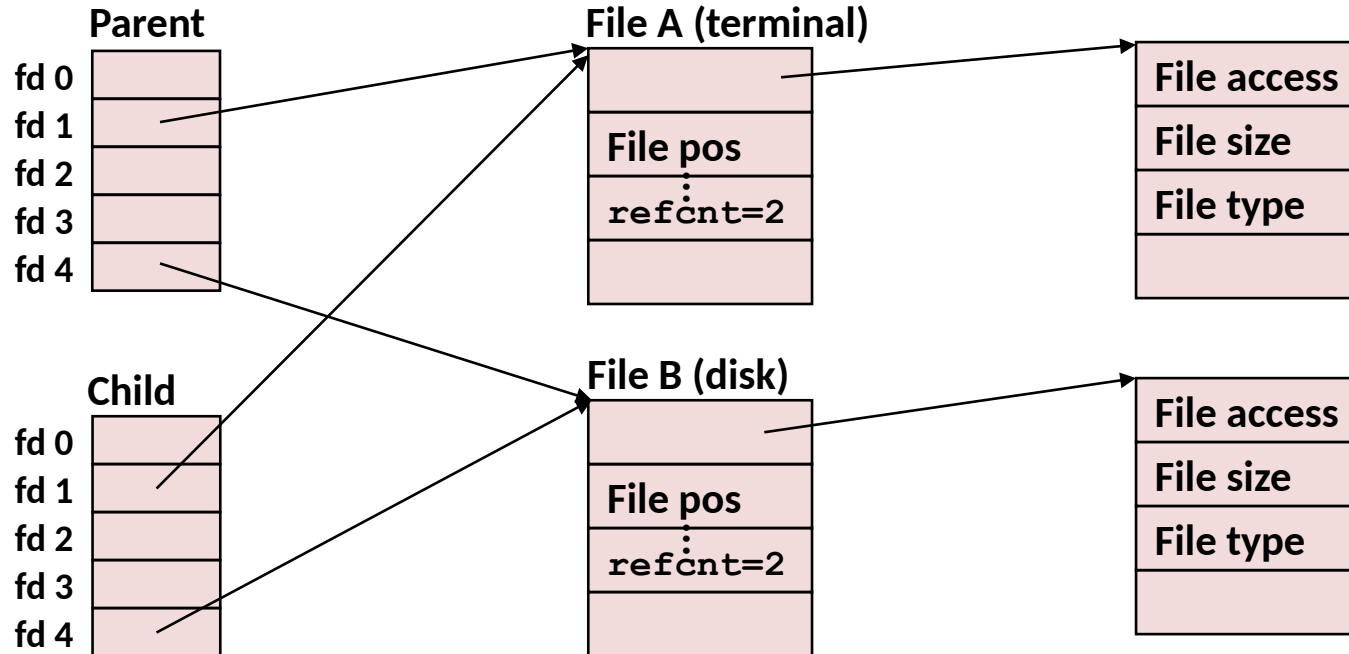




# How Processes Share Files: fork

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

**Descriptor table** [one table per process]      **Open file table** [shared by all processes]      **v-node table** [shared by all 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)`

