System I/O

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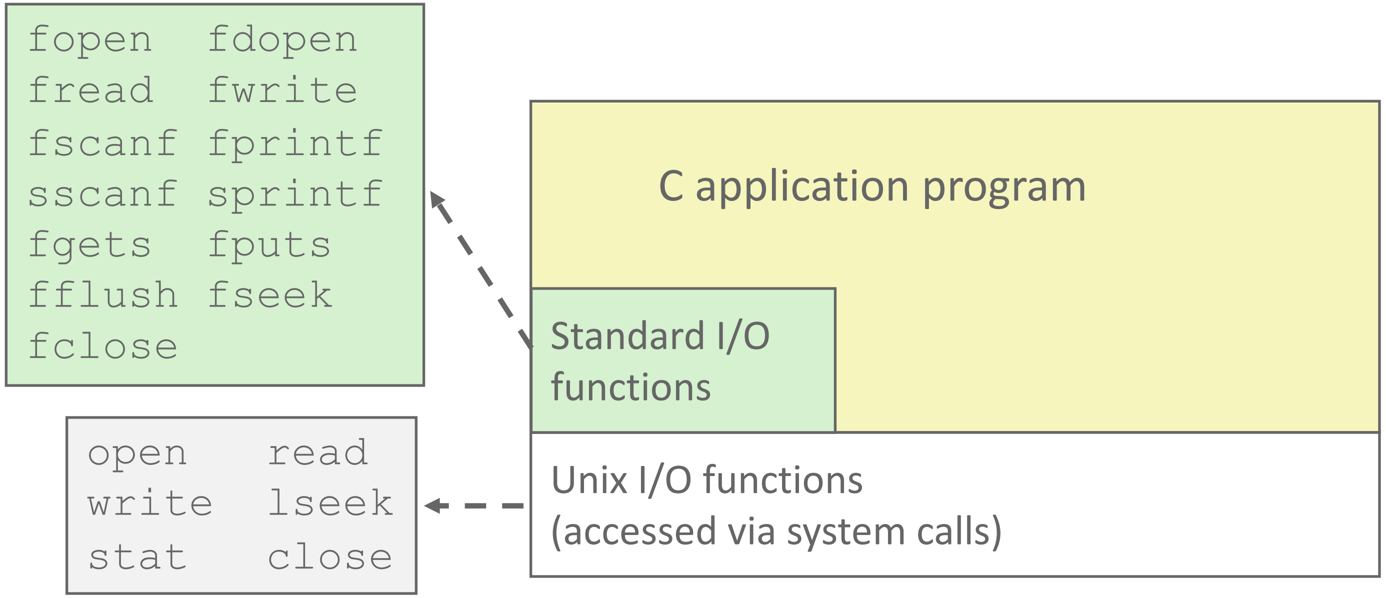
Today: Unix I/O and C Standard I/O

- Two sets: system-level and C level

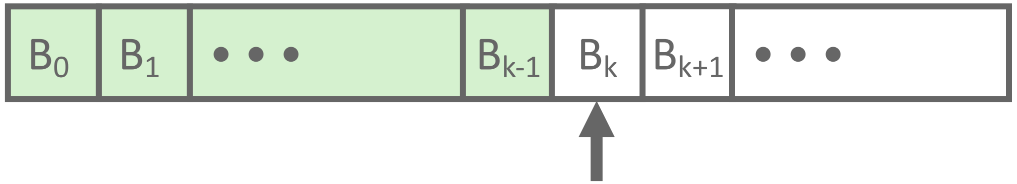


Unix I/O Overview

- A Linux *file* is a sequence of *m* bytes:
  - $B_0, B_1, \ldots, B_k, \ldots, B_{m-1}$
- Cool fact: All I/O devices are represented as files:
  - **`/dev/sda2`** (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

