15-213

"The course that gives CMU its Zip!"

System-Level I/O
April 6, 2006

Topics

- More on Cyclone
- Unix I/O
- Robust reading and writing
- Reading file metadata
- Sharing files
- I/O redirection
- Standard I/O

Unsafe Features in C

Remember this "check list" (with cyclone solutions)

- Pointer arithmetic (fat pointers, bounded pointers)
- Some casts to pointers (disallow certain casts)
- Unions (tagged unions)
- Printf and scanf (use tagged unions)
- Uninitialized variables (check if vars initialized before use)
- Malloc/free (no free; garbage collection; regions)
- Returning stack locations (regions)
- Linking (type information in object files)

Need to know pitfalls to avoid them

Important debugging aid

Can help identify good coding practices, even in C

(Even if you will never write a line of Cyclone code)

SAL

SAL is an annotation language for C

- Similar to the primitives in Cyclone
- Pre- and post-conditions for all functions
- Tries to avoid the same unsafe features of C
- Bug finding instead of safety guarantee

Used at Microsoft, especially in Vista development

- All code must pass checker before release into main branch
- Encourages good coding style
- Not all correct code checks
- Occasionally, must escape checker (with peer review)

Successful in drastically reducing number of bugs

Ideas behind SAL, Cyclone will be mainstream in much of industrial systems programming

Example from Exam2, S'05

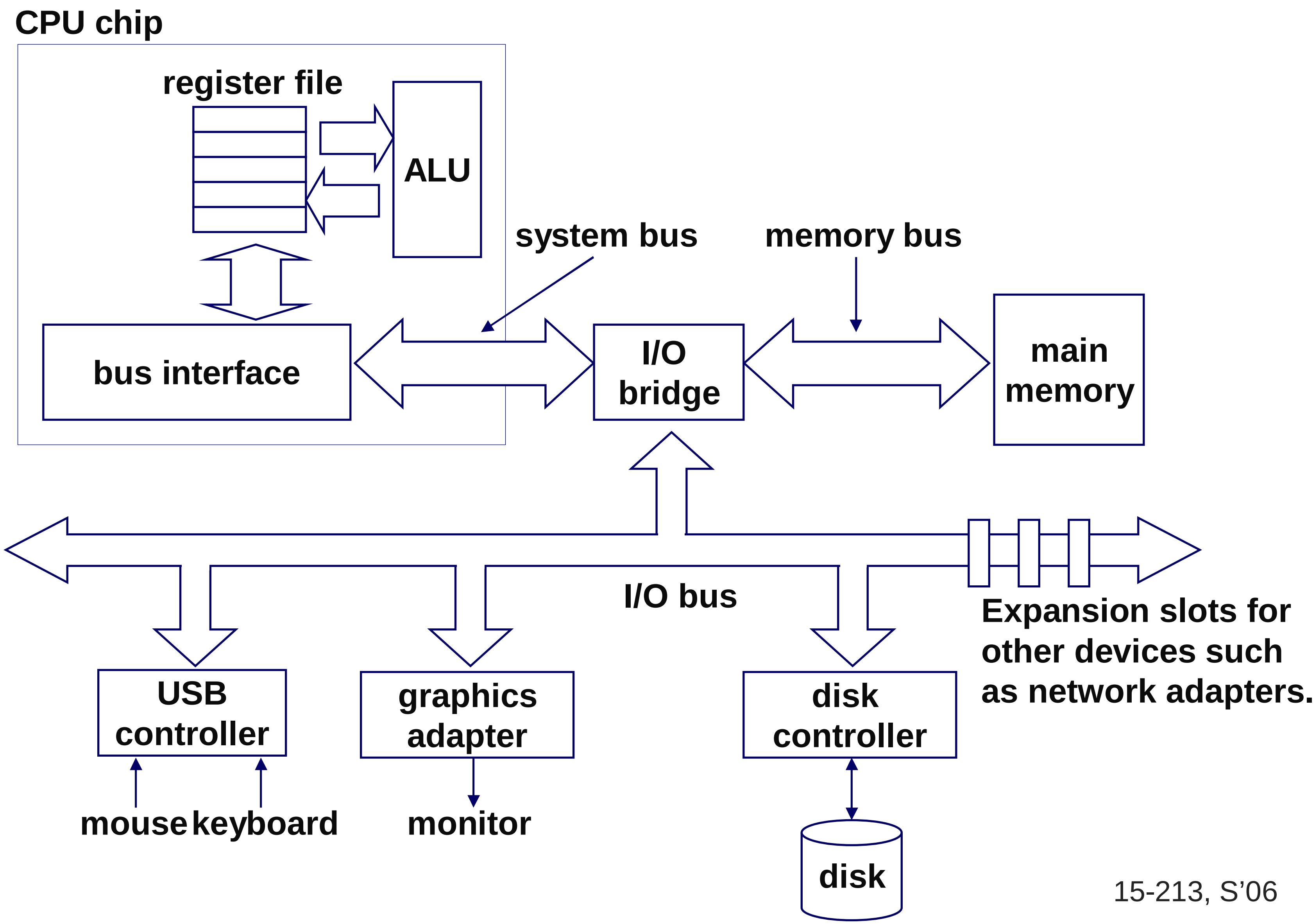
Recognize fat and thin (bounded) pointers