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

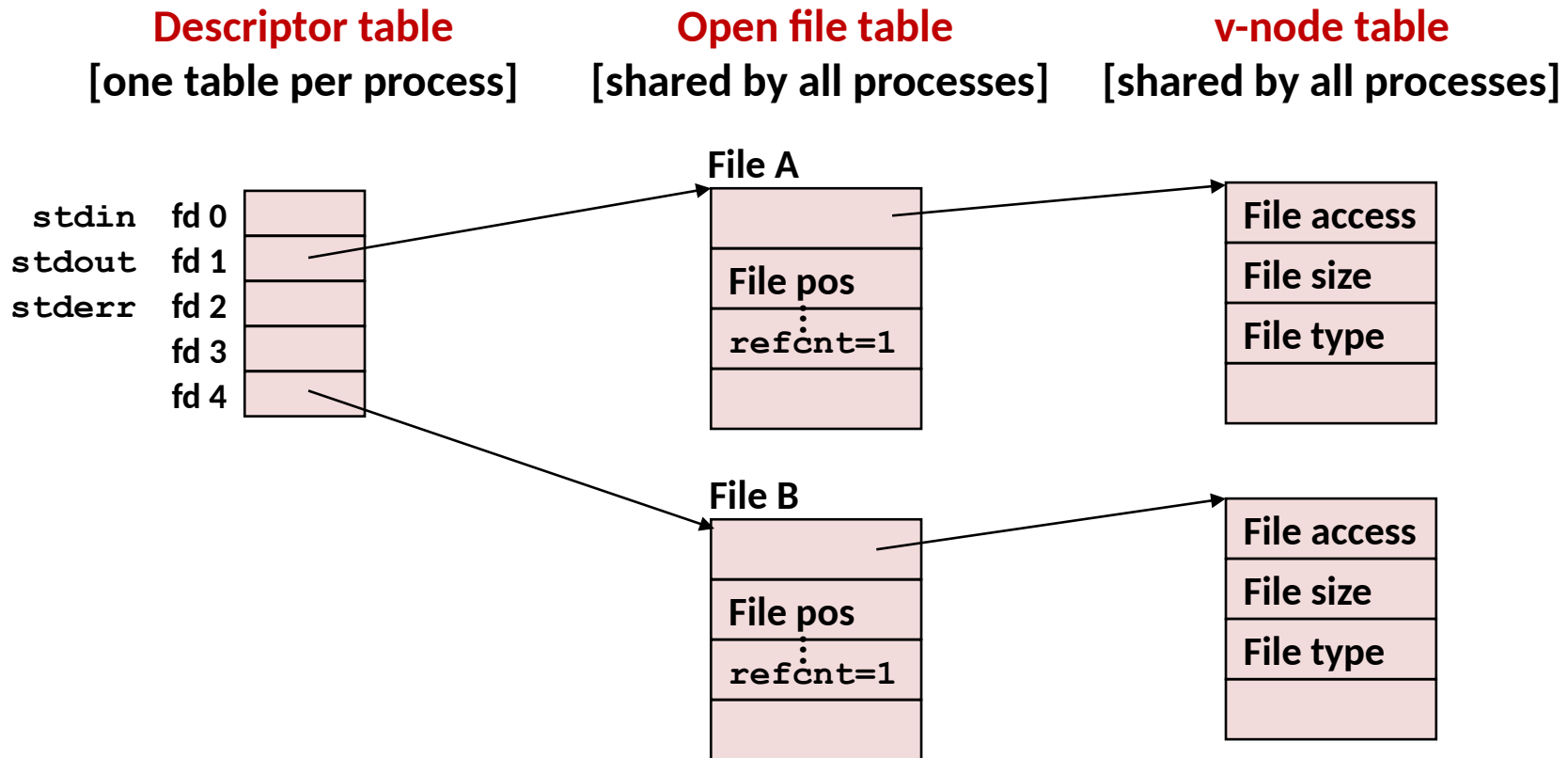


Descriptor table  
*after* `dup2 (4 , 1)`

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

### Descriptor table

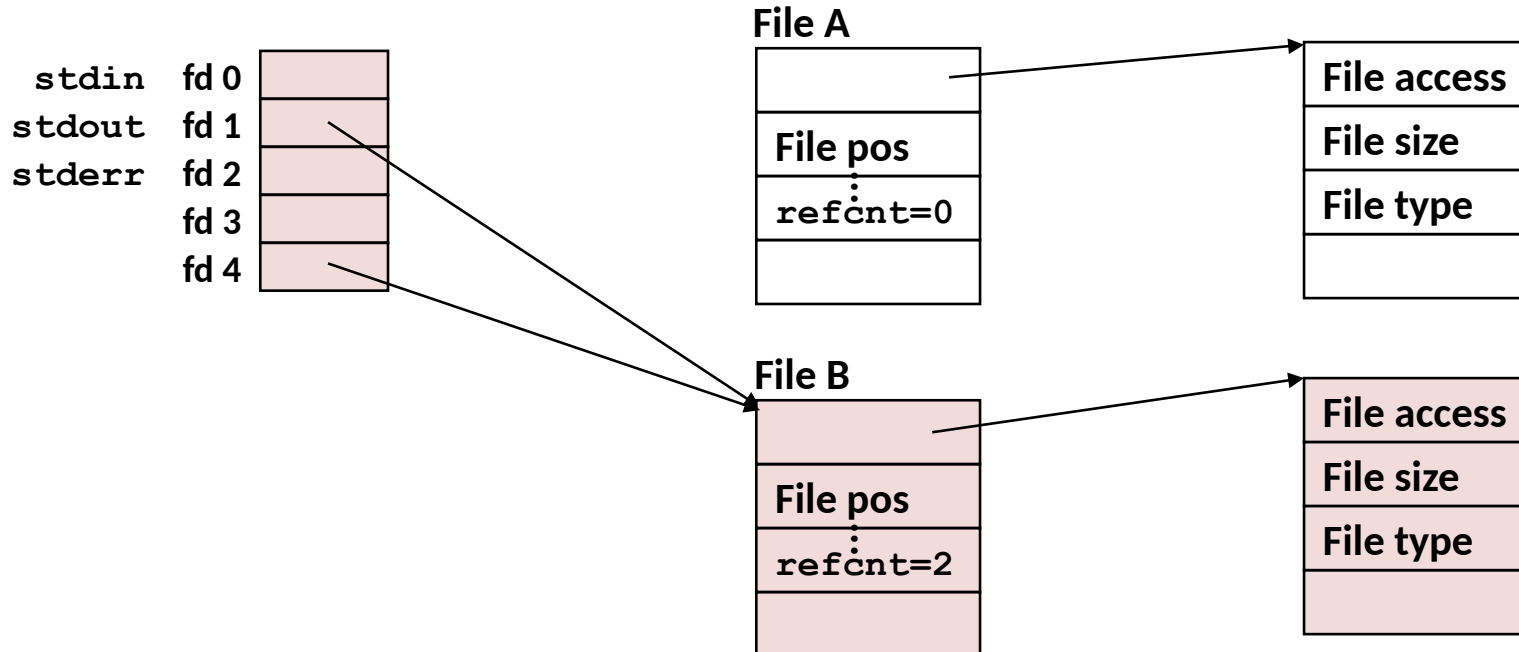
[one table per process]

### Open file table

[shared by all processes]

### v-node table

[shared by all processes]



# Today

- 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 8.2 of your C book
  - Or read the manpages!
- 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

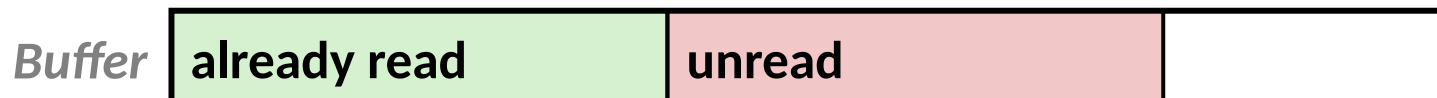
- Standard I/O models open files as *streams*