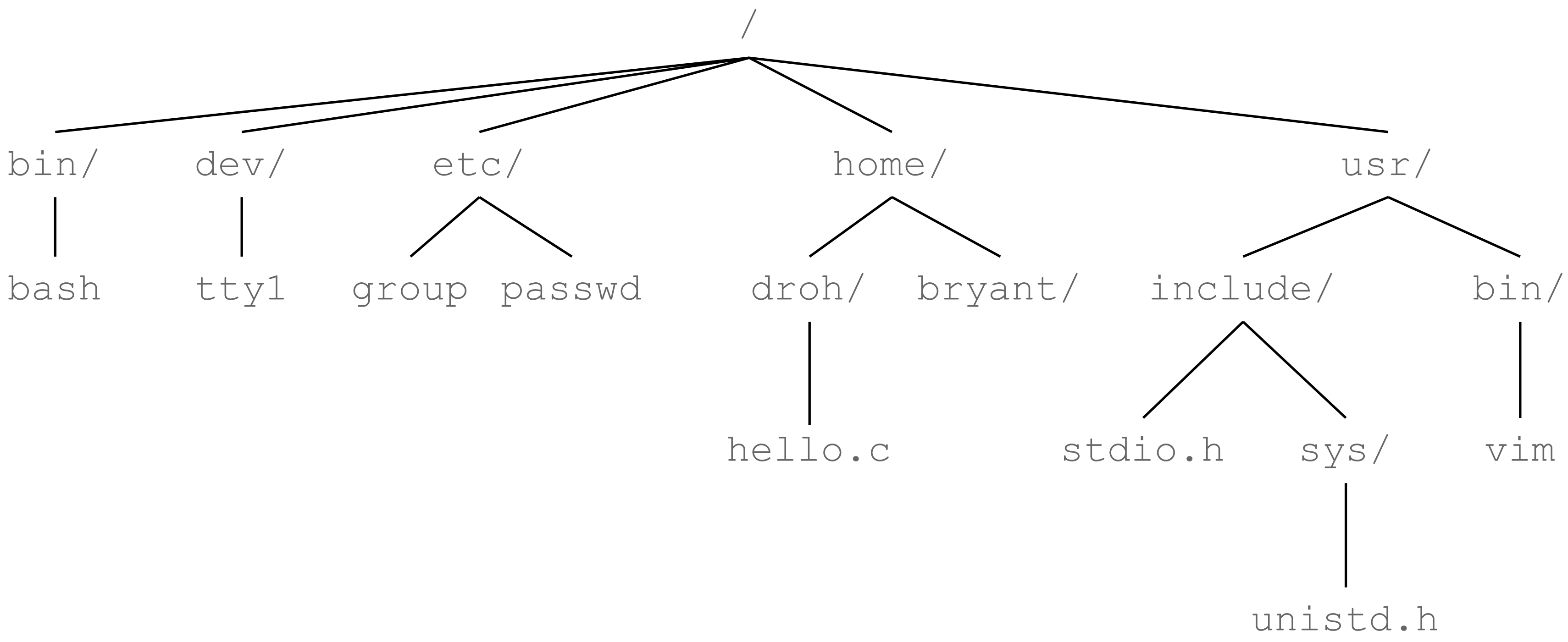
- A regular file contains arbitrary data
- Applications often distinguish between *text files* and *binary files*
  - Text files are regular files with only ASCII or Unicode characters
  - Binary files are everything else
    - e.g., object files, JPEG images
  - Kernel doesn't know the difference!
- Text file is sequence of *text lines*
  - Text line is sequence of chars terminated by *newline char* (**'\n'**)
    - Newline is **0xa**, same as ASCII line feed character (LF)
- End of line (EOL) indicators in other systems
  - Linux and Mac OS: **'\n'** (**0xa**)
    - line feed (LF)
  - Windows and Internet protocols: **'\r\n'** (**0xd 0xa**)
    - Carriage return (CR) followed by line feed (LF)

Directories

- Directory consists of an array of *links*
  - Each link maps a *filename* to a file
- Each directory contains at least two entries
  - `.` (dot) is a link to itself
  - `..` (dot dot) is a link to *the parent directory* in the *directory hierarchy* (next slide)
- Commands for manipulating directories
  - **`mkdir`**: create empty directory
  - **`ls`**: view directory contents
  - **`rmdir`**: delete empty directory

