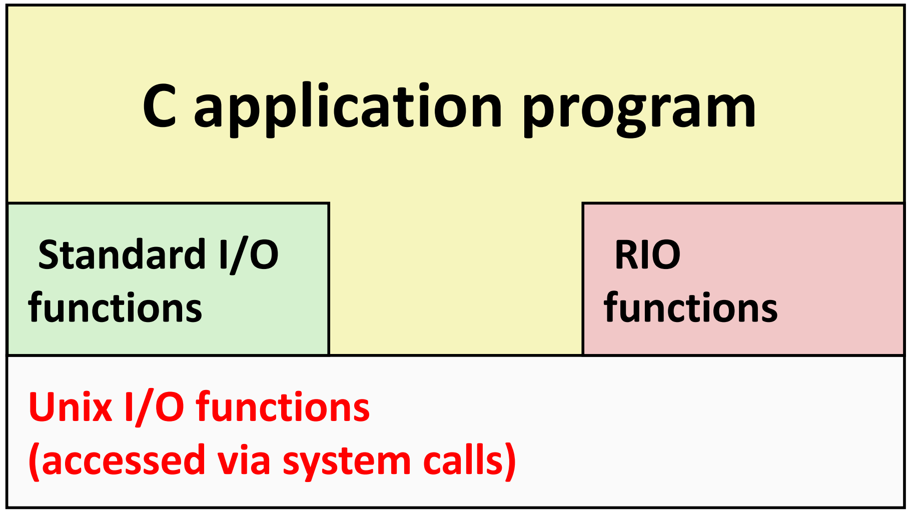
System-Level I/O

System Programming

Woong Sul

Today

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



Unix I/O Overview

- Input/output (or I/O) is the process of copying data between main memory and external devices
- 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 (Cnt'd)

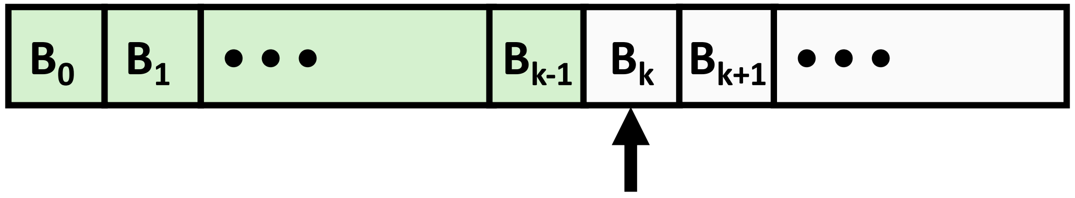
- Elegant mapping of files to devices allows kernel to export **simple interface** called **Unix I/O**
  - Opening and closing files

    `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

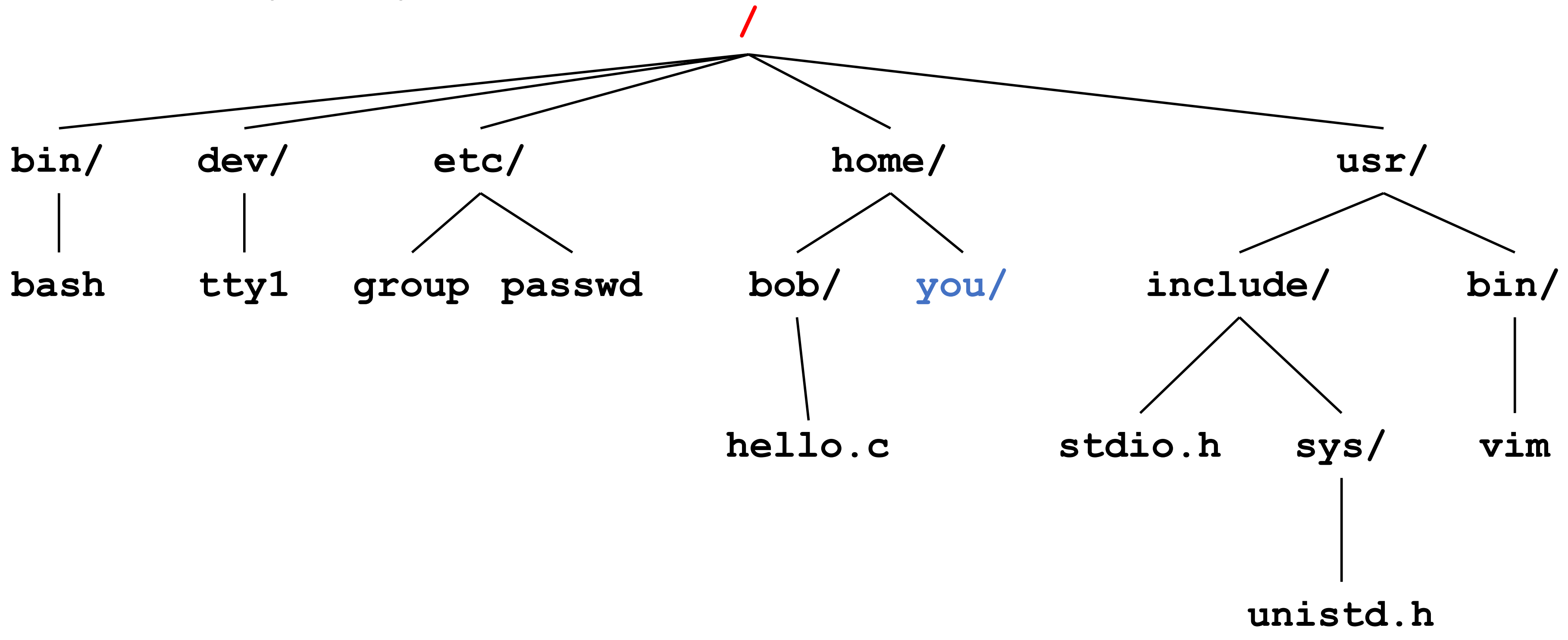
- A regular file contains arbitrary data
- Applications often distinguish between text files and binary files
  - Text files are regular files with only ASCII or Unicode characters
  - Binary files are everything else
    - e.g., object files, JPEG images
  - Kernel does not know the difference!
- Text 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