Recognize if pointers may be NULL or not

Tell which regions pointers point to

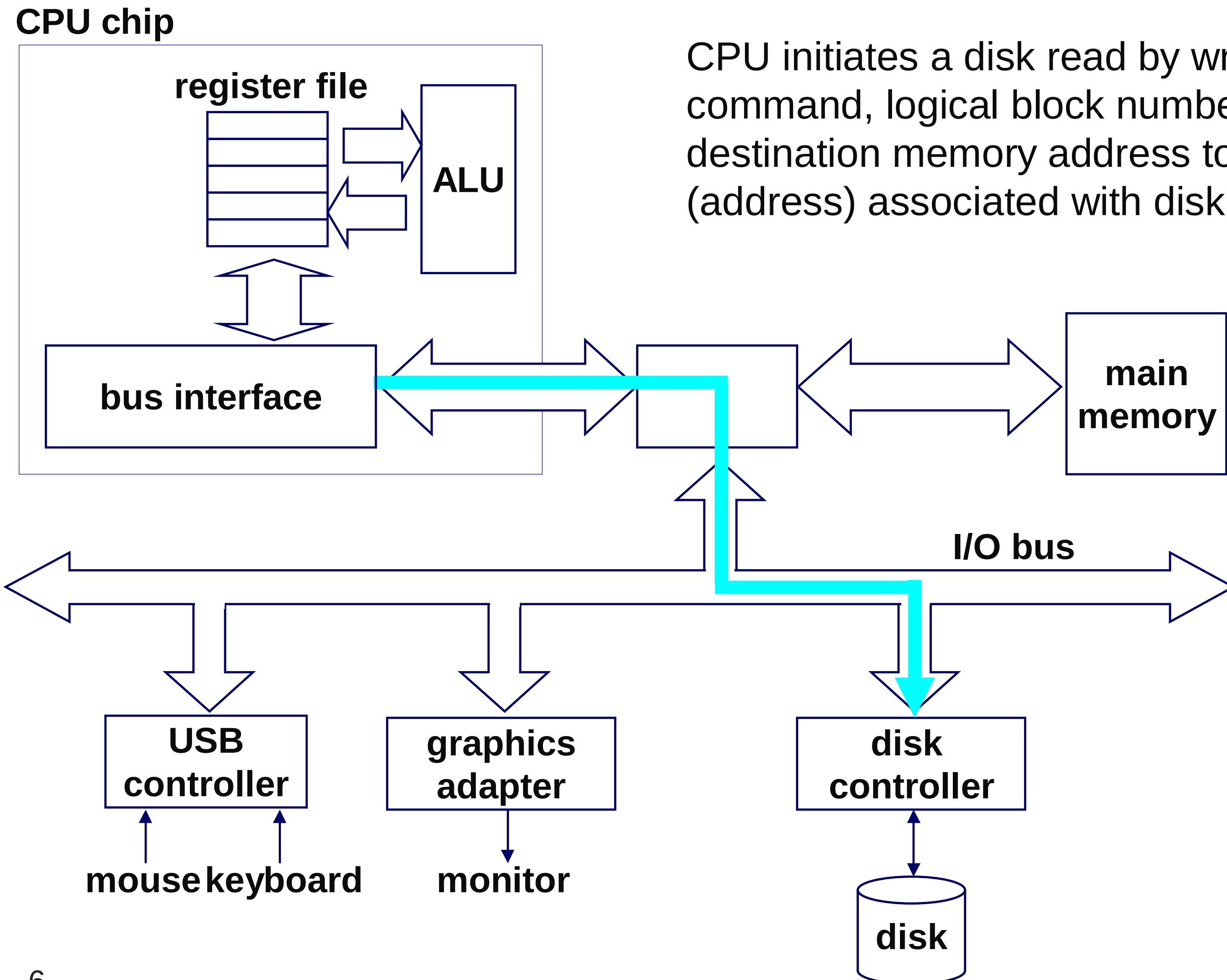
Common idiom: pass array and its size (also in SAL)

A Typical Hardware System



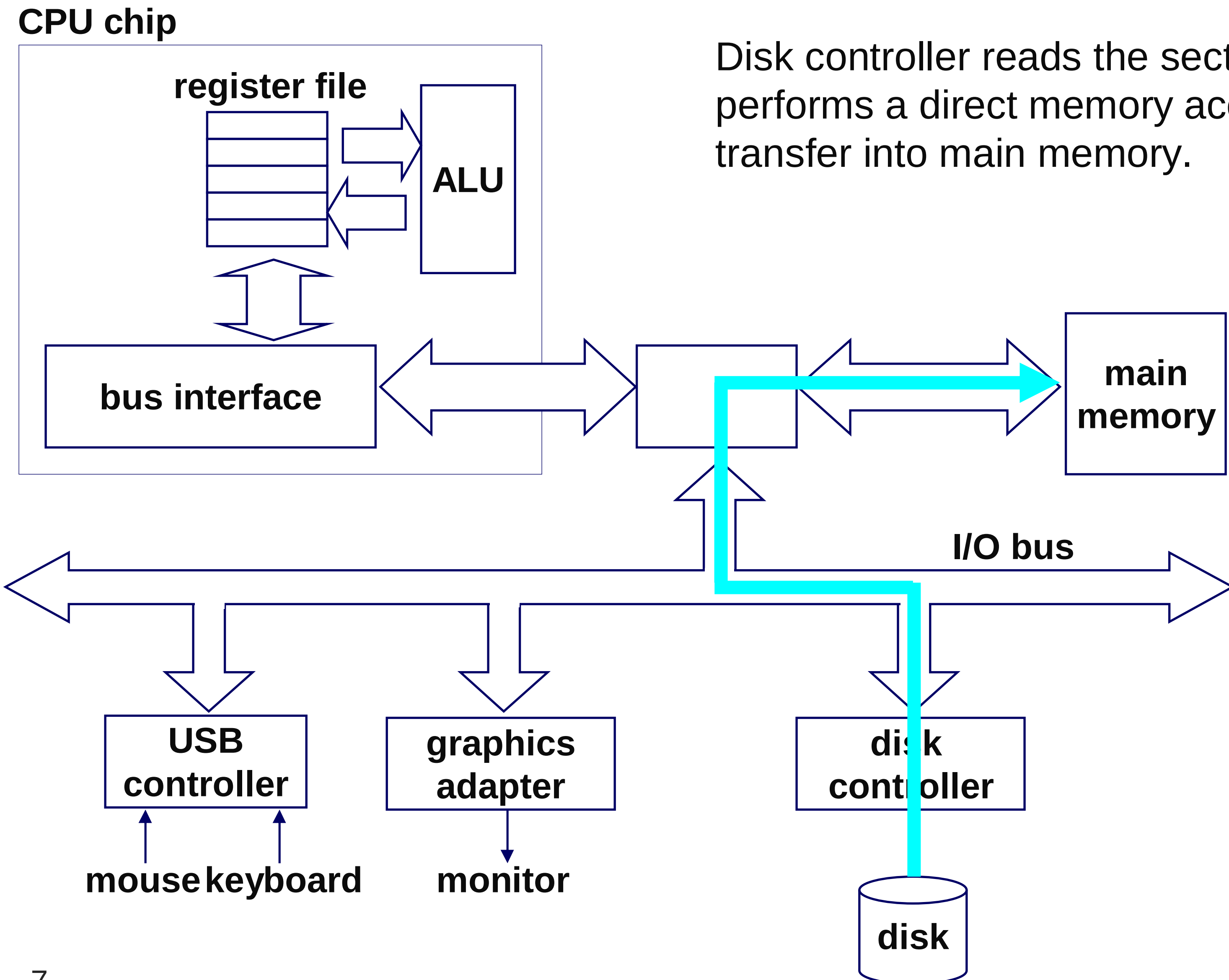
Reading a Disk Sector: Step 1

CPU initiates a disk read by writing a command, logical block number, and destination memory address to a port (address) associated with disk controller.