Directory Hierarchy

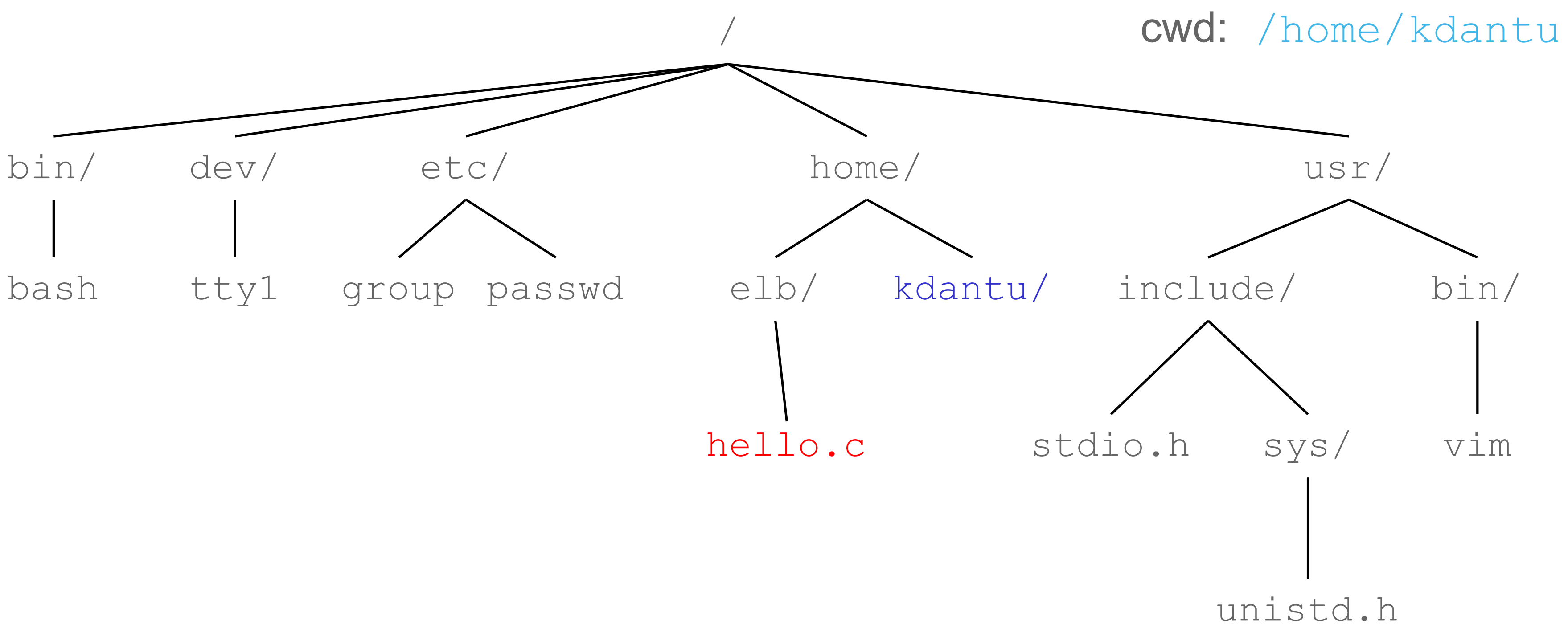
- All files are organized as a hierarchy anchored by root directory named / (slash)



- Kernel maintains *current working directory (cwd)* for each process
  - Modified using the **`cd`** command

Pathnames

- Locations of files in the hierarchy denoted by *pathnames*
  - *Absolute pathname* starts with '/' and denotes path from root
    - **`/home/elb/hello.c`**
  - *Relative pathname* denotes path from current working directory
    - **`../home/elb/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 file to stdout, one byte at a time

```
#include <unistd.h>
#include <fcntl.h>

int main(int argc, char *argv[])
{
    char c;
    int infd;
    if (argc == 2) {
        infd = open(argv[1], O_RDONLY);
    }
    while(read(infd, &c, 1) != 0)
        write(1, c, sizeof(c));
    exit(0);
}
```

- Demo:

```
linux> strace ./showfile1_nobuf names.txt
```

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.