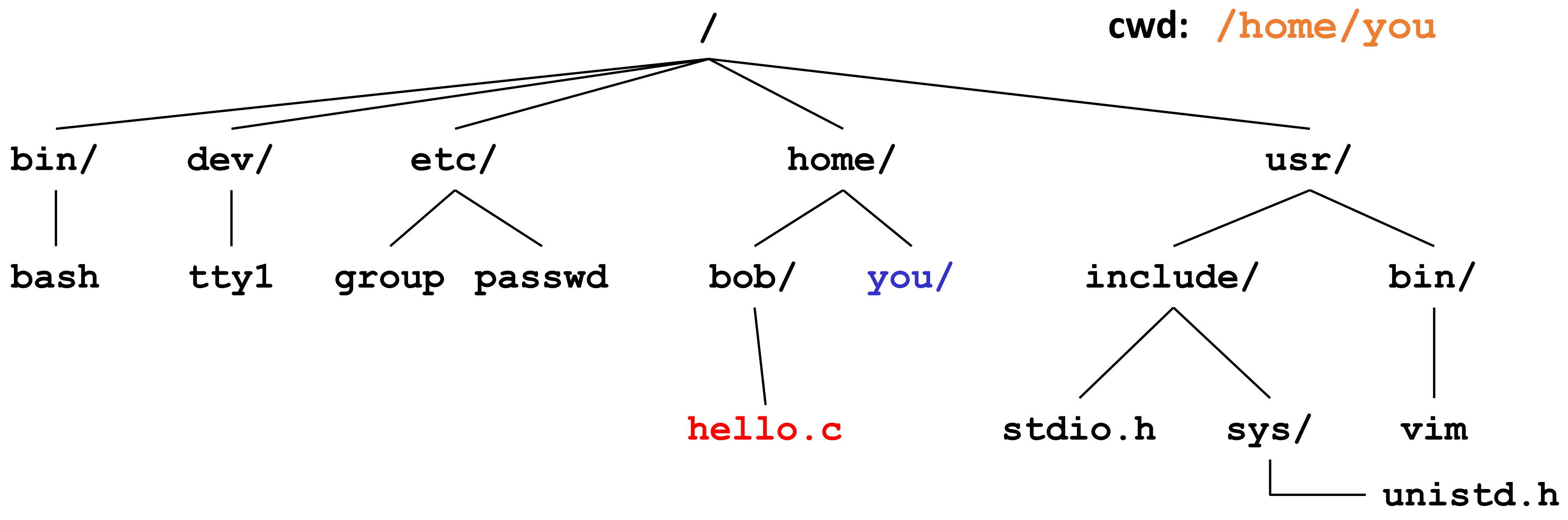
- All files are organized as a hierarchy anchored by ***root*** directory named / (slash)



- 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/bob/hello.c`
  - *Relative pathname* denotes path from current working directory
    - `../home/bob/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
  - Files is viewed as a sequence of bytes → ***stream***

```
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);
}
```

Reading Files (Cnt'd)

- `read()` returns number of bytes read from file **`fd`** into **`usrbuf`**

```
ssize_t read(int fd, void *usrbuf, size_t n);
```

- `ssize_t` vs. `size_t`
  - Calling `read()` with **`n`** bytes whose type is `size_t`
  - `read()` returns up to **`n`** bytes whose type is `ssize_t`

- **`ssize_t`** is ***signed*** integer
  - `nbytes == sizeof(buf)`
  - `nbytes < 0` indicates that an error occurred
  - `nbytes < sizeof(buf)` ➔ ***Short counts (Not an error!)***

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);
}
```

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**
- 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

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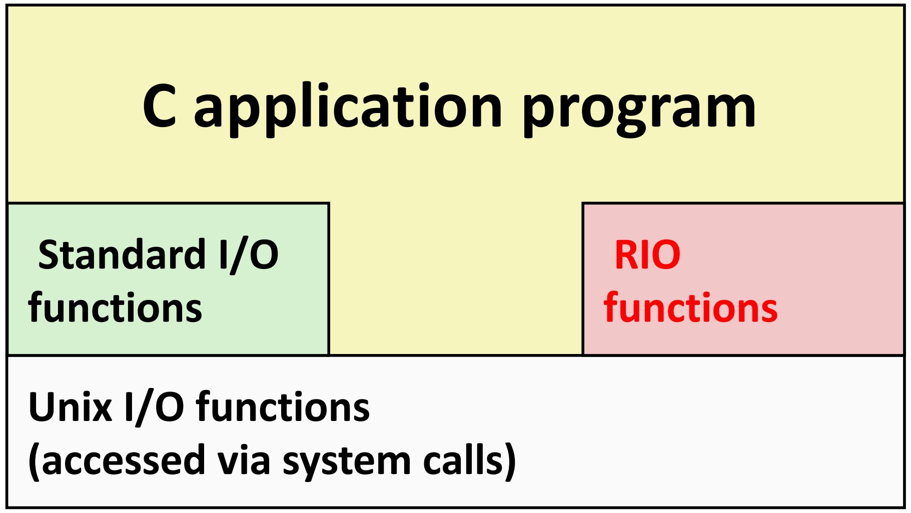


The RIO Package

- **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_readnb`** and **`rio_readlineb`**
    - Buffered RIO routines are thread-safe and can be interleaved arbitrarily on the same descriptor

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 a ***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 */
}
```

csapp.c

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 (Cnt'd)

