Computer Architecture and Operating Systems
Lecture 7: I/O and Files

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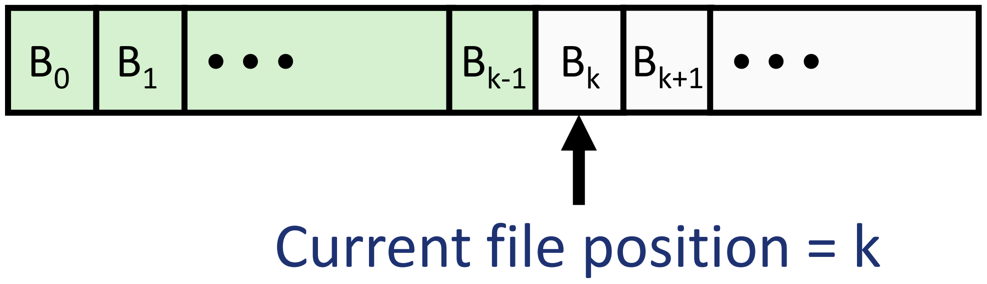
Unix I/O Overview

- A Linux *file* is a sequence of *m* bytes:
  - $B_0, B_1, \ldots, B_k, \ldots, B_{m-1}$
- All I/O devices are represented as files:
  - **`/dev/sda2`** (**`/usr`** disk partition)
  - **`/dev/tty2`** (terminal)
- Even the kernel is represented as a file:
  - **`/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
- Other file types
  - *Named pipes (FIFOs)*
  - *Symbolic links*
  - *Character and block devices*
  - *Sockets for communicating with a process on another machine*

Regular Files

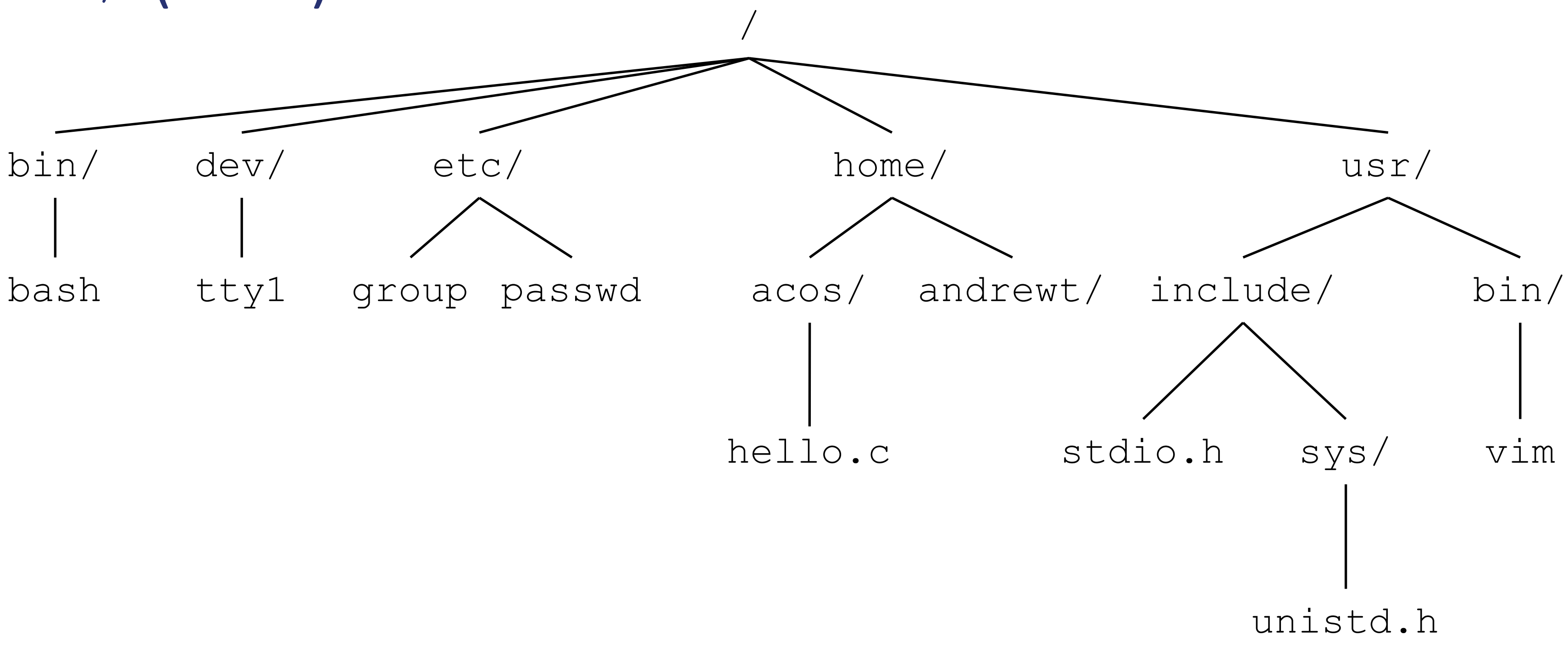
- A regular file contains arbitrary data
- Applications often distinguish between *text files* and *binary files*
  - Text files are regular files with only ASCII or Unicode characters
  - Binary files are everything else
    - e.g., object files, JPEG images
  - Kernel does not know the difference!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

