15-213
"The course that gives CMU its Zip!"

System-Level I/O
March 31, 2005

Topics

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

Unix I/O Key Characteristics

Classic Unix/Linux I/O:

I/O operates on linear streams of Bytes

- Can reposition insertion point and extend file at end

I/O tends to be synchronous

- Read or write operation block until data has been transferred

Fine grained I/O

- One key-stroke at a time
- Each I/O event is handled by the kernel and an appropriate process

Mainframe I/O:

I/O operates on structured records

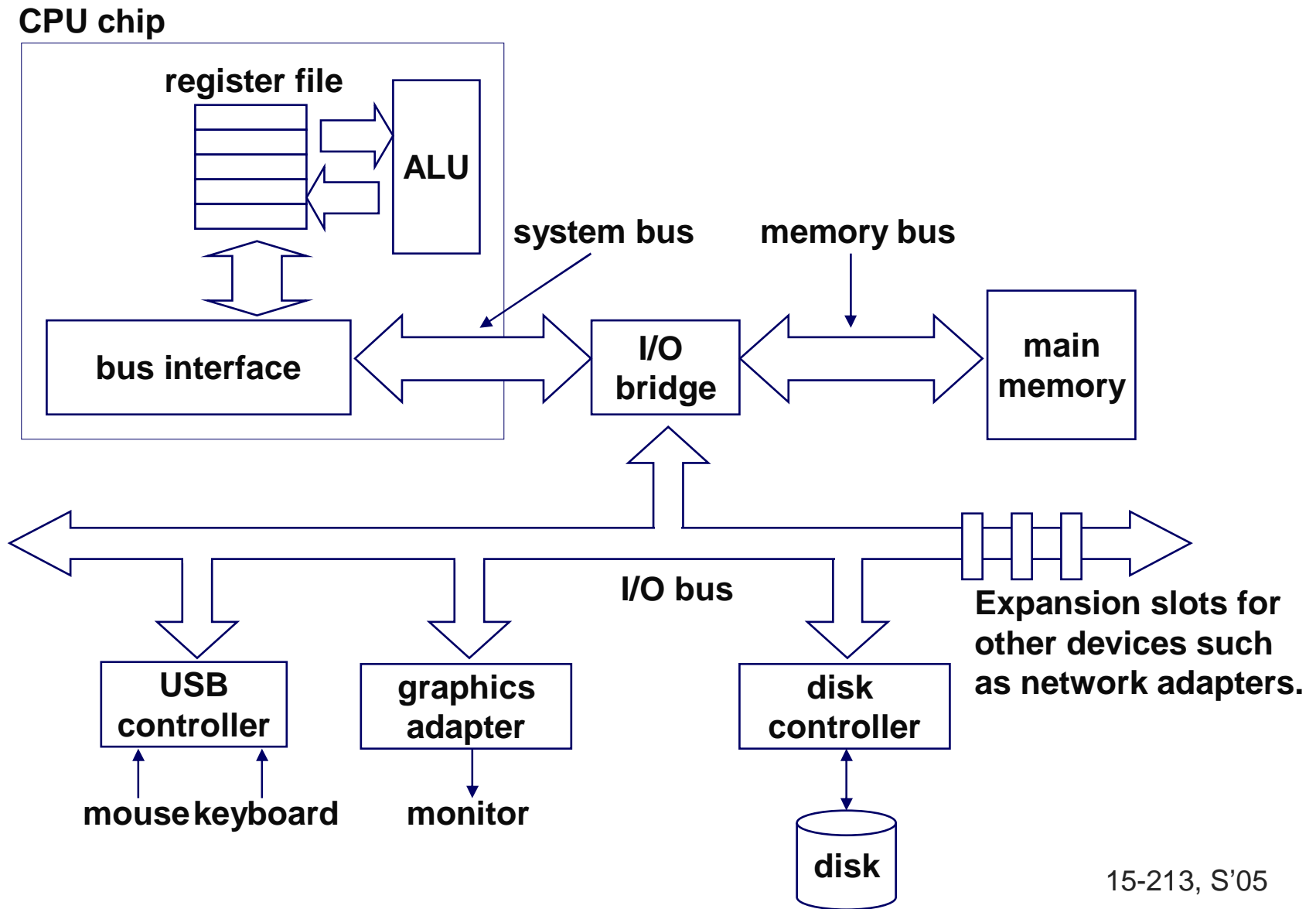- Functions to locate, insert, remove, update records