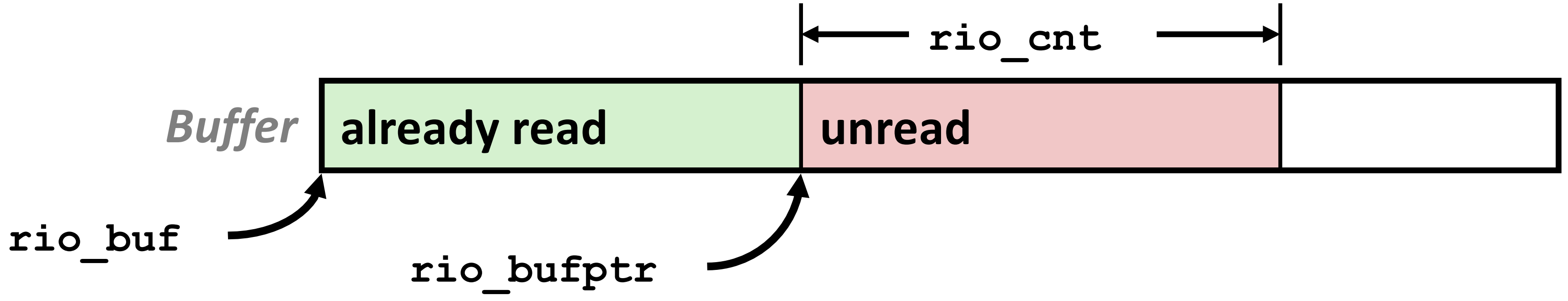
```
#include "csapp.h"

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

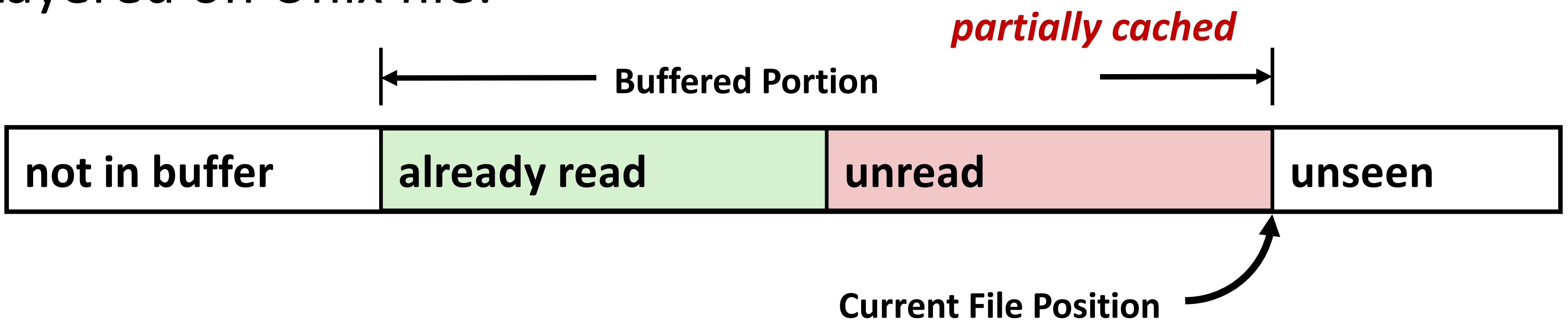
- **`rio_readnb`** reads up to ***n*** bytes from file **`fd`**
- Stopping conditions
  - **`maxlen`** bytes read
  - EOF encountered
- Calls to **`rio_readlineb`** and **`rio_readnb`** can be interleaved arbitrarily on the same descriptor
  - Warning: Do not interleave with calls to **`rio_readn`**

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

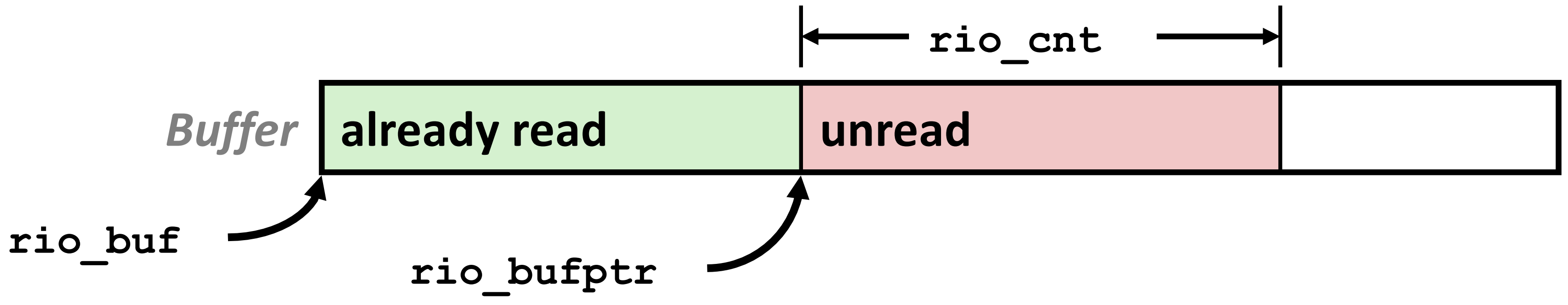


- Layered on Unix file:



Buffered I/O: Declaration

- All information contained in `rio_t`



```
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

```
typedef struct {
    int rio_fd;
    int rio_cnt;
    char *rio_bufptr;
    char rio_buf[RIO_BUFSIZE];
} rio_t;
```

```
#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

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File Metadata

- File contents are data
  - A Linux file is a sequence of m bytes

B_0	B_1	B_2	B_3	B_4	B_5	B_6	B_7	…	B_{m-1}

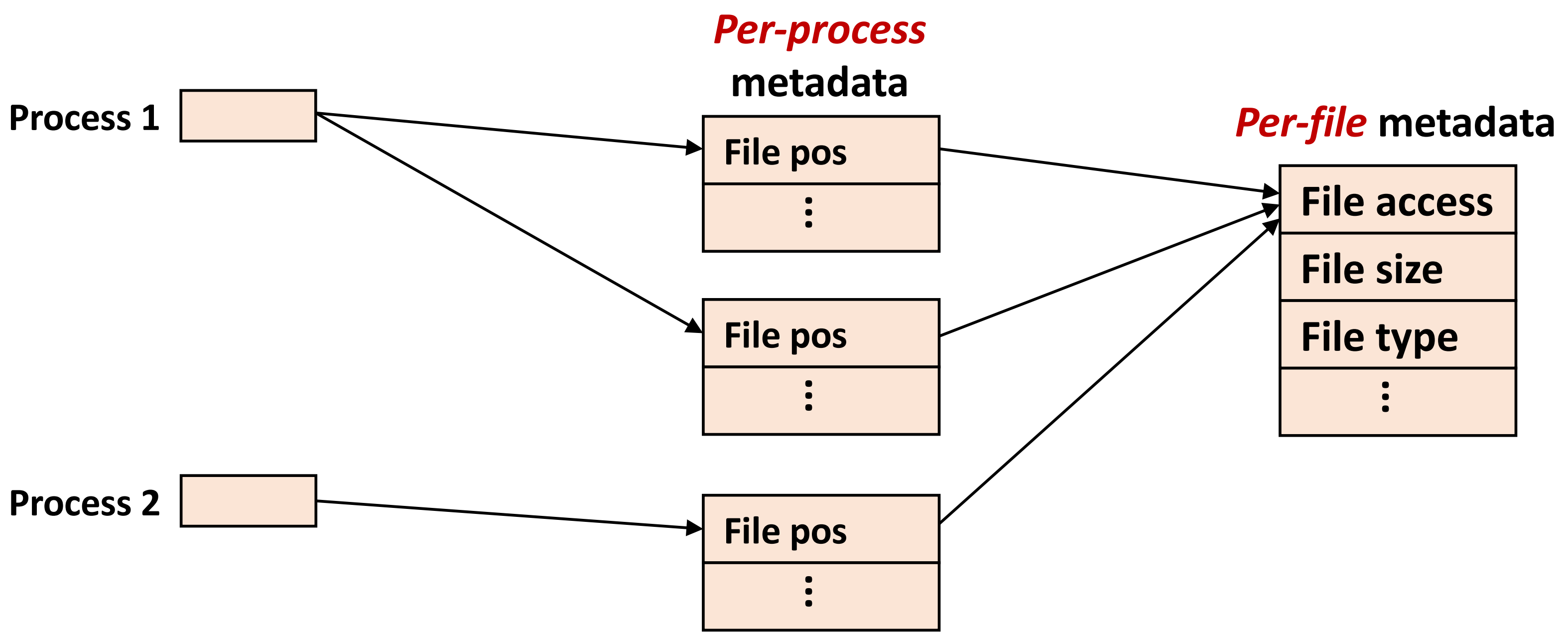
→ Each process manages its own file cursor

- *Metadata* is data about data
  - File access: read/write/execution permission
  - File size
  - File type

→ Processes manages the same metadata about the same file

File Metadata (Cnt'd)

- *Per-process* metadata maintained by kernel
  - Different processes manage different file cursors
  - A processes manages different cursors in the same file
- *Per-file* metadata maintained by kernel
  - accessed by users with the `stat` and `fstat` functions



File Metadata (Cnt'd)

- 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

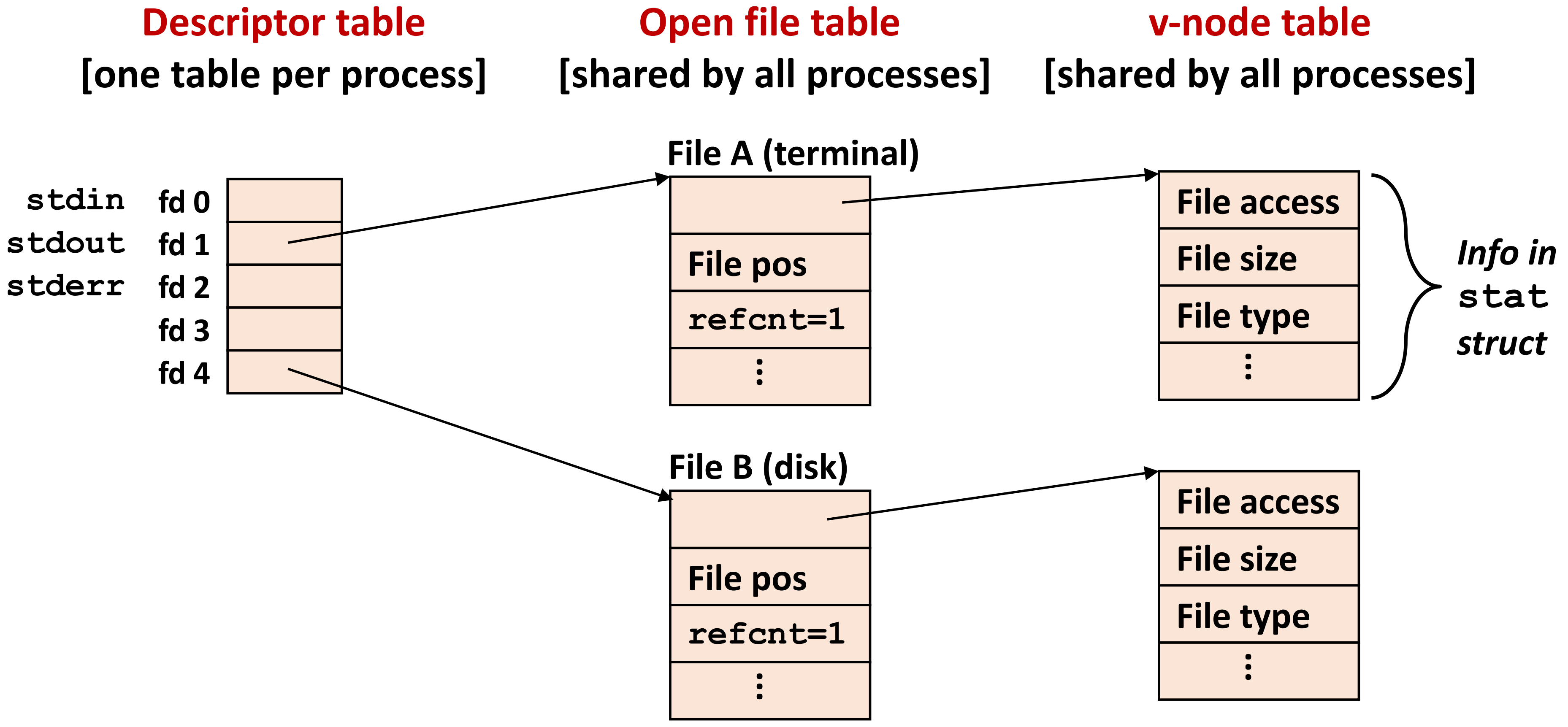
```
linux> ./statcheck statcheck.c
type: regular, read: yes
linux> chmod 000 statcheck.c
linux> ./statcheck statcheck.c
type: regular, read: no
linux> ./statcheck ..
type: directory, read: yes
```