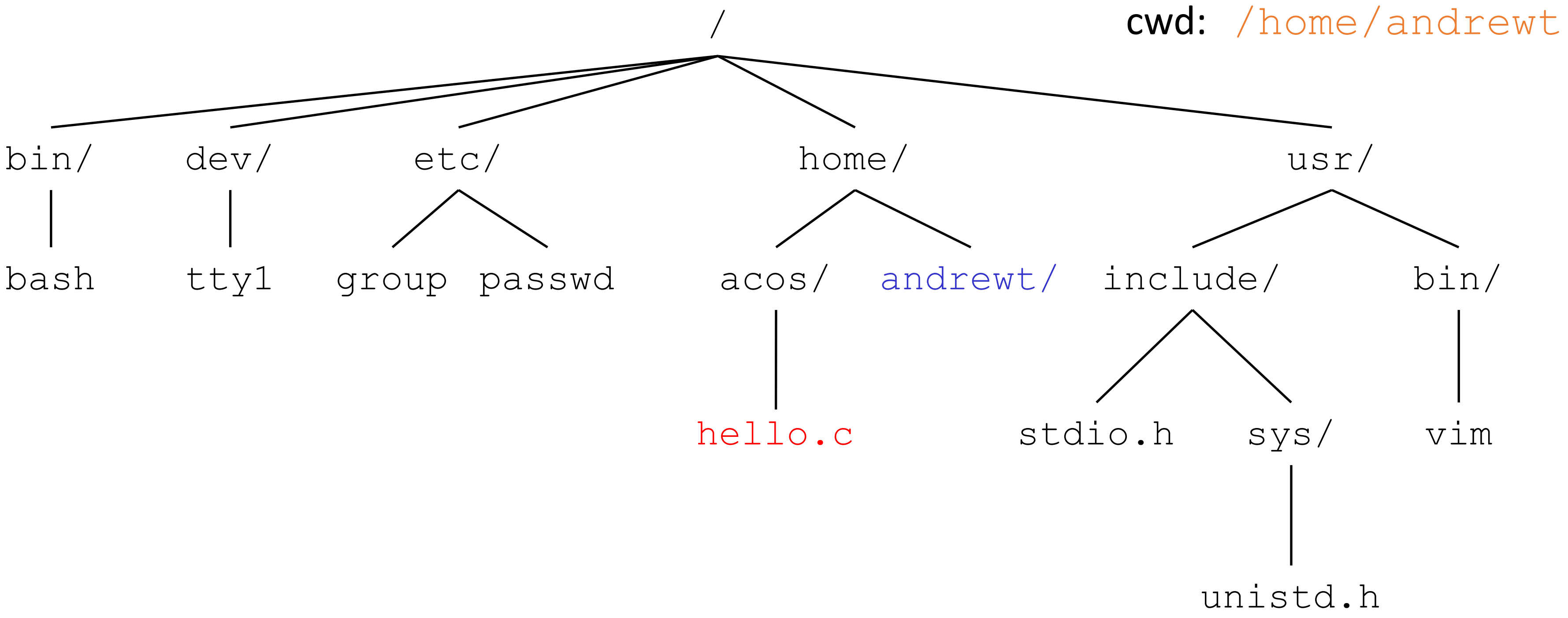
- All files are organized as a hierarchy anchored by root directory named / (slash)



- 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/acos/hello.c`
  - *Relative pathname* denotes path from current working directory
    - `../home/acos/hello.c`



Linux Filesystem Hierarchy Standard

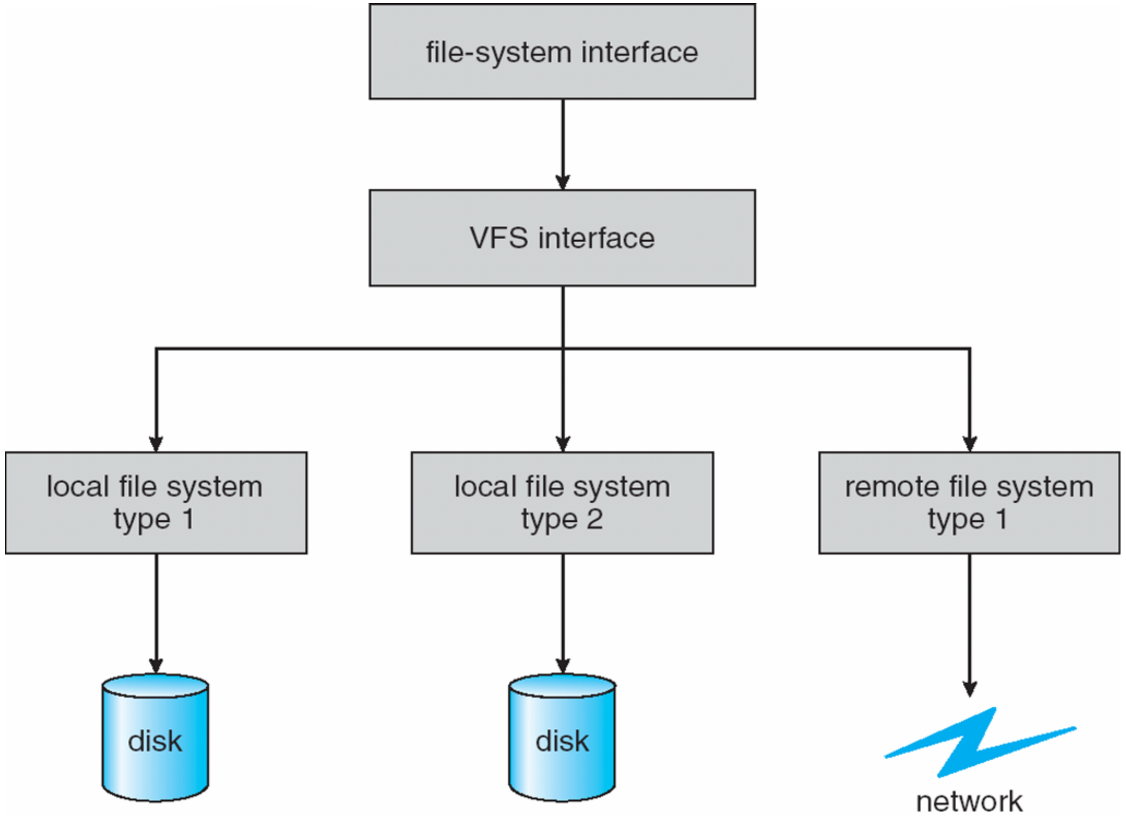
- **/bin** – Essential user command binaries (for use by all users)
- **/boot** – Static files of the boot loader
- **/dev** – Device files
- **/etc** – Host-specific system configuration
- **/home** – User home directories (optional)
- **/lib** – Essential shared libraries and kernel modules
- **/lib<qual>** – Alternate format essential shared libraries (optional)
- **/media** – Mount point for removable media
- **/mnt** – Mount point for a temporarily mounted filesystem
- **/opt** – Add-on application software packages
- **/root** – Home directory for the root user
- **/proc** – Virtual filesystem providing process and kernel information as files
- **/run** – Run-time variable data
- **/sbin** – System binaries
- **/srv** – Data for services provided by this system
- **/sys** – Kernel and system information virtual filesystem
- ***/tmp*** – Temporary files
- **/usr** – Secondary hierarchy for read-only user data; contains the majority of (multi-) user tools
- **/var** – Variable files: files whose content is expected to change during normal operation of the system

Virtual File Systems

- **Virtual File Systems** (**VFS**) on Unix provide an object-oriented way of implementing file systems
- VFS allows the same system call interface (the API) to be used for different types of file systems
  - Separates file-system generic operations from implementation details
  - Implementation can be one of many file systems types, or network file system
    - Implements **vnodes** which hold inodes or network file details
  - Then dispatches operation to appropriate file system implementation routines

Virtual File Systems (Cont.)