Home-grown buffered I/O code

- Copying file to stdout, BUFSIZE bytes at a time

```
#include <stdio.h>
#define BUFSIZE 64

int main(int argc, char *argv[])
{
    char buf[BUFSIZE];
    int infd = 1; // 1 - STDOUT
    if (argc == 2) {
        infd = open(argv[1], O_RDONLY);
    }
    while((nread = read(infd, &buf, BUFSIZE)) != 0)
        write(1, buf, sizeof(buf));
    exit(0);
}
```

- Demo:

```
linux> strace ./showfile2_buf names.txt
```

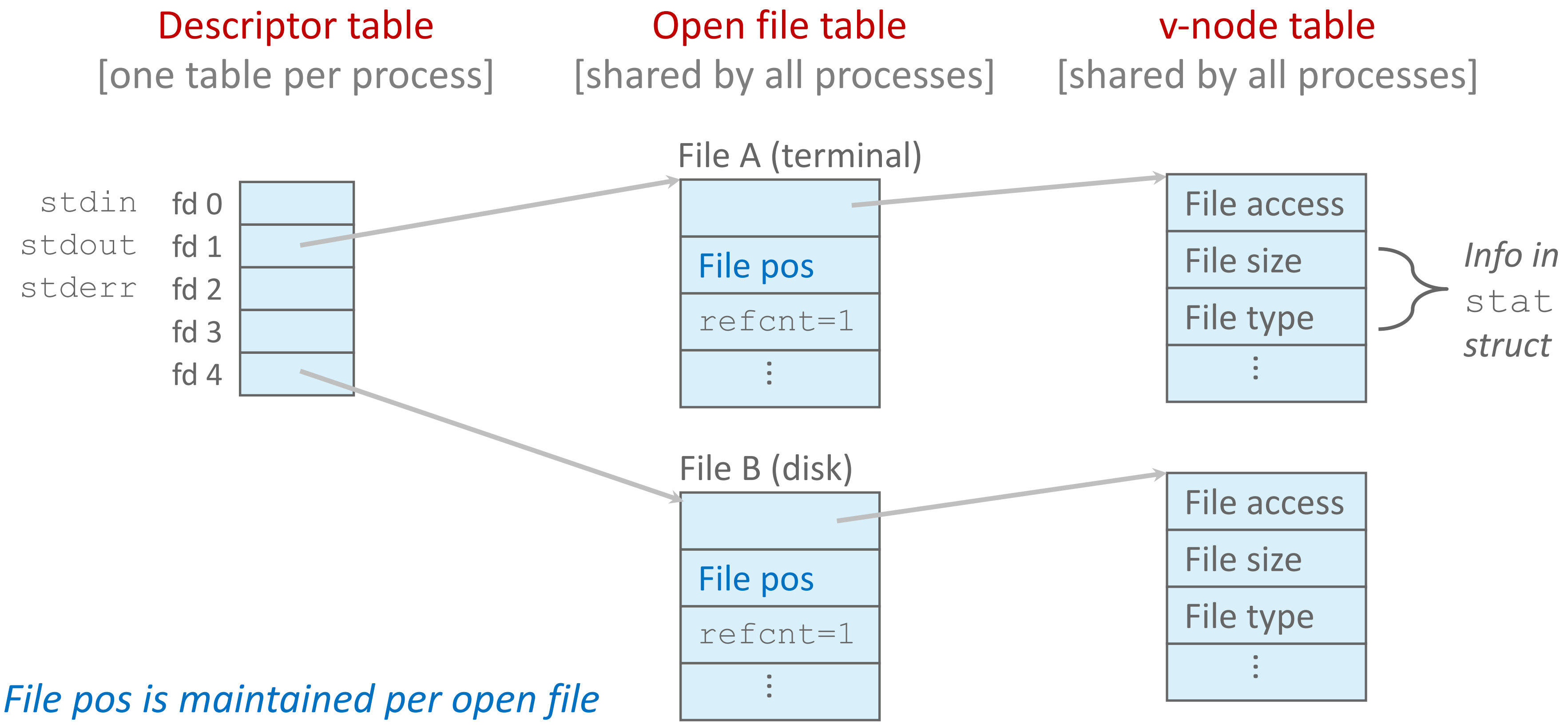
File Metadata

- *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 */
};
```

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 pos is maintained per open file

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)`