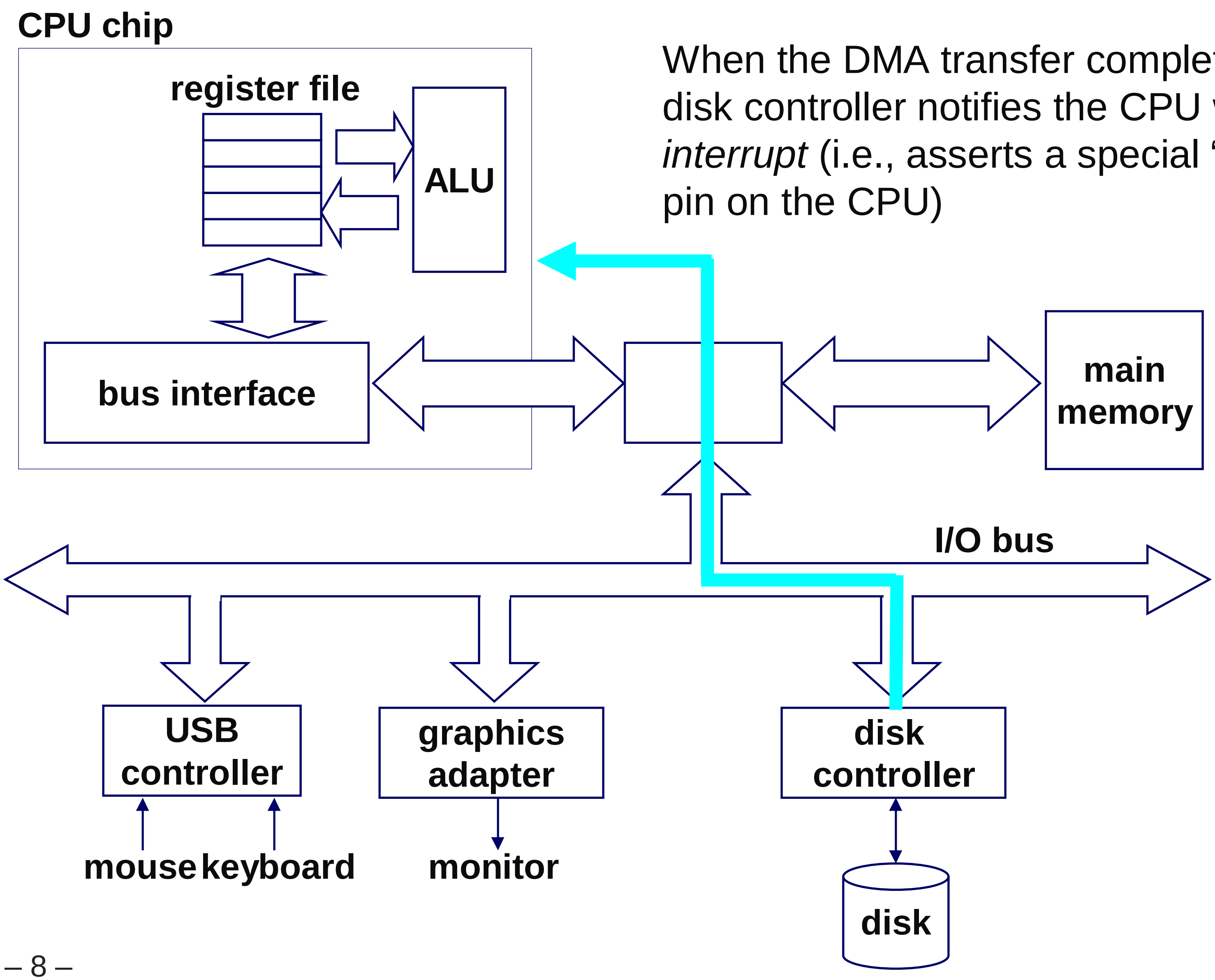
Reading a Disk Sector: Step 2

Disk controller reads the sector and performs a direct memory access (DMA) transfer into main memory.



Reading a Disk Sector: Step 3

When the DMA transfer completes, the disk controller notifies the CPU with an *interrupt* (i.e., asserts a special "interrupt" pin on the CPU)



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

- Binary or text file.
- Unix does not know the difference!

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 interprocess communication

Socket

- A file type used for network communication between processes

Unix I/O

The elegant mapping of files to devices allows kernel to export simple interface called Unix I/O.

Key Unix 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()`
- Changing the *current file position* (seek)
  - `lseek` (not discussed)
- Reading and writing a file
  - `read()` and `write()`

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`

- `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!

Transfers up to 512 bytes from address `buf` to file `fd`

Unix I/O Example

Copying standard input to standard output 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);
}
```

Note the use of error handling wrappers for read and write (Appendix B).

Dealing with 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.

How should you deal with short counts in your code?

- Use the RIO (Robust I/O) package from your textbook's `csapp.c` file (Appendix B).

The RIO Package

RIO is a set of wrappers that provide efficient and robust I/O in applications 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`
  - Cleans up some problems with Stevens's `readline` and `readn` functions.
  - Unlike the Stevens routines, the buffered RIO routines are *thread-safe* and can be interleaved arbitrarily on the same descriptor.

Download from

`csapp.cs.cmu.edu/public/ics/code/src/csapp.c`
`csapp.cs.cmu.edu/public/ics/code/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(nt 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 it encounters EOF.**
- **`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 */
}
```