- The API is to the VFS interface, rather than any specific type of file system



Virtual File System Implementation

- For example, Linux has four object types:
  - inode, file, superblock, dentry
- VFS defines set of operations on the objects that must be implemented
  - Every object has a pointer to a function table
    - Function table has addresses of routines to implement that function on that object
    - For example:
    - • `int open(...)` — Open a file
    - • `int close(...)` — Close an already-open file
    - • `ssize t read(...)` — Read from a file
    - • `ssize t write(...)` — Write to a file
    - • `int mmap(...)` — Memory-map a file

5 parts of a Linux Disk

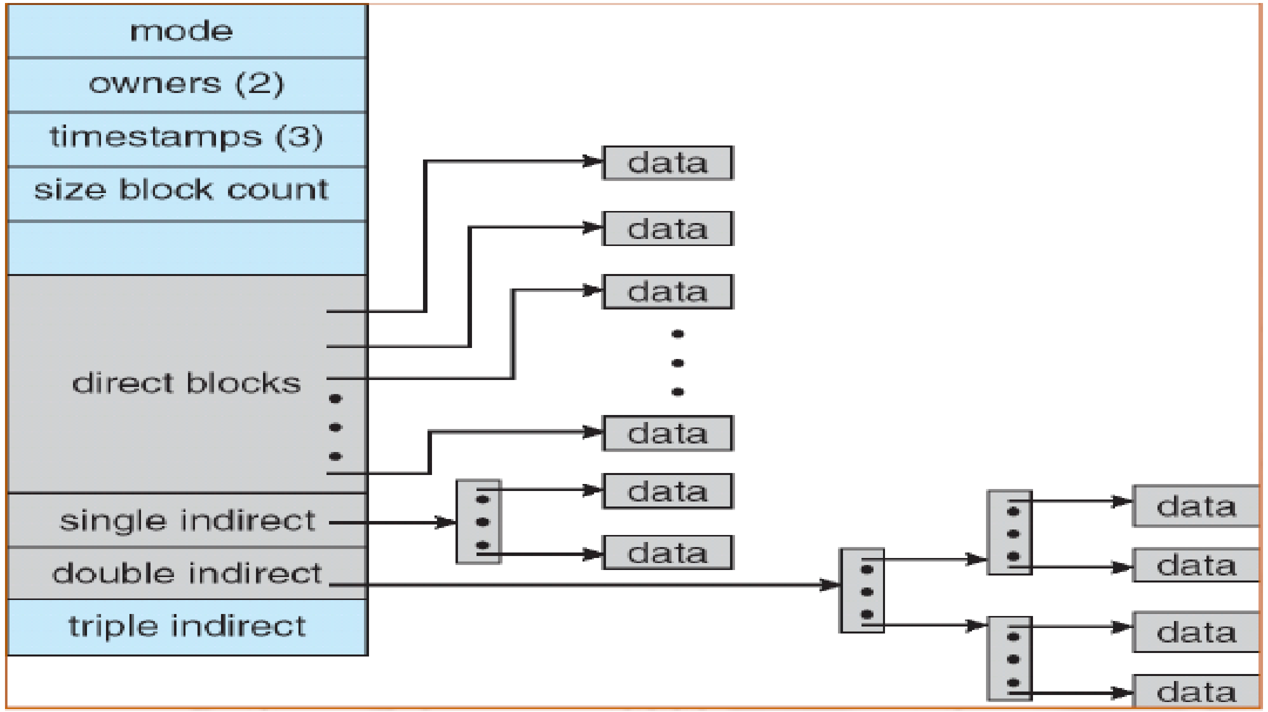
- Boot Block
  - Contains boot loader
- Superblock
  - The file systems “header”
  - Specifies location of file system data structures
- inode area
  - Contains descriptors (inodes) for each file on the disk
  - All inodes are the same size
  - Head of the inode free list is stored in superblock
- File contents area
  - Fixed size blocks containing data
  - Head of freelist stored in superblock
- Swap area
  - Part of disk given to virtual memory system

Inode Format

- User and group IDs
- Protection bits
- Access times
- File Type
  - Directory, normal file, symbolic link, etc
- Size
  - Length in bytes
- Block list
  - Location of data blocks in file contents area
- Link Count
  - Number of directories (hard links) referencing this inode

Unix Filesystem (Inodes)

- Metadata
  - Ownership, permissions
  - Access/Modification times
  - etc…
- Direct blocks:
  - Array of consecutive data blocks
  - Block size = 512 bytes
  - Inlined in the inode



- **Indirect blocks:**
  - i-node only holds a small number of data block pointers (direct pointers)
  - For larger files, i-node points to an indirect block containing 1024 4-byte entries in a 4K block
  - Each indirect block entry points to a data block
  - Can have multiple levels of indirect blocks for even larger files

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 <unistd.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.