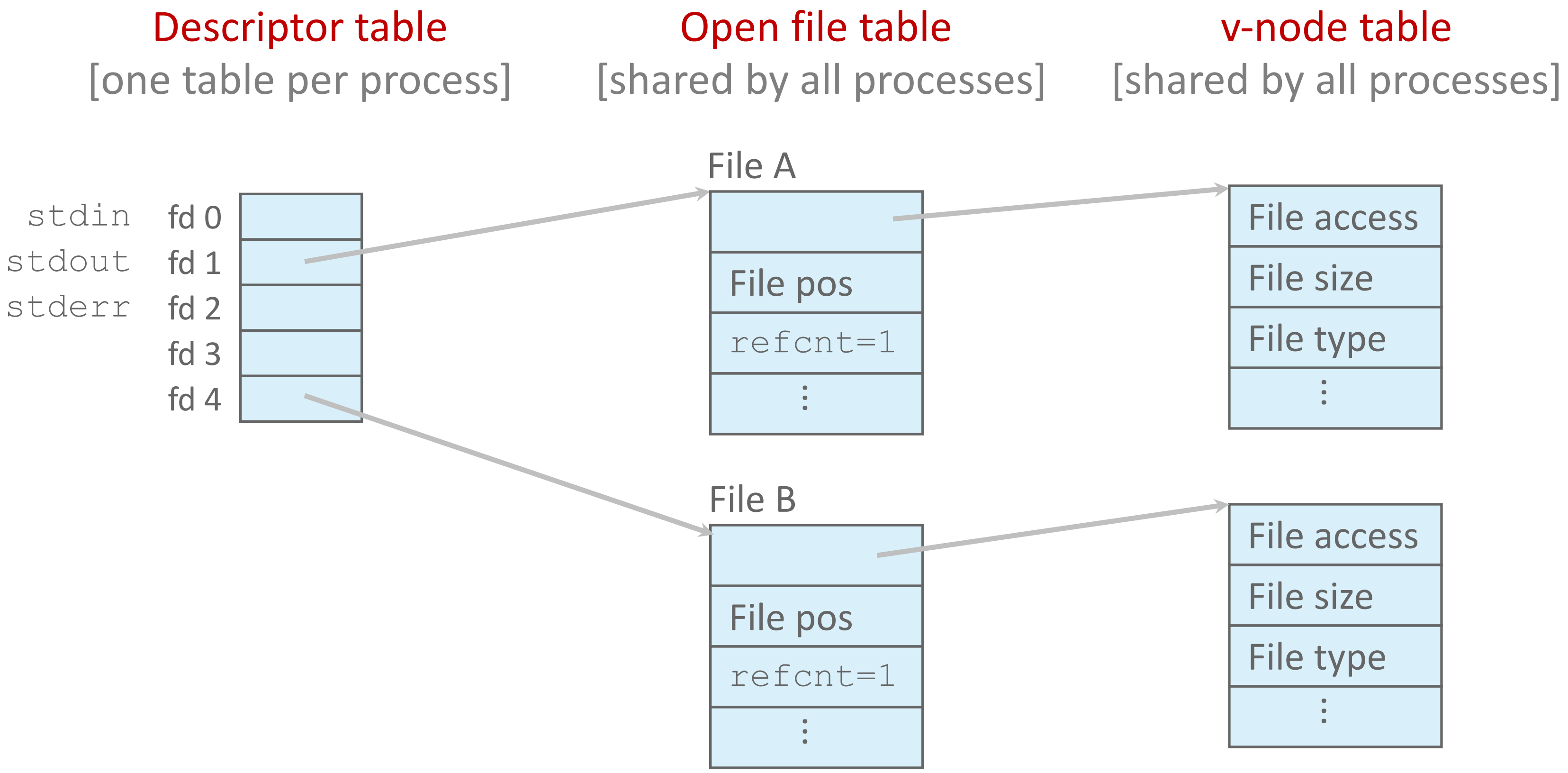
fd 0	
fd 1	a
fd 2	
fd 3	
fd 4	b

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

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

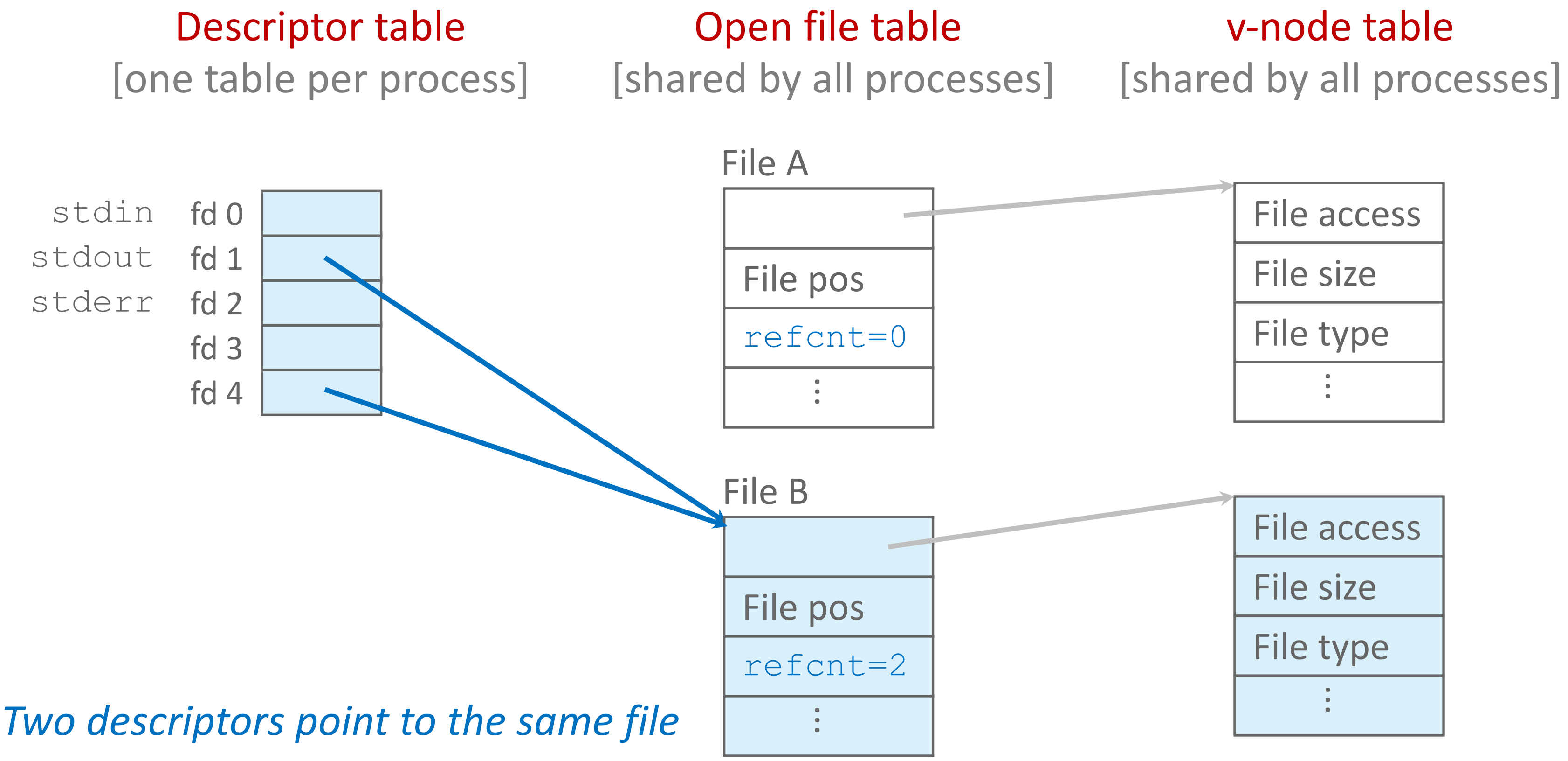
I/O Redirection Example

- 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



Two descriptors point to the same file

Warm-Up: I/O and Redirection Example