```
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

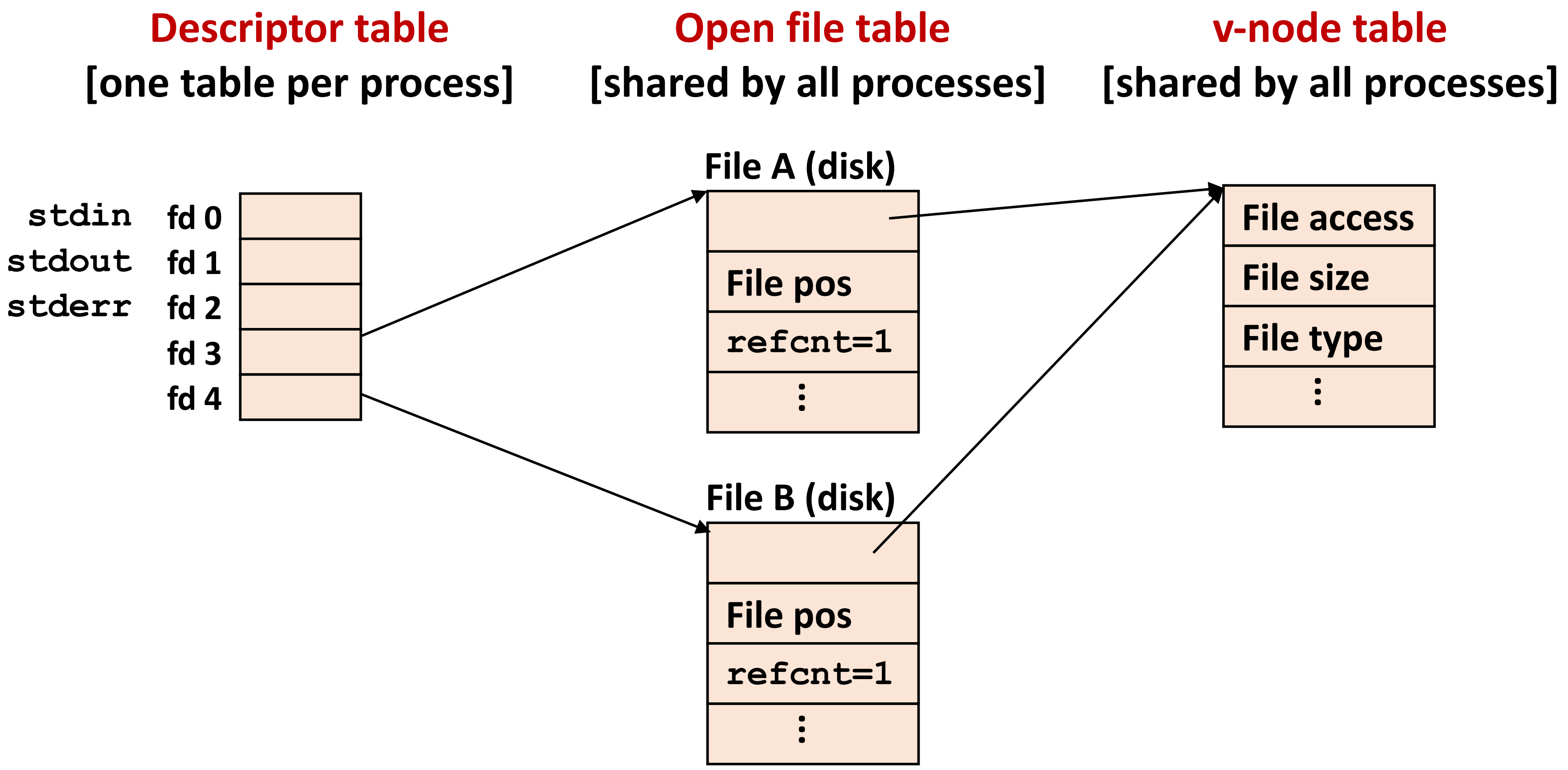
- Two descriptors referencing two distinct open files
  - Descriptor 1 (stdout) points to terminal, and descriptor 4 points to open disk file