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

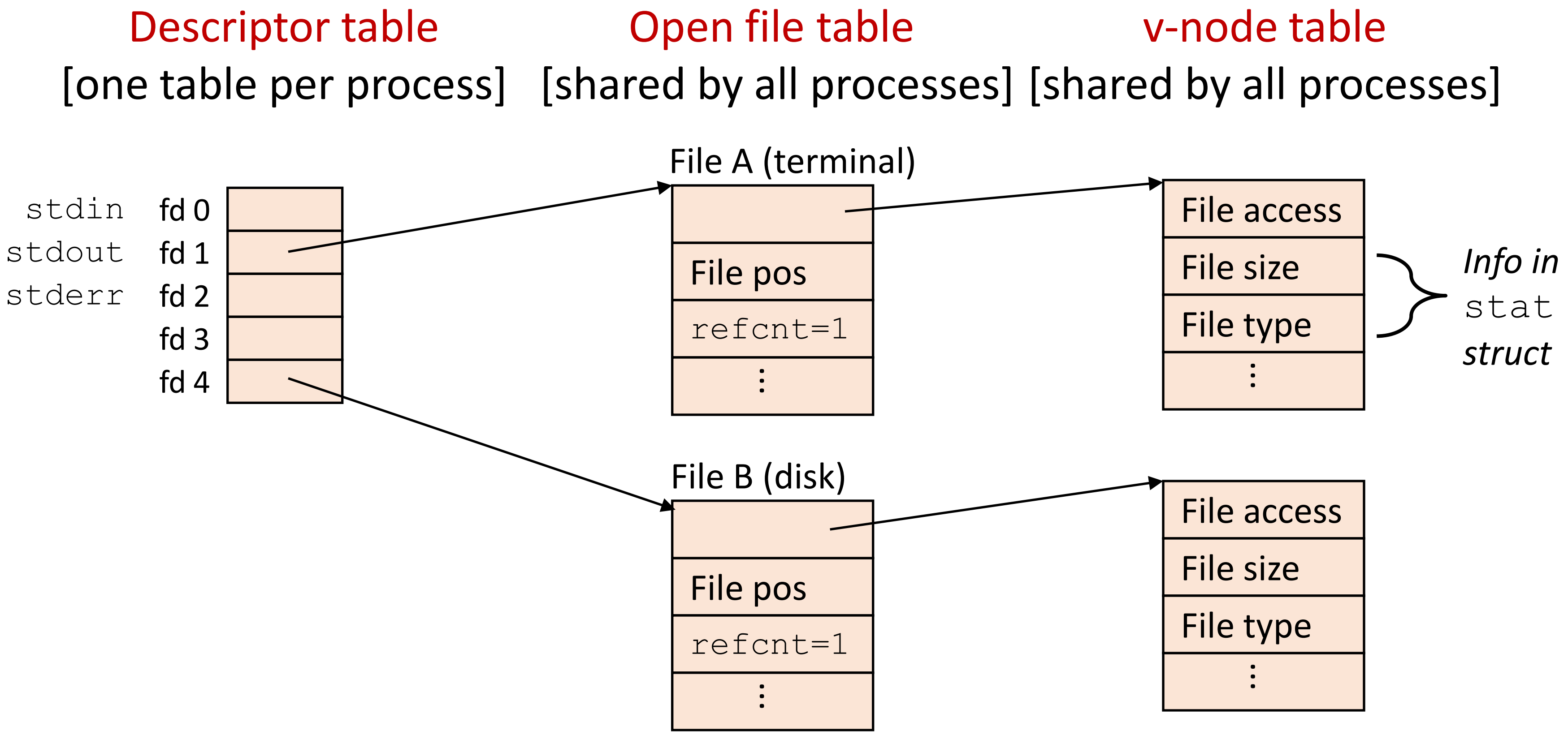
statcheck.c

```
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);
}
```

```
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
```

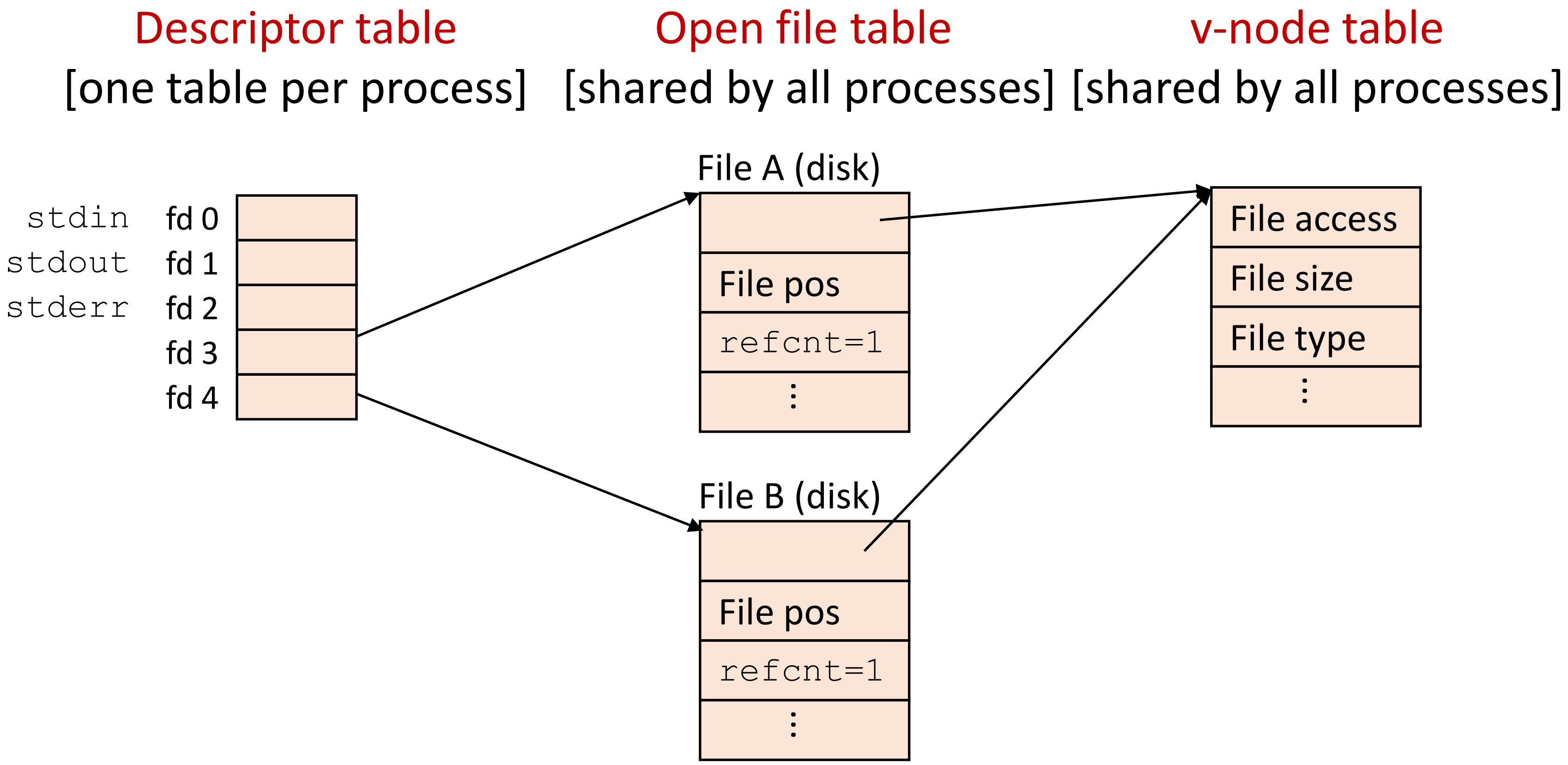
How the Unix Kernel Represents Open Files