```
#include <stdio.h>
#include <unistd.h>

int main(int argc, char *argv[])
{
    FILE *fd1, *fd2, *fd3;
    char c1, c2, c3;
    char *fname = argv[1];
    fd1 = fopen(fname, O_RDONLY);
    fd2 = fopen(fname, O_RDONLY);
    fd3 = fopen(fname, O_RDONLY);
    dup2(fd2, fd3);
    fread(&c1, 1, 1, fd1)));
    fread(&c2, 1, 1, fd2)));
    fread(&c3, 1, 1, fd3)));
    printf("c1 = %c, c2 = %c, c3 = %c\n", c1, c2, c3);
    return 0;
}
```

- What would this program print for file containing "`abcde`"?

Warm-Up: I/O and Redirection Example

```
#include <stdio.h>
#include <unistd.h>

int main(int argc, char *argv[])
{
    FILE *fd1, *fd2, *fd3;
    char c1, c2, c3;
    char *fname = argv[1];
    fd1 = fopen(fname, O_RDONLY);
    fd2 = fopen(fname, O_RDONLY);
    fd3 = fopen(fname, O_RDONLY);
    dup2(fd2, fd3);
    fread(&c1, 1, 1, fd1)));
    fread(&c2, 1, 1, fd2)));
    fread(&c3, 1, 1, fd3)));
    printf("c1 = %c, c2 = %c, c3 = %c\n", c1, c2, c3);
    return 0;
}
```

```
c1 = a, c2 = a, c3 = b
```

```
dup2(oldfd, newfd)
```

- What would this program print for file containing "abcde"?

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");
}
```