  - Abstraction for a file descriptor and a buffer in memory
- C programs begin life with three open streams (defined in `stdio.h`)
  - `stdin` (standard input)
  - `stdout` (standard output)
  - `stderr` (standard error)

```
#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

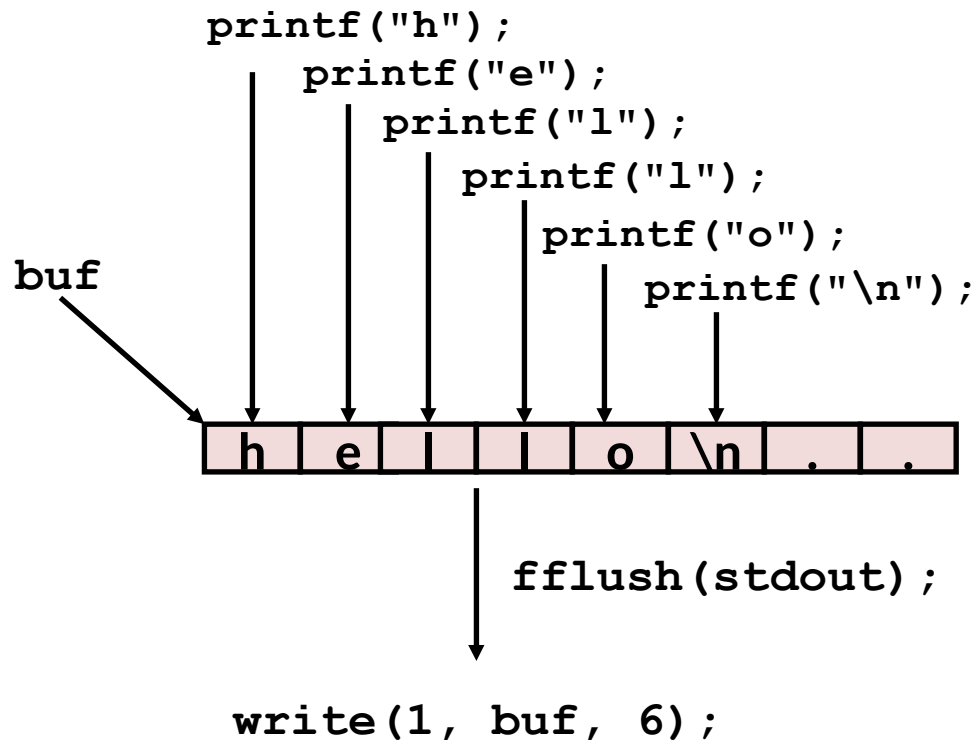
- Applications often read/write one character at a time
  - `getc`, `putc`, `ungetc`
  - `gets`, `fgets`
    - Read line of text one character at a time, stopping at newline
- Implementing as Unix I/O calls expensive
  - `read` and `write` require Unix kernel calls
    - > 10,000 clock cycles
- Solution: 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);
}
```