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



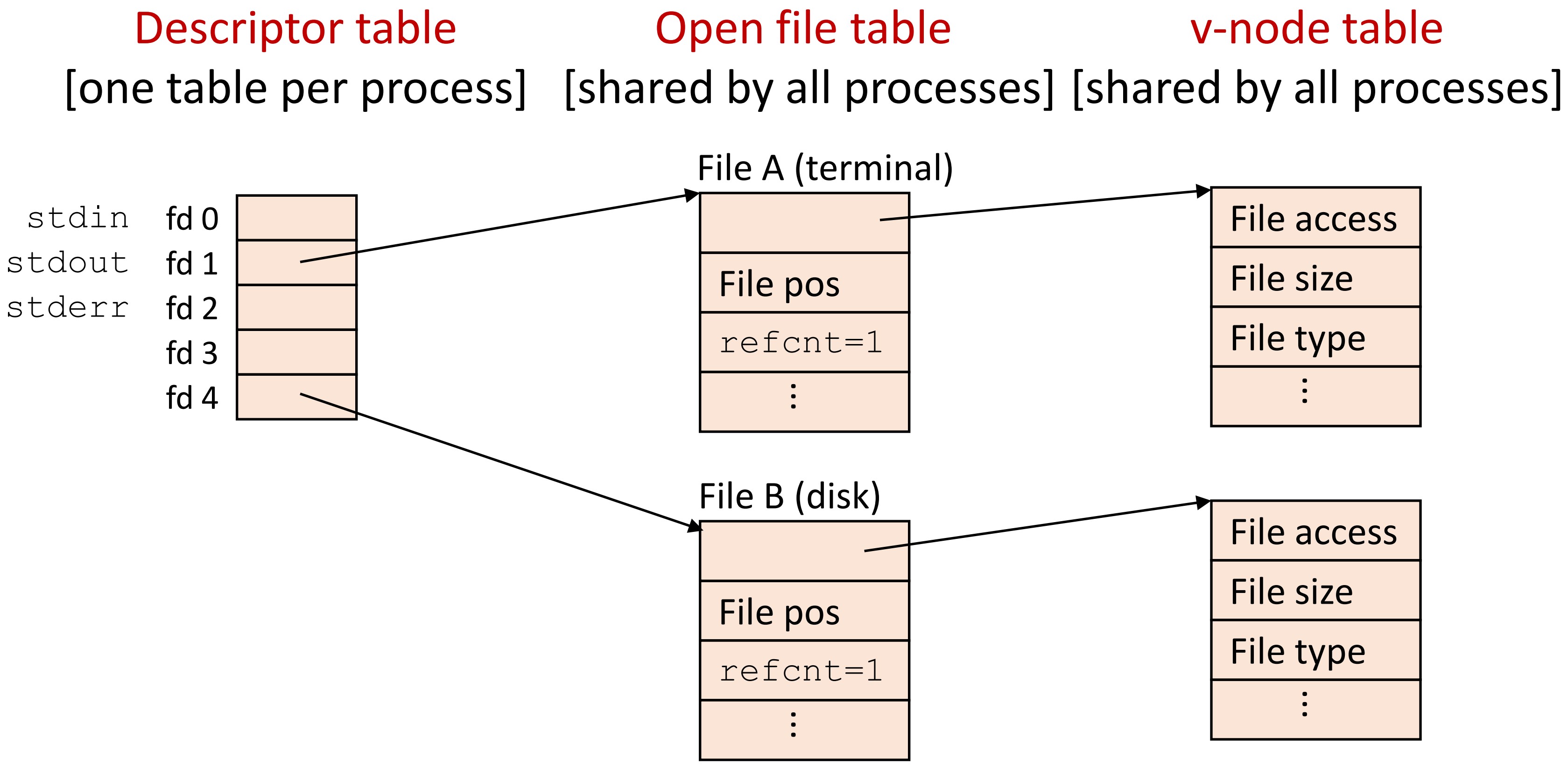
File Sharing

- 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



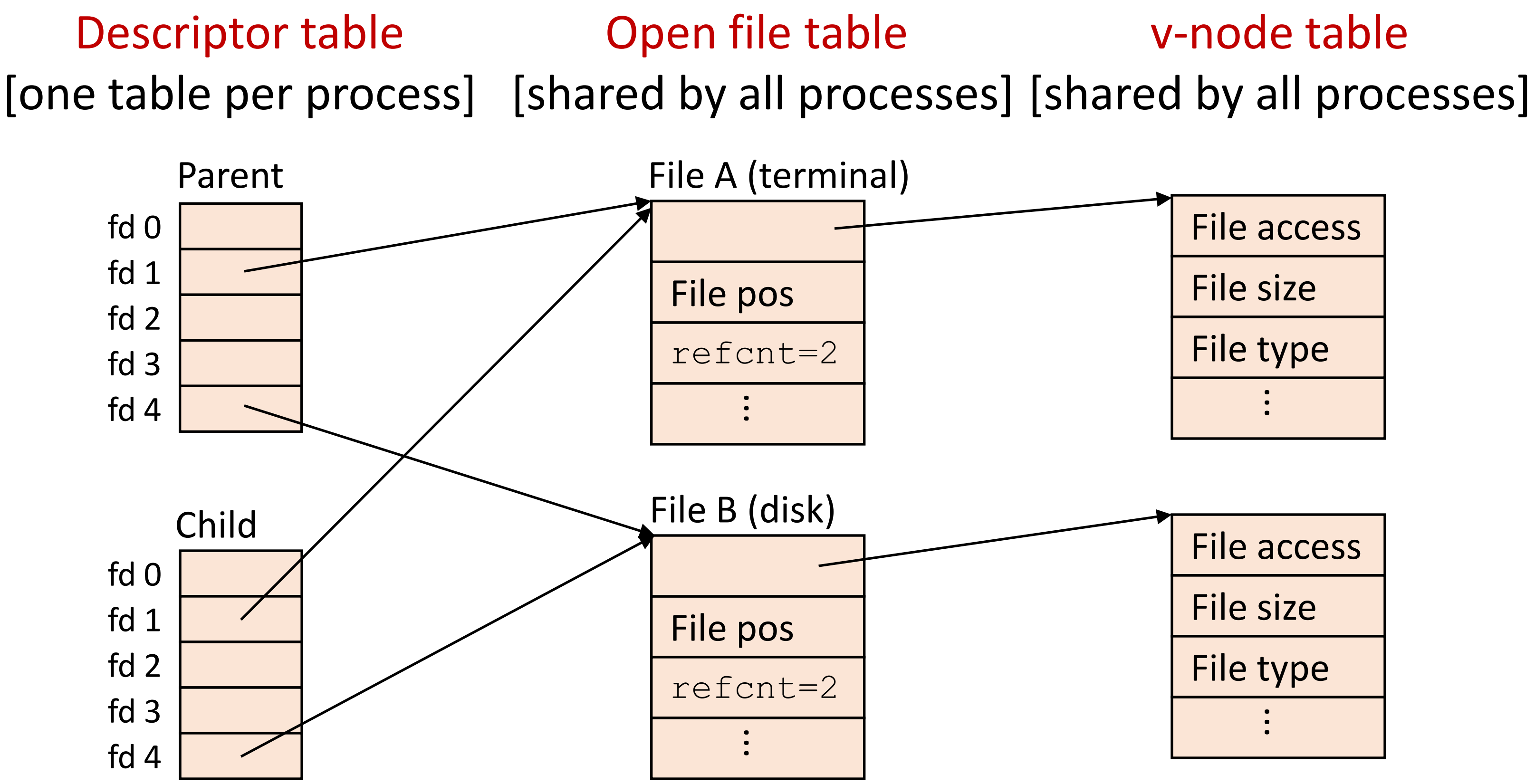