How the Unix Kernel Represents Open Files

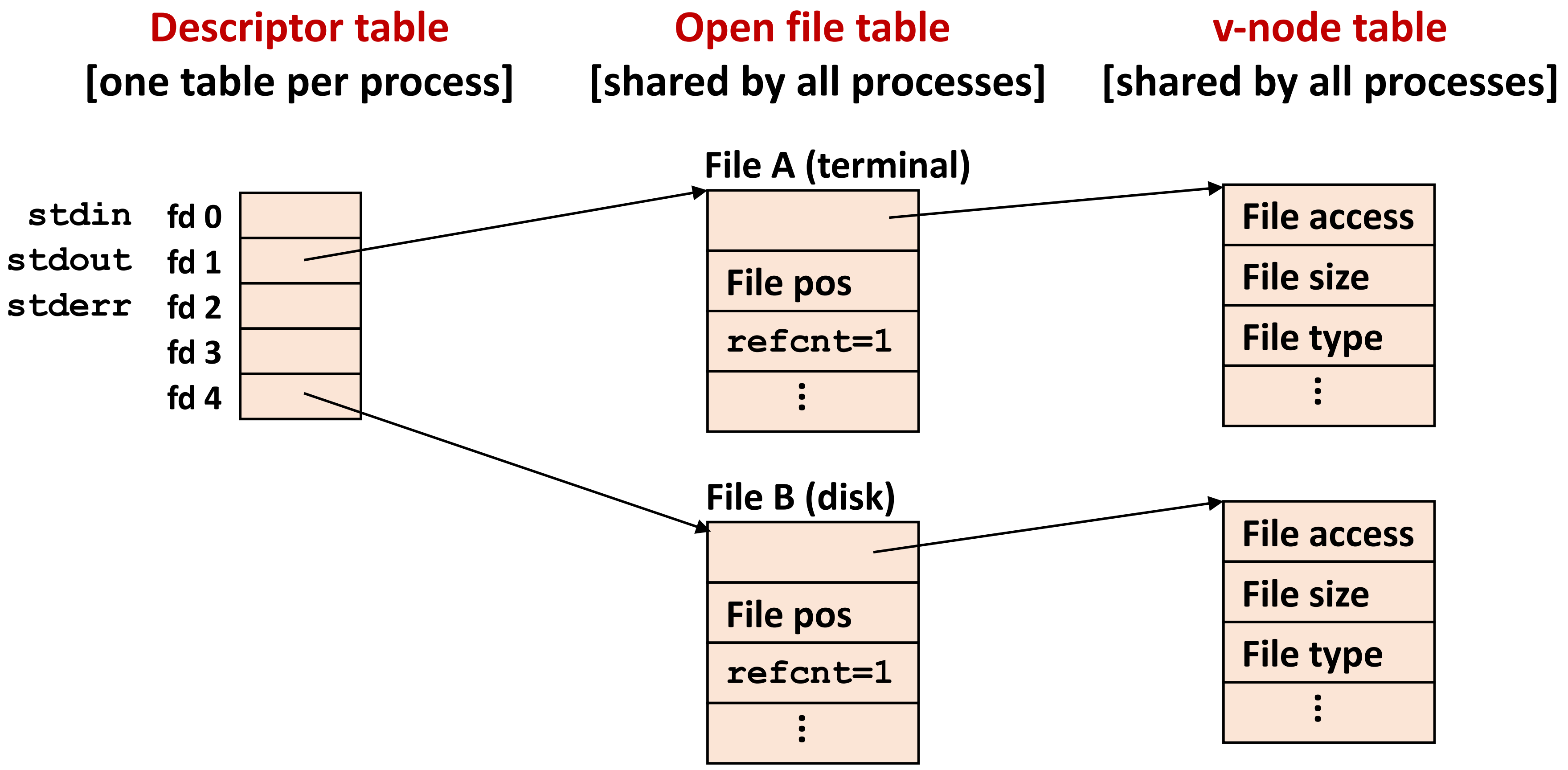
- Two distinct descriptors sharing the same disk file through two distinct open file table entries