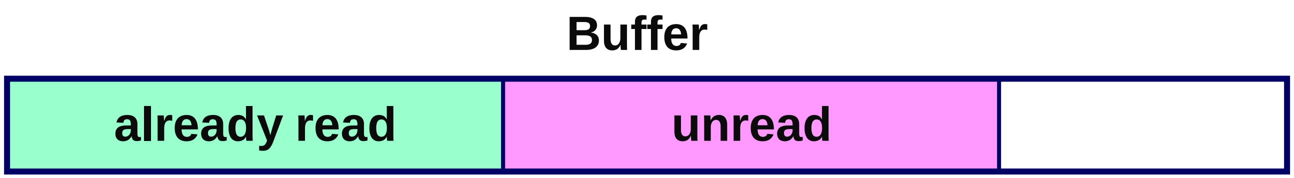
Buffered I/O: Motivation

I/O Applications Read/Write One Character at a Time

- getc, putc, ungetc
- gets
  - Read line of text, stopping at newline

Implementing as Calls to Unix I/O Expensive

- Read & Write involve require Unix kernel calls
  - > 10,000 clock cycles

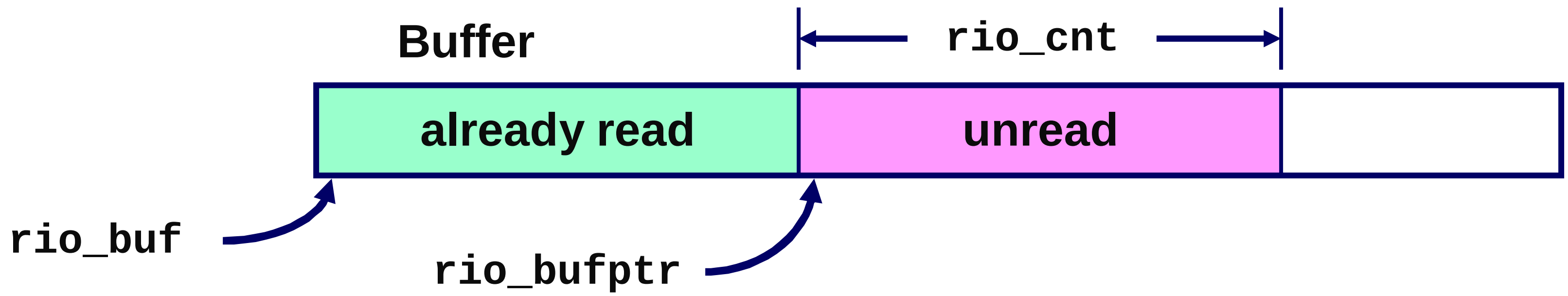


Buffered Read

- Use Unix read to grab block of characters
- User input functions take one character at a time from buffer
  - Refill buffer when empty

Buffered I/O: Implementation

- File has associated buffer to hold bytes that have been read from file but not yet read by user code




```
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 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.
- `rio_readnb` reads up to n bytes from file `fd`.
- Calls to `rio_readlineb` and `rio_readnb` can be interleaved arbitrarily on the same descriptor.
  - Warning: Don’t interleave with calls to `rio_readn`

RIO Example

Copying the lines of a text file from standard input to standard output.

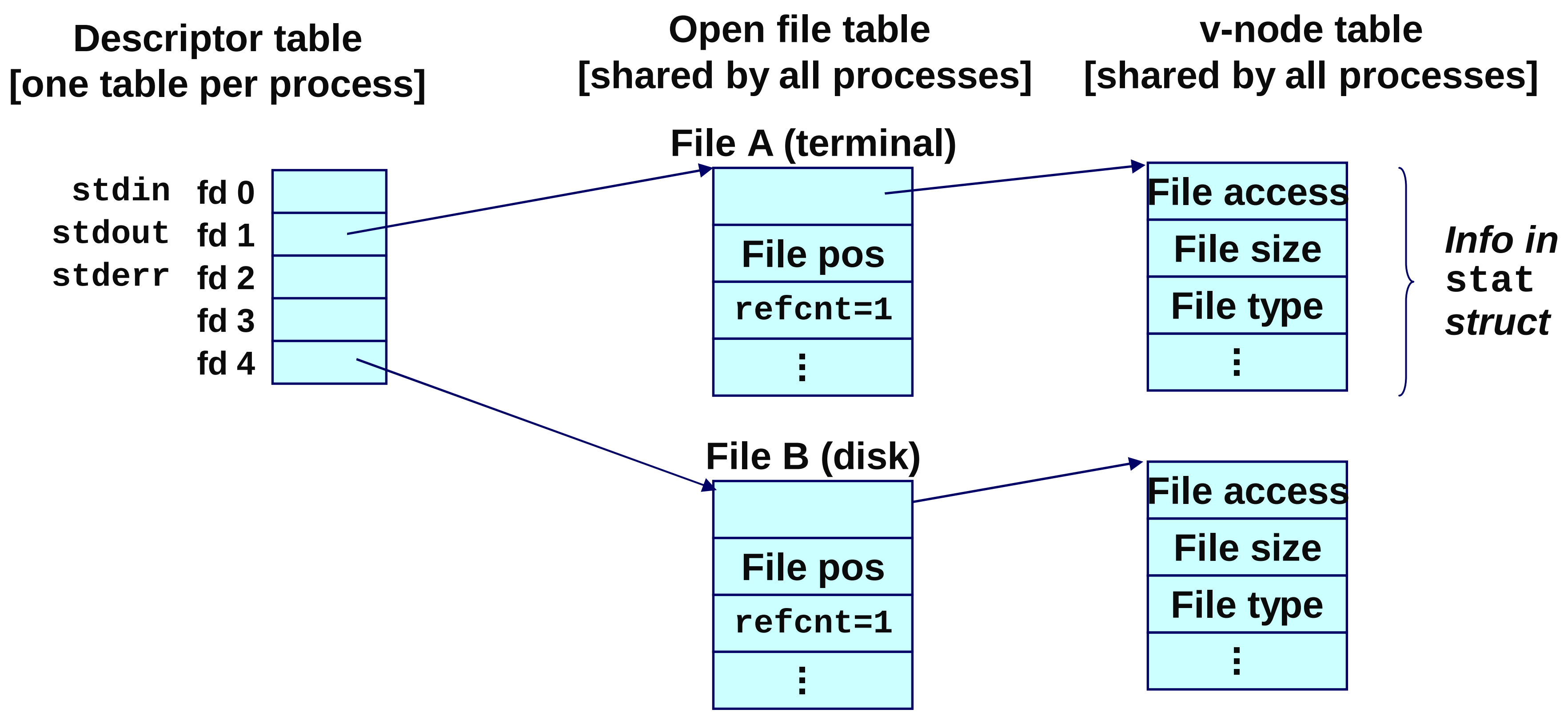
```
#include "csapp.h"