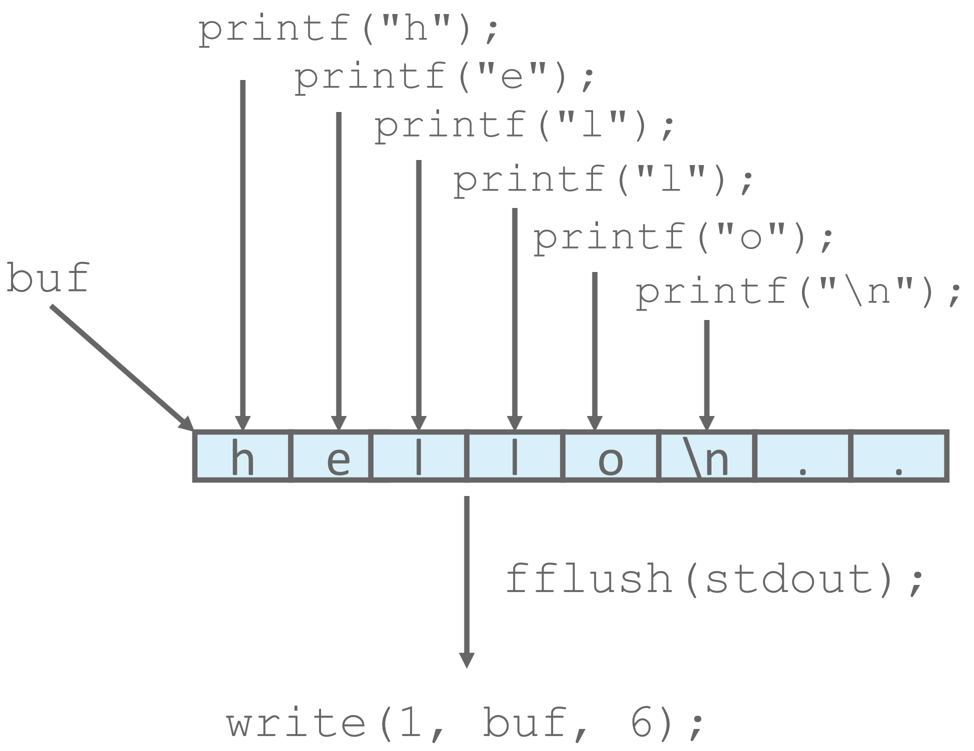
Buffered I/O: Motivation

- 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)                            = ?
```

Standard I/O Example

- Copying file to stdout, line-by-line with stdio

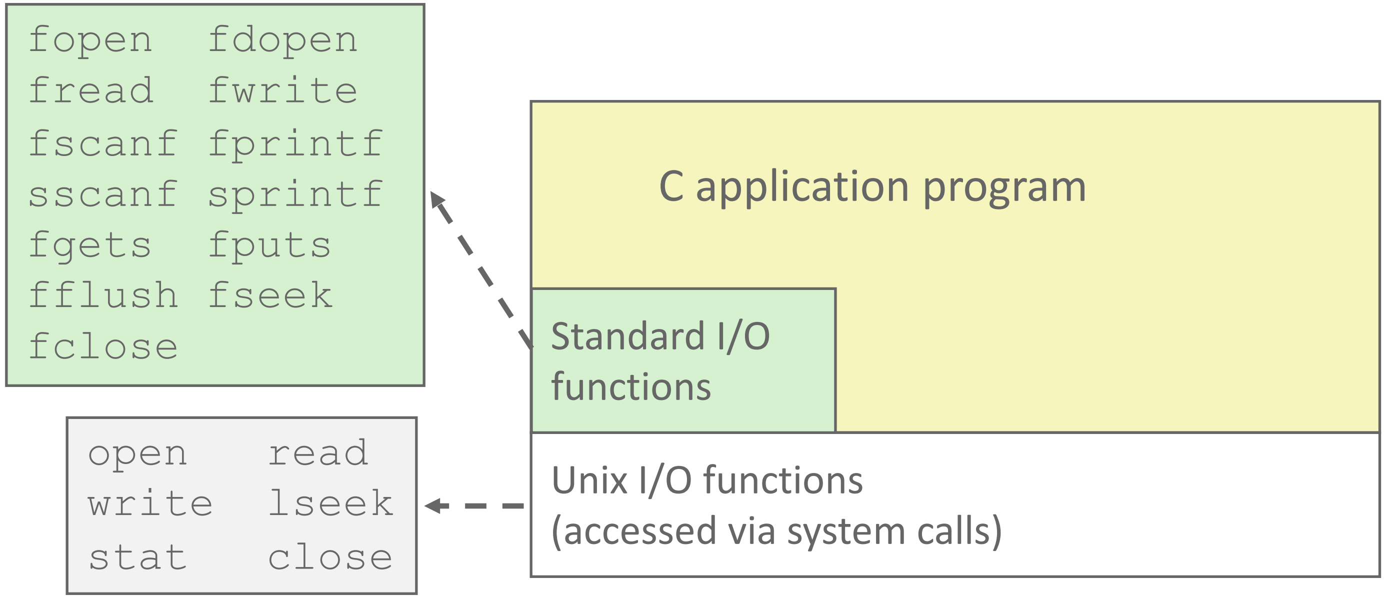
```
#include <stdio.h>
#define MLINE 1024

int main(int argc, char *argv[])
{
    char buf[MLINE];
    FILE *infile = stdin;
    if (argc == 2) {
        infile = fopen(argv[1], "r");
        if (!infile) exit(1);
    }
    while(fgets(buf, MLINE, infile) != NULL)
        fprintf(stdout, buf);
    exit(0);
}
```

- Demo:

```
linux> strace ./showfile3_stdio names.txt
```

Today: Unix I/O and C Standard I/O

- Two *incompatible* libraries building on Unix I/O
- Robust I/O (RIO): 15-213 special wrappers
  good coding practice: handles error checking, signals, and "short counts"



Unix I/O Recap

```
/* Read at most max_count bytes from file into buffer.
   Return number bytes read, or error value */
ssize_t read(int fd, void *buffer, size_t max_count);
```

```
/* Write at most max_count bytes from buffer to file.
   Return number bytes written, or error value */
ssize_t write(int fd, void *buffer, size_t max_count);
```

- 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.

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

- Binary File
  - Sequence of arbitrary bytes
  - Including byte value 0x00
- 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

Required Reading