E.g., Calling **`open`** twice with the same **`filename`** argument



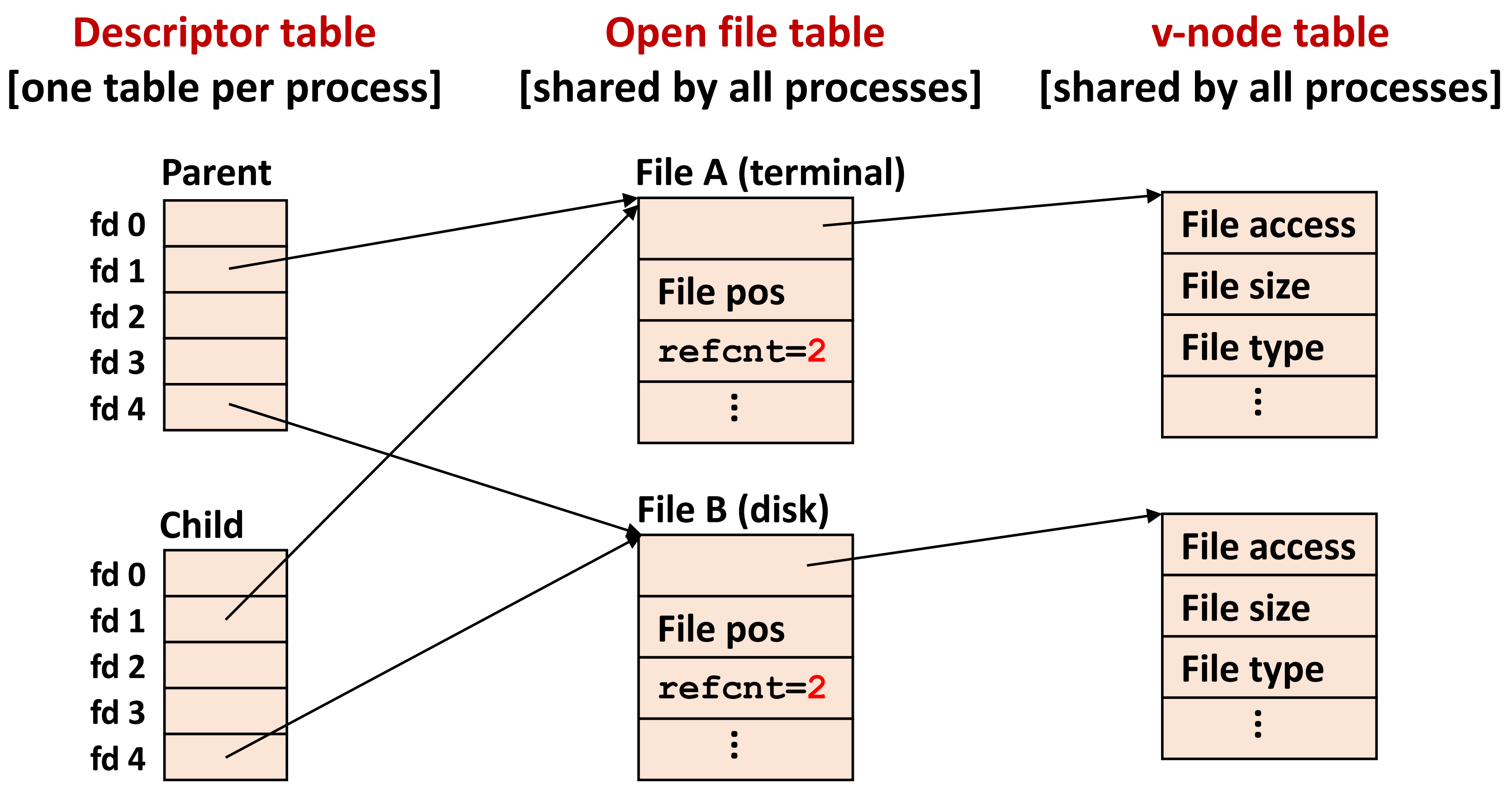
How Processes Share Files: `fork`

- 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` (Cnt'd)