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);
}
```

How the Unix Kernel Represents Open Files

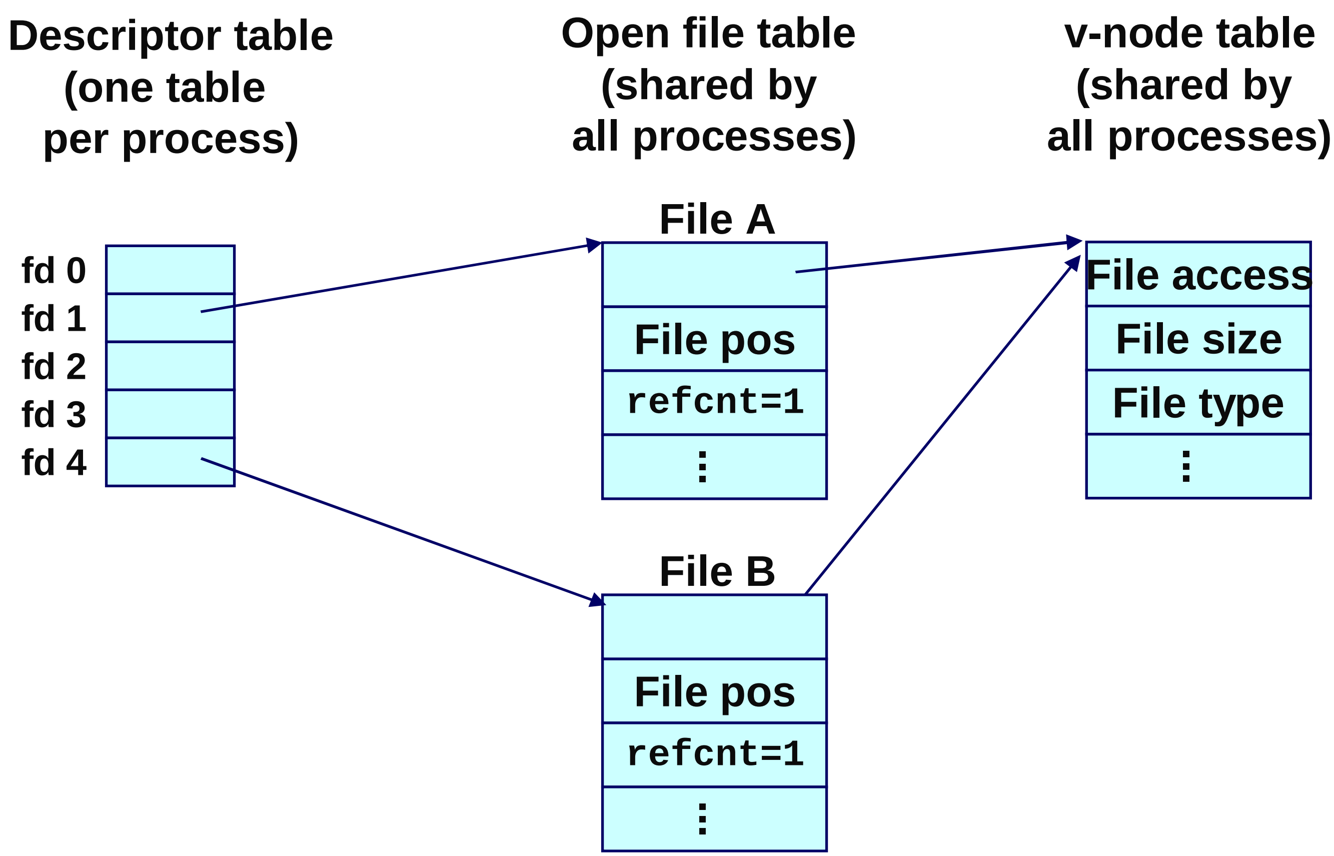
Two descriptors referencing two distinct open disk files. Descriptor 1 (stdout) points to terminal, and descriptor 4 points to open disk file.



File Sharing

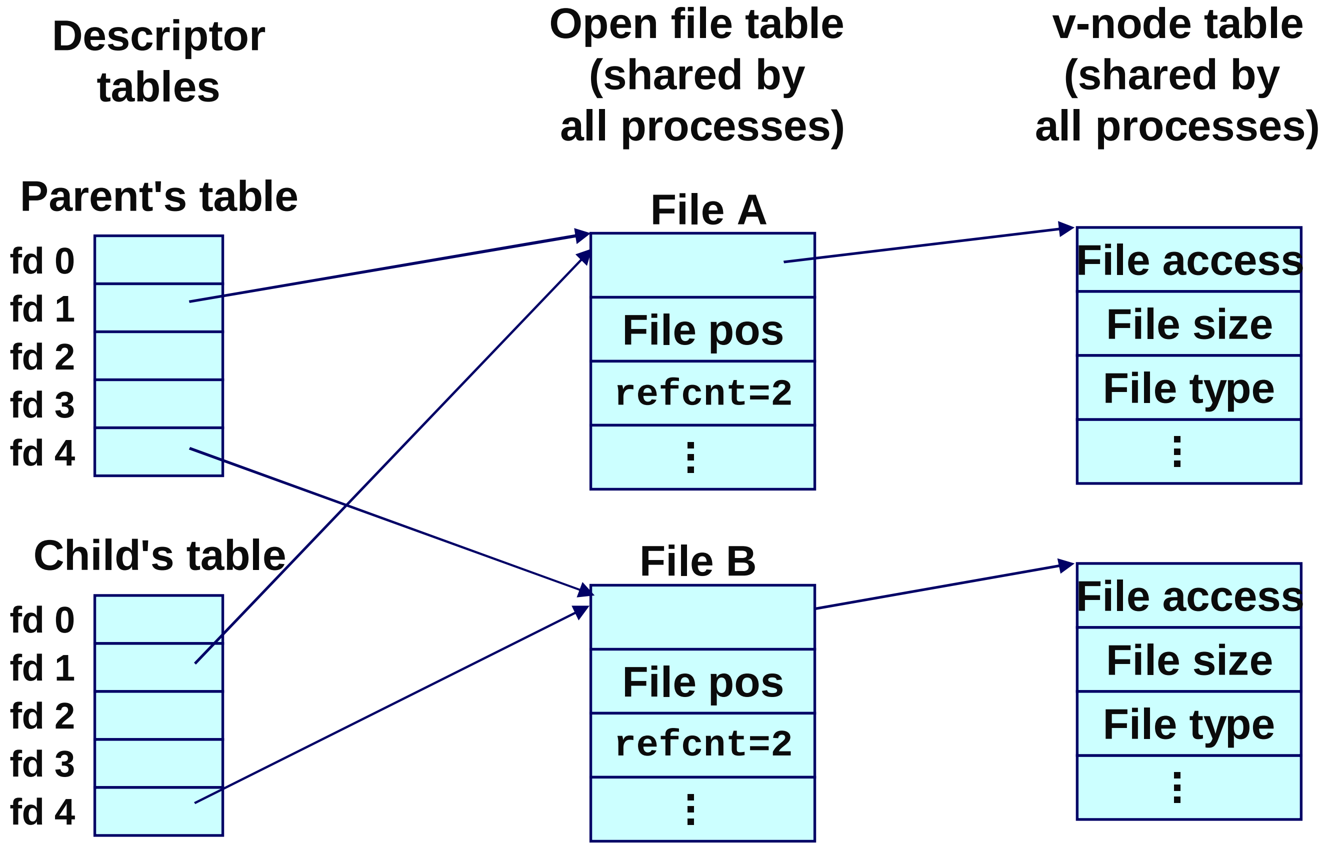
Two distinct descriptors sharing the same disk file through two distinct open file table entries

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



How Processes Share Files

A child process inherits its parent's open files. Here is the situation immediately after a `fork`



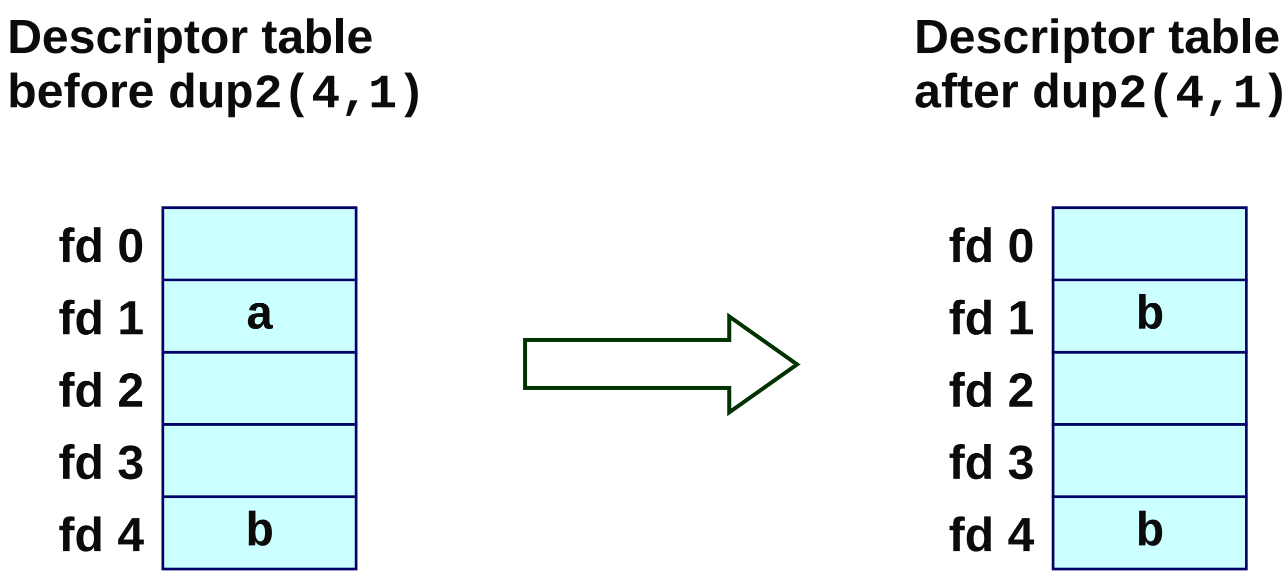
I/O Redirection

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