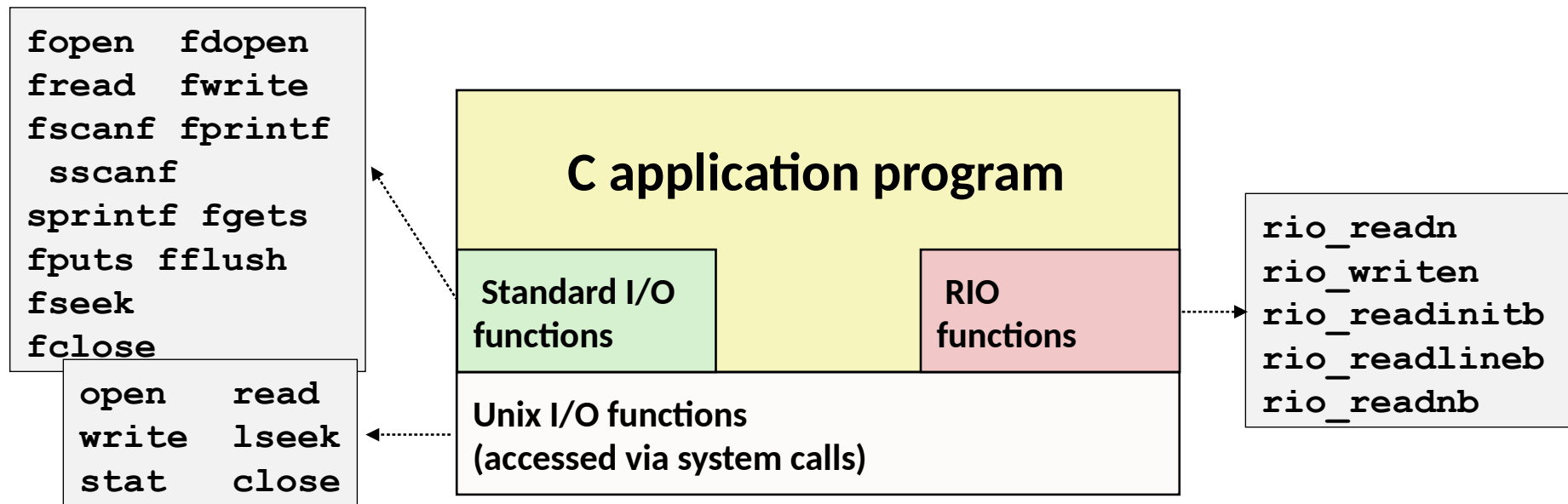
```
linux> strace ./hello
execve("./hello", ["hello"], [/* ... */]).
...
write(1, "hello\n", 6)                = 6
...
exit_group(0)                        = ?
```

# Today

- 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: 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*, 2<sup>nd</sup> 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);
}
```