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

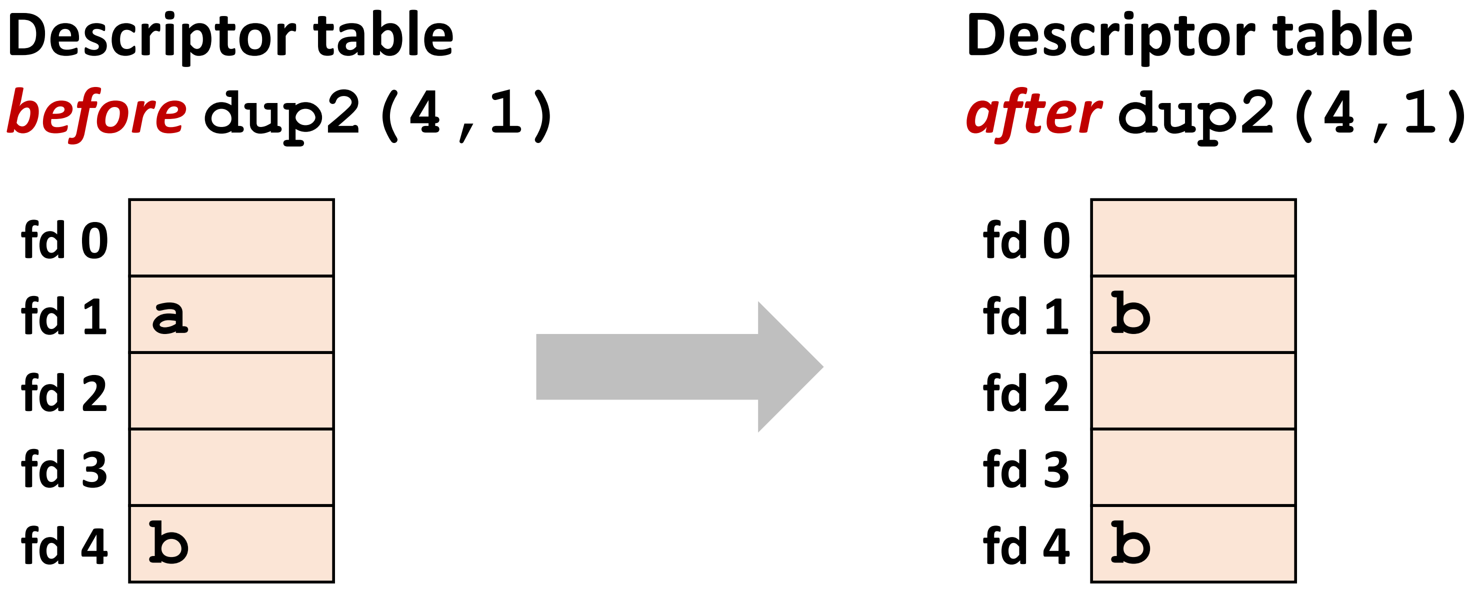


I/O Redirection

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

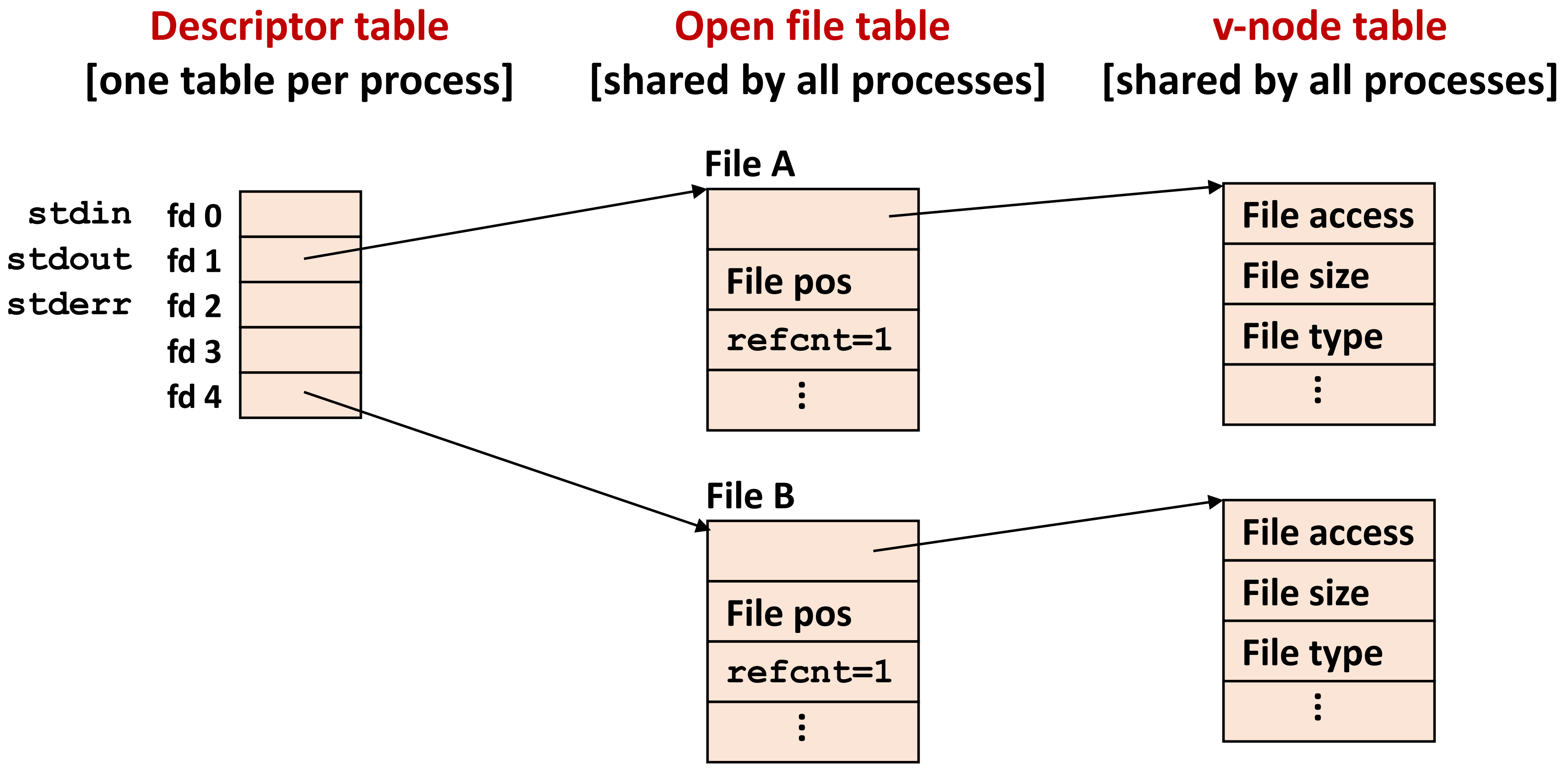
```
linux> ls > foo.txt
```

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



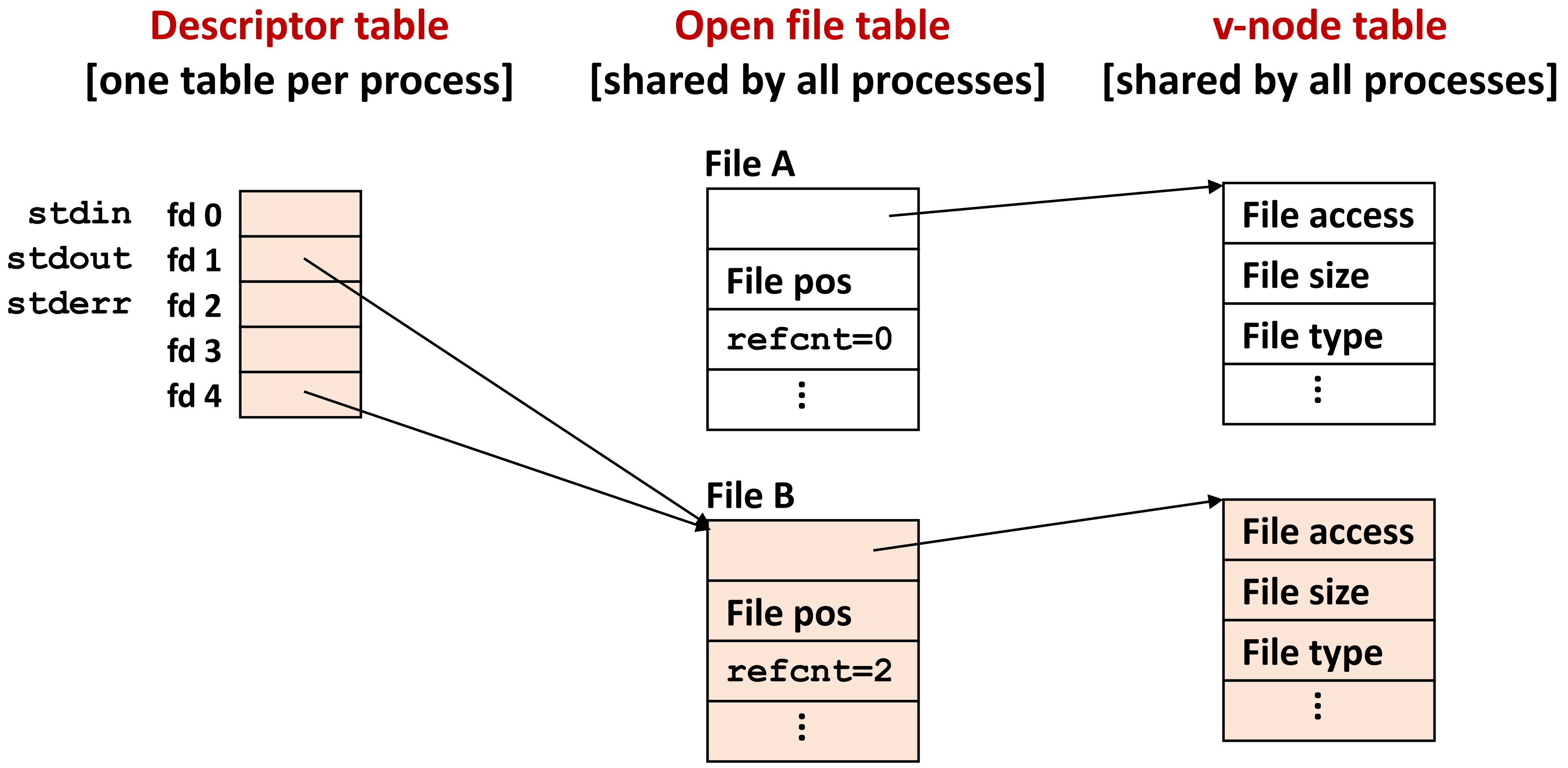
I/O Redirection Example

- Step #1: open file to which stdout should be redirected
  - Happens in child executing shell code, before **`exec`**



I/O Redirection Example (Cnt'd)

- Step #2: call `dup2(4,1)`
  - cause `fd=1` (stdout) to refer to disk file pointed at by `fd=4`



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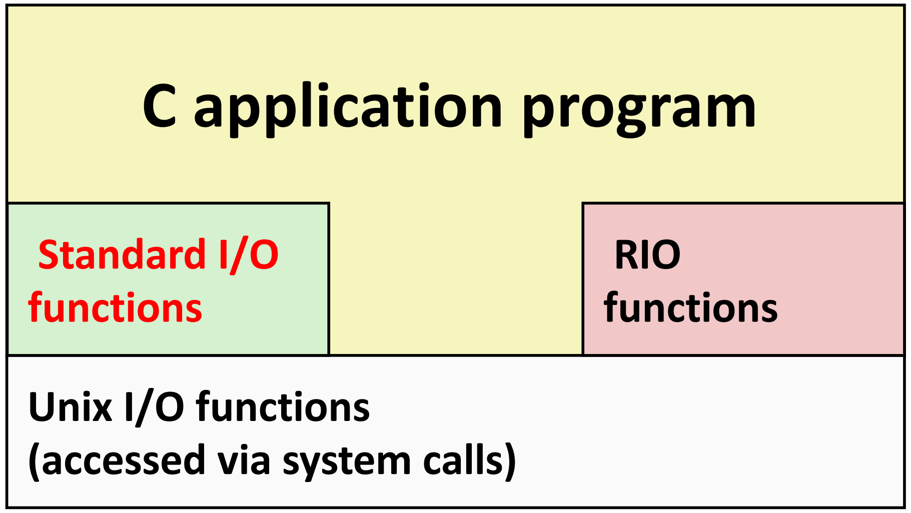