```
unix> ls > foo.txt
```

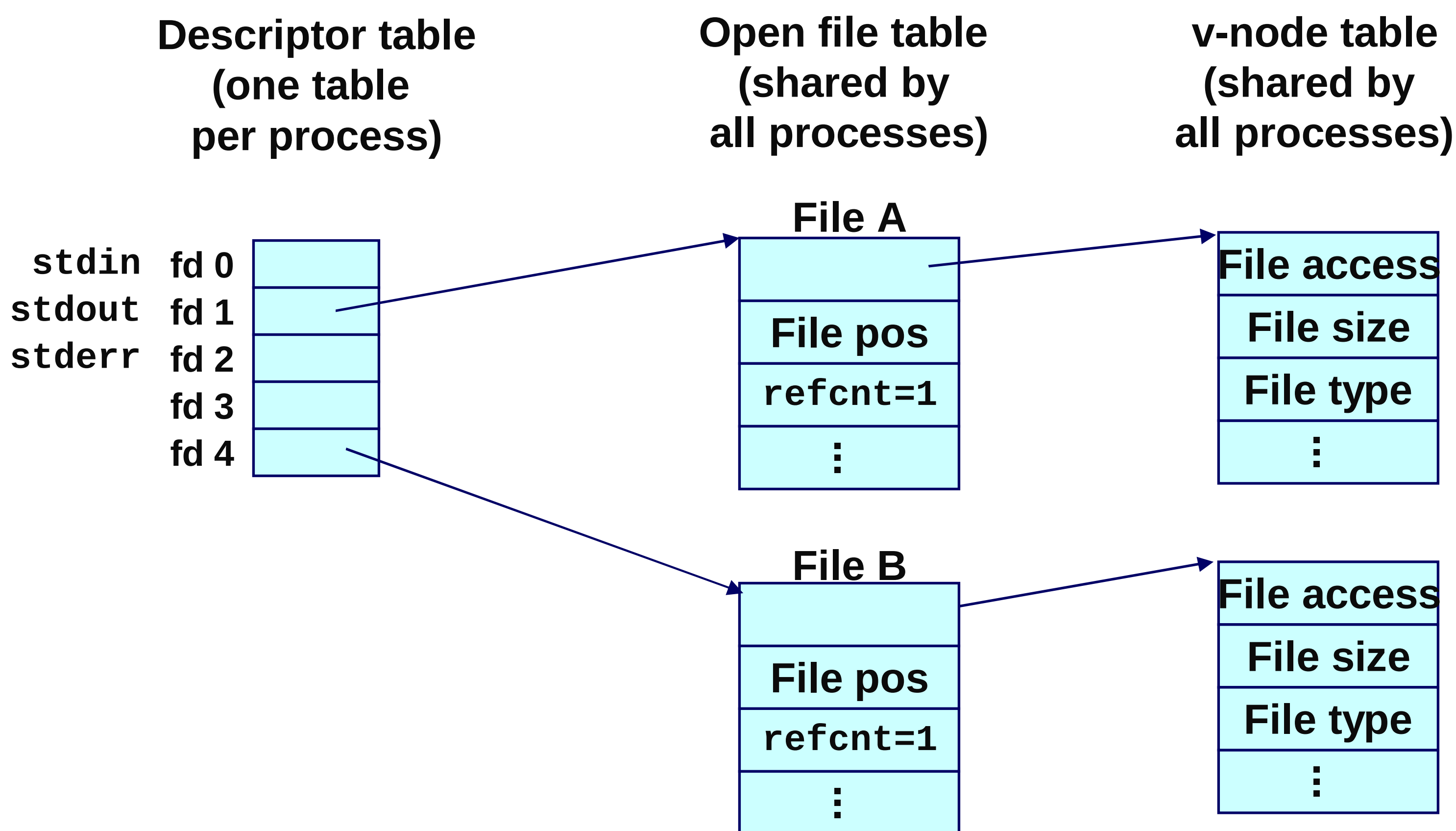
Answer: By calling the `dup2(oldfd, newfd)` function

- Copies (per-process) descriptor table entry `oldfd` to entry `newfd`



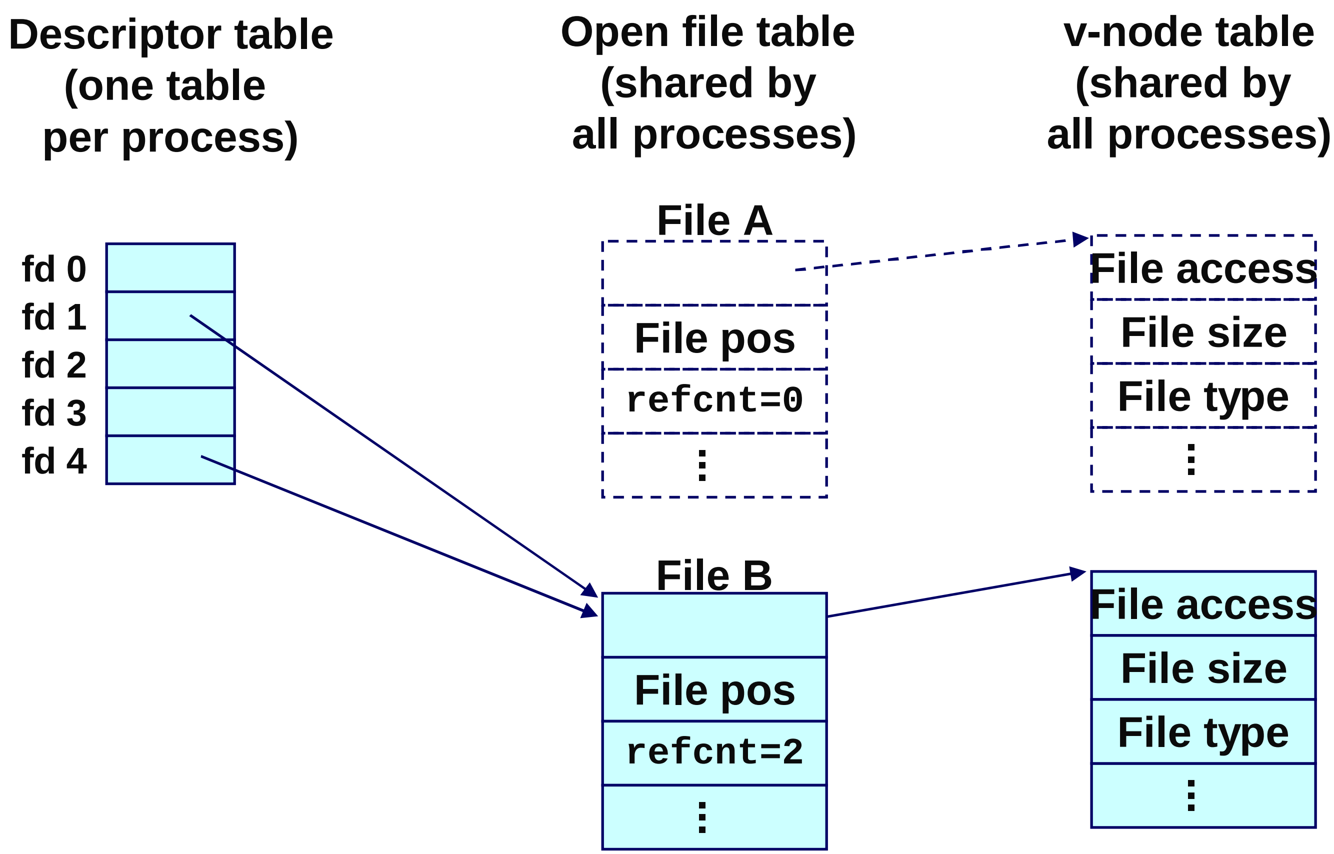
I/O Redirection Example

- Before calling `dup2(4,1)`, stdout (descriptor 1) points to a terminal and descriptor 4 points to an open disk file.



I/O Redirection Example (cont)

After calling `dup2(4,1)`, stdout is now redirected to the disk file pointed at by descriptor 4.



Standard I/O Functions

The C standard library (`libc.a`) 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`)

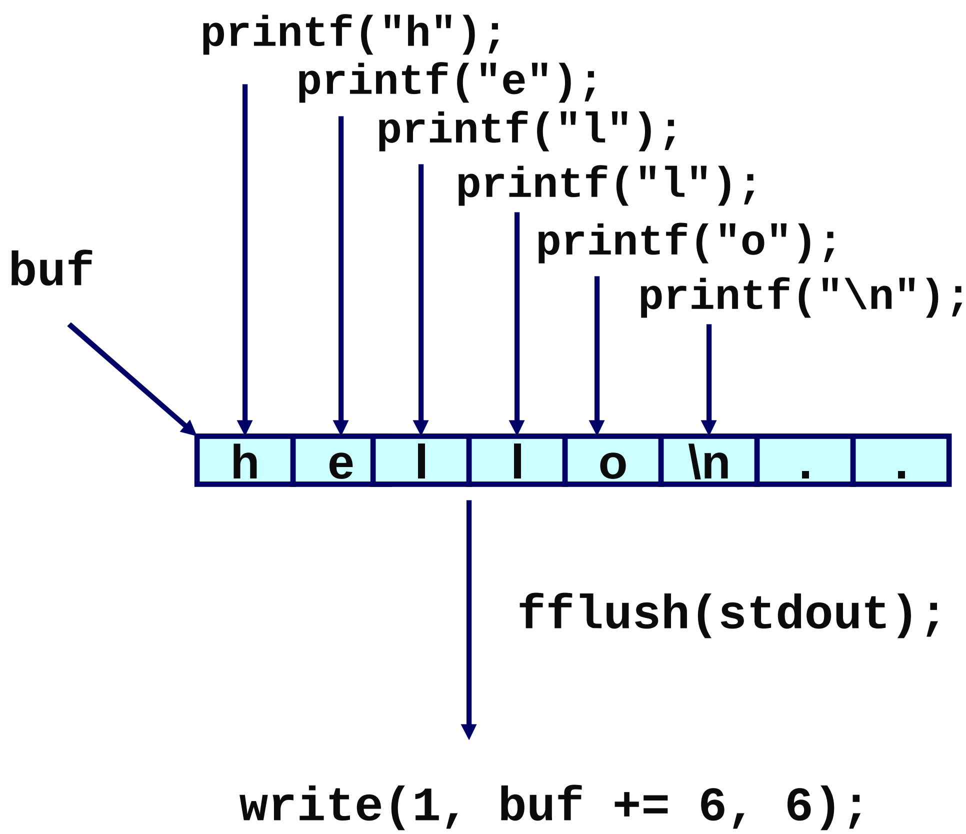
- `stdin` (standard input)
- `stdout` (standard output)
- `stderr` (standard error)