How Processes Share Files: fork

- 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

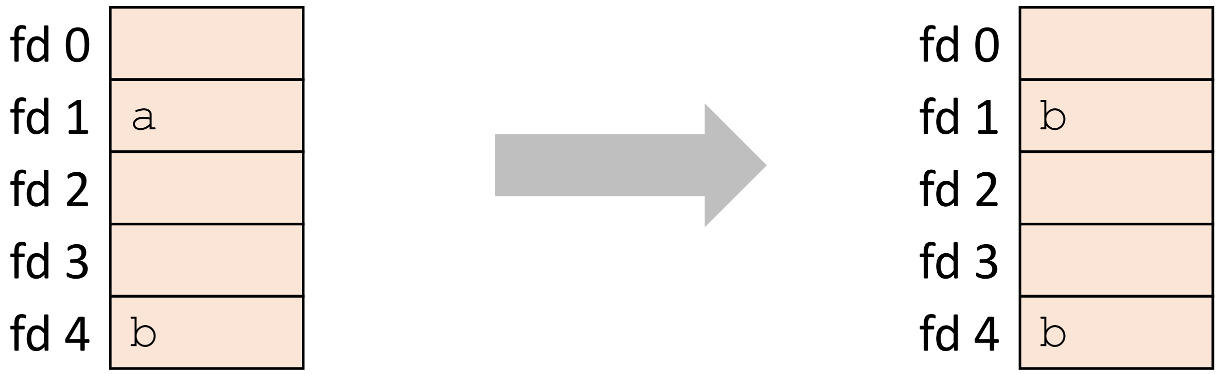
- Question: How does a shell implement I/O redirection?