I/O tends to be asynchronous

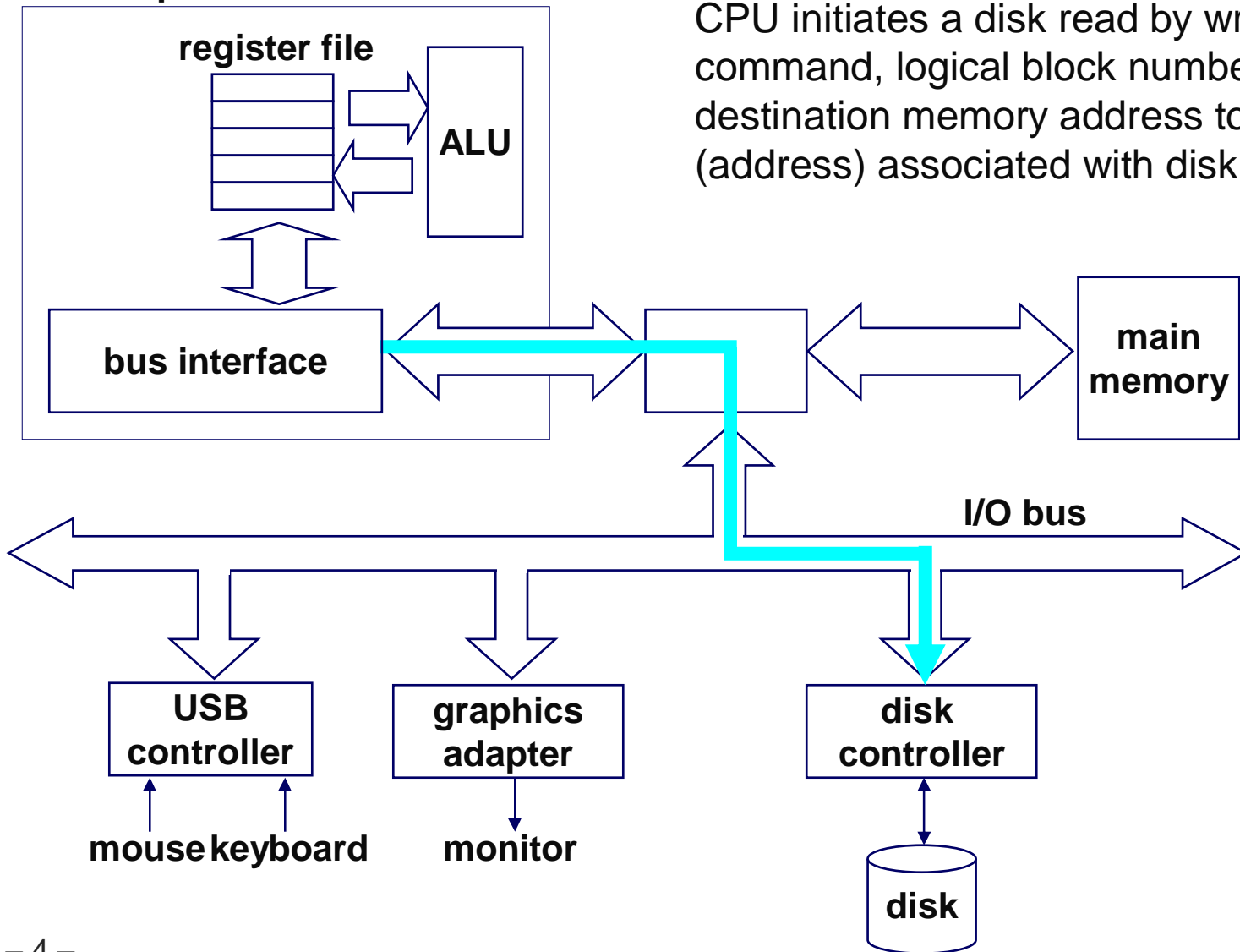- Overlap I/O and computation within a process

Coarse grained I/O

- Process writes "channel programs" to be executed by the I/O hardware
- Many I/O operations are performed autonomously with one interrupt at completion

15-213, S'05

A Typical Hardware System

CPU chip

register file

ALU

bus interface

system bus

memory bus

I/O bridge

main memory

I/O bus

Expansion slots for other devices such as network adapters.