```
#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");
}
```

Buffering in Standard I/O

Standard I/O functions use buffered I/O



Standard I/O Buffering in Action

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

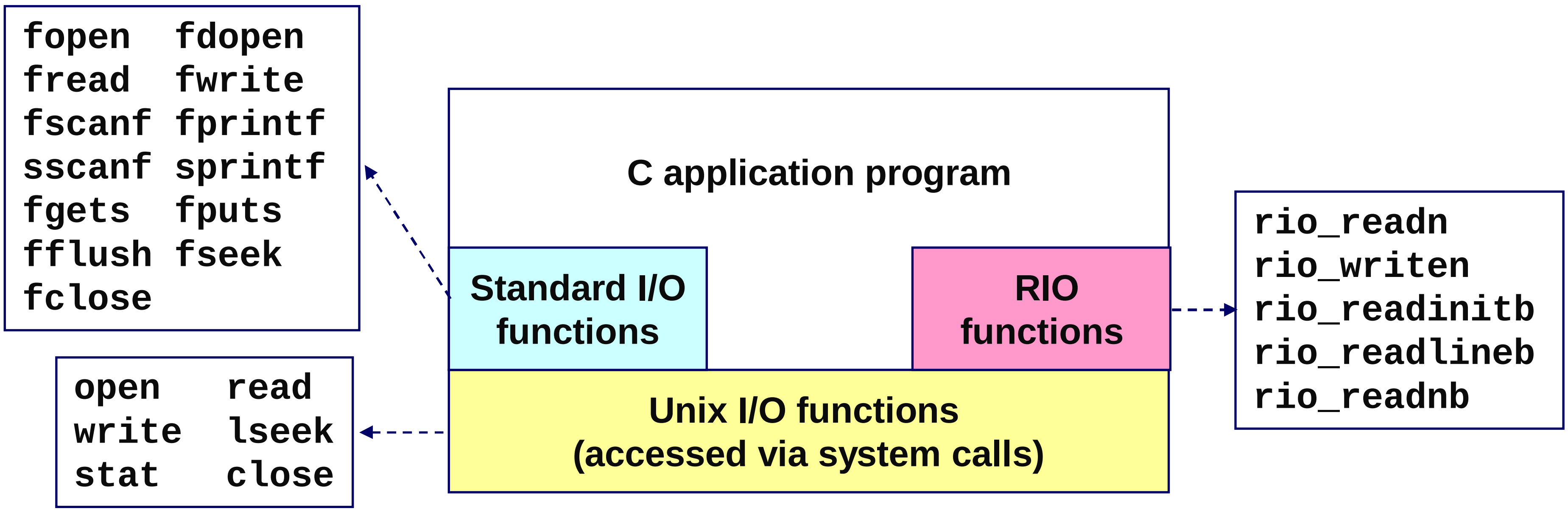
```
#include <stdio.h>