  `linux> ls > foo.txt`

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

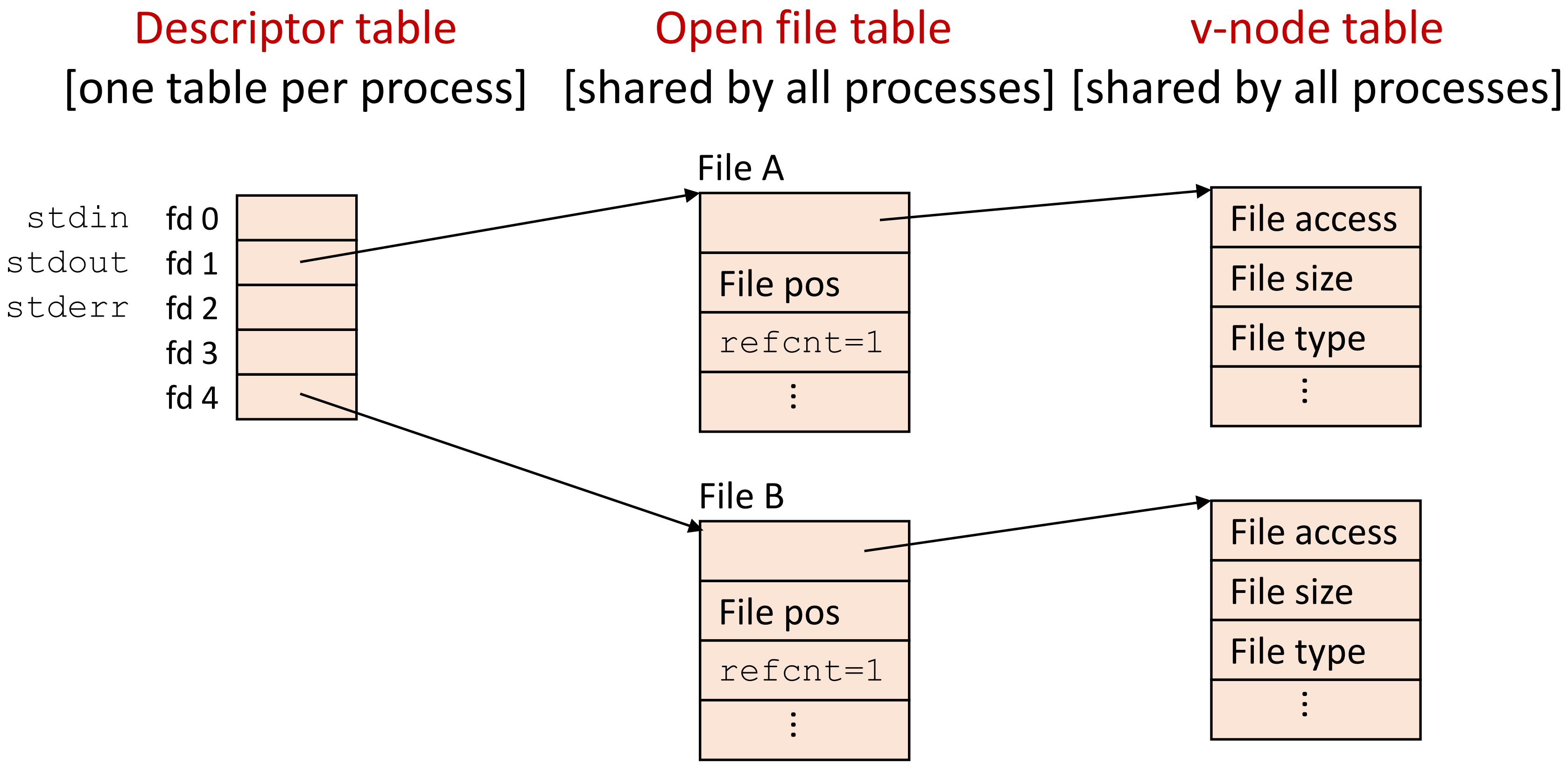
Descriptor table *before* `dup2(4,1)`

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



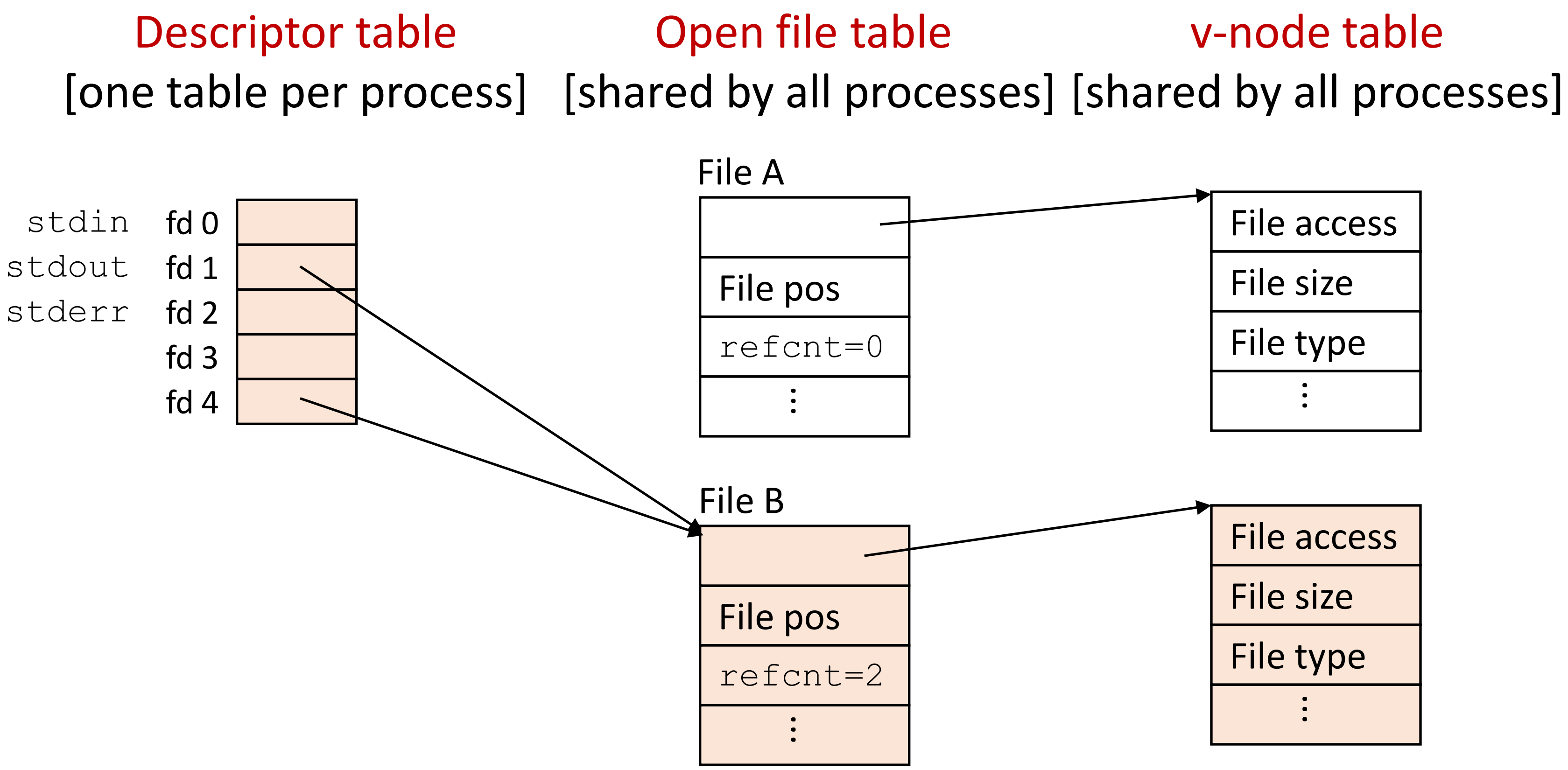
I/O Redirection Example

- 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



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

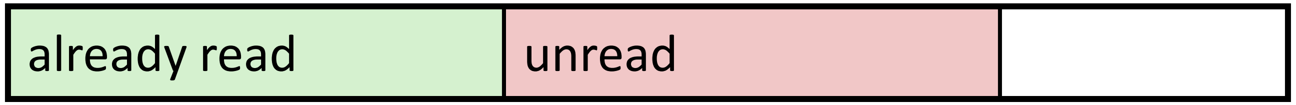
- Standard I/O models open files as *streams*
  - Abstraction for a file descriptor and a buffer in memory
- C programs begin life with three open streams (defined in `stdio.h`)
  - **`stdin`** (standard input)
  - **`stdout`** (standard output)
  - **`stderr`** (standard error)

```
#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

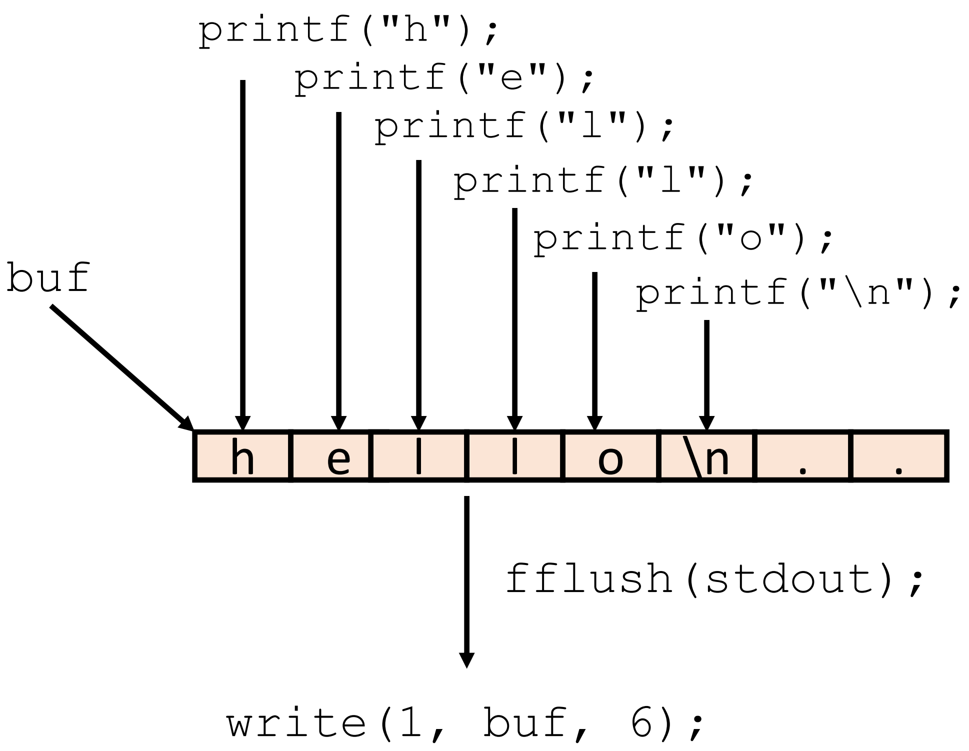
- Applications often read/write one character at a time
  - `getc, putc, ungetc`
  - `gets, fgets`
    - Read line of text one character at a time, stopping at newline
- Implementing as Unix I/O calls expensive
  - `read` and `write` require Unix kernel calls
    - > 10,000 clock cycles
- Solution: Buffered read
  - Use Unix `read` to grab block of bytes
  - User input functions take one byte at a time from buffer