Standard I/O Functions

- The C standard library (`libc.so`) contains a collection of higher-level *standard I/O* functions
  - Documented in Appendix B of K&R

- 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

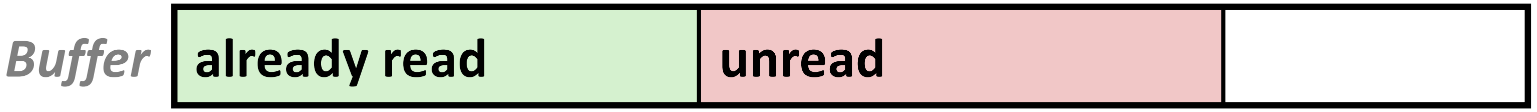
- Standard I/O models open files as *streams*
  - Abstraction for a file descriptor and a buffer in memory
- C programs begin life with three open streams (defined in `stdio.h`)
  - **`stdin`** (standard input)
  - **`stdout`** (standard output)
  - **`stderr`** (standard error)

```
#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");
}
```

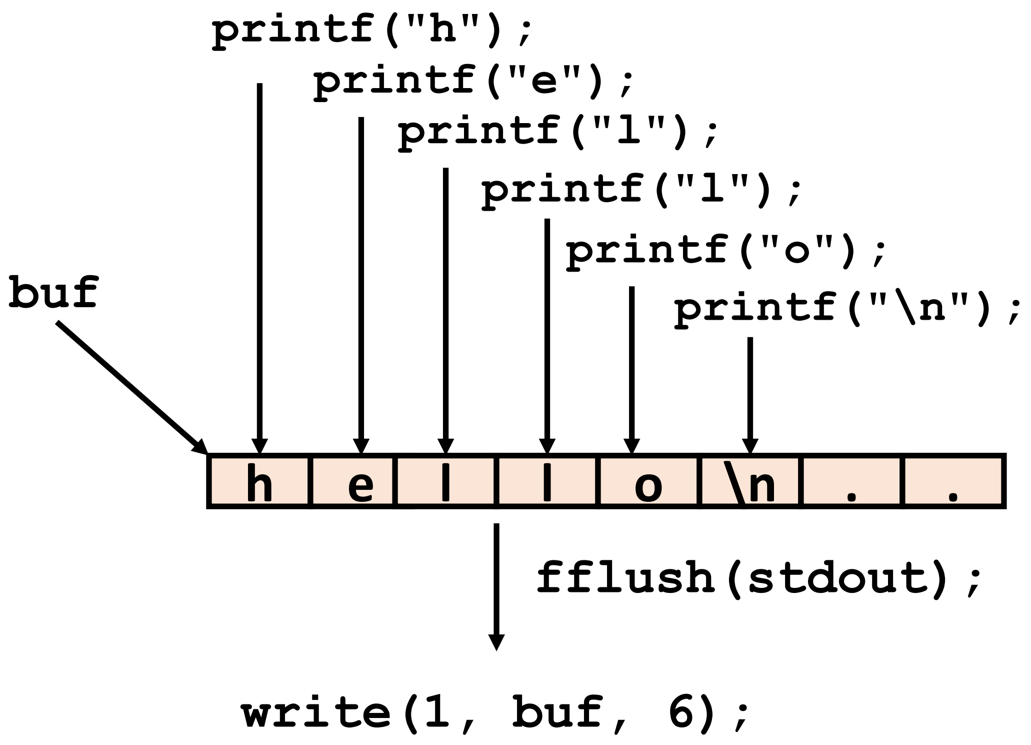
Buffered I/O: Motivation

- 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

  * `strace` : traces system calls and signals

```
#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)                            = ?
```

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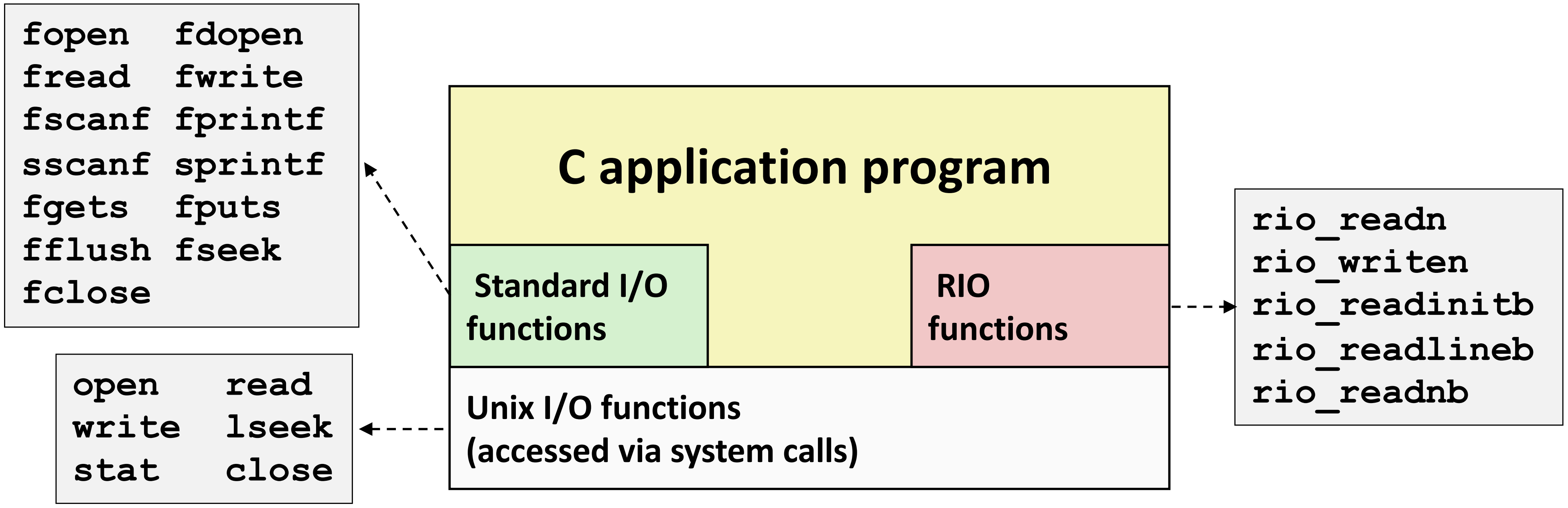
Unix I/O vs. Standard I/O vs. RIO

- Standard I/O and RIO are implemented using 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***, 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