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(0)                                  = ?
```

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.

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 is not appropriate for input and output on network sockets
- There are poorly documented restrictions on streams that interact badly with restrictions on sockets

Pros and Cons of Standard I/O (cont)

Restrictions on streams:

- **Restriction 1: input function cannot follow output function without intervening call to `fflush`, `fseek`, `fsetpos`, or `rewind`.**
  - **Latter three functions all use `lseek` to change file position.**
- **Restriction 2: output function cannot follow an input function with intervening call to `fseek`, `fsetpos`, or `rewind`.**

Restriction on sockets:

- **You are not allowed to change the file position of a socket.**

Pros and Cons of Standard I/O (cont)

Workaround for restriction 1:

- **Flush stream after every output.**

Workaround for restriction 2:

- **Open two streams on the same descriptor, one for reading and one for writing:**

```
FILE *fpin, *fpout;

fpin = fdopen(sockfd, "r");
fpout = fdopen(sockfd, "w");
```

- **However, this requires you to close the same descriptor twice:**

```
fclose(fpin);
fclose(fpout);
```

- **Creates a deadly race in concurrent threaded programs!**

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.

When to use standard I/O?

- When working with disk or terminal files.

When to use raw Unix I/O

- When you need to fetch file metadata.
- In rare cases when you need absolute highest performance.

When to use RIO?

- When you are reading and writing network sockets or pipes.
- Never use standard I/O or raw Unix I/O on sockets or pipes.

For Further Information

The Unix bible:

- W. Richard Stevens, Advanced Programming in the Unix Environment, Addison Wesley, 1993.
  - Somewhat dated, but still useful.
- W. Richard Stevens, Unix Network Programming : Networking APIs: Sockets and XTI (Volume 1), 1998

Stevens is arguably the best technical writer ever.

- Produced authoritative works in:
  - Unix programming
  - TCP/IP (the protocol that makes the Internet work)
  - Unix network programming
  - Unix IPC programming.

Tragically, Stevens died Sept 1, 1999.