    - Refill buffer when empty

Buffer



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

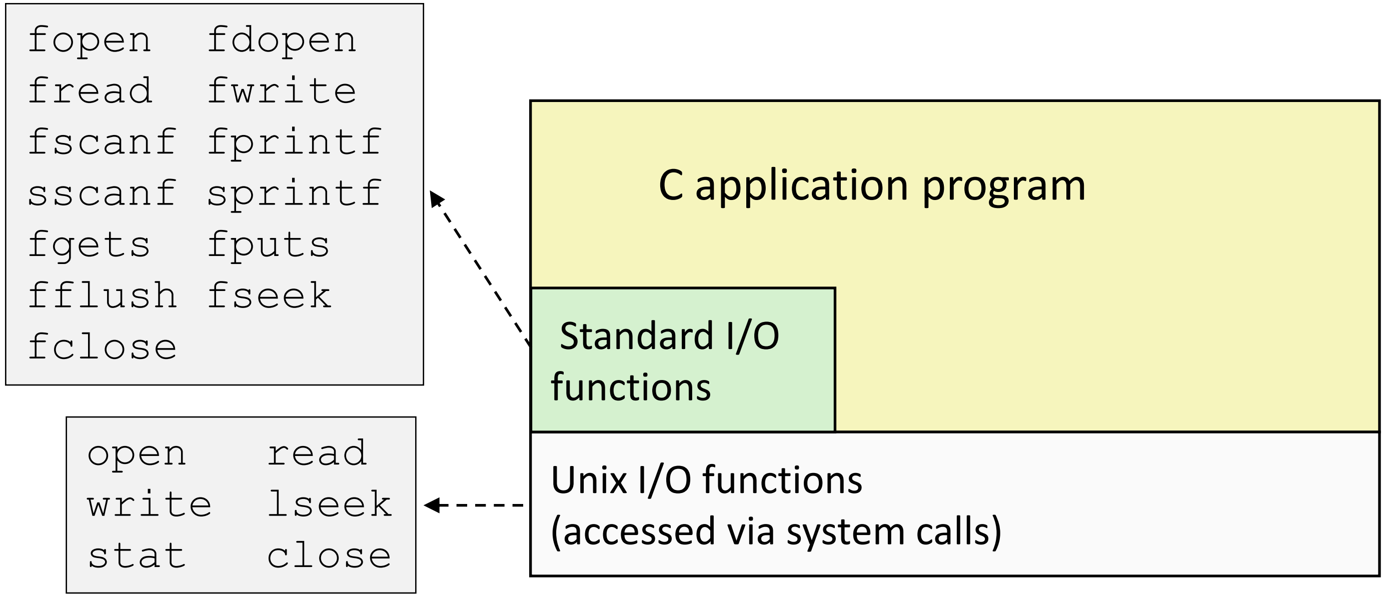
- You can see this buffering in action for yourself, using the always fascinating Linux `strace` program:

```
#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)                            = ?
```

Unix I/O vs. Standard I/O

- Standard I/O 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

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`**
    - Interpret EOL characters
  - String functions
    - **`strlen, strcpy, strcat`**
    - Interprets byte value 0 (end of string) as special

Fun with File Descriptors (1)

```
#include <unistd.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 <unistd.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 <unistd.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);
}
```

Any Questions?

```
            .text
__start:    addi t1, zero, 0x18
            addi t2, zero, 0x21
cycle:      beq t1, t2, done
            slt t0, t1, t2
            bne t0, zero, if_less
            nop
            sub t1, t1, t2
            j cycle
            nop
if_less:    sub t2, t2, t1
            j cycle
done:       add t3, t1, zero
```