USB controller

graphics adapter

disk controller

mouse keyboard

monitor

disk

Reading a Disk Sector: Step 1
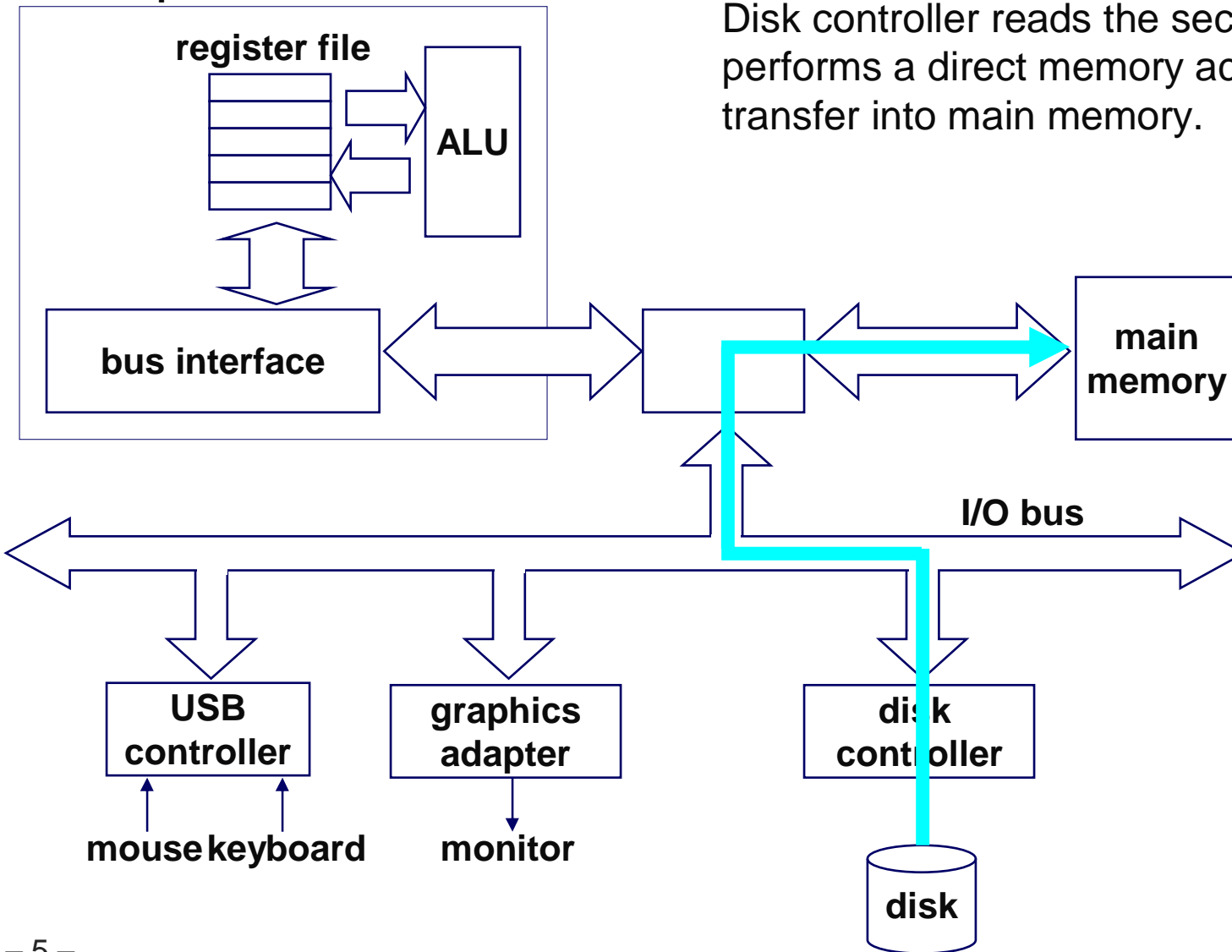
CPU chip

register file

ALU

bus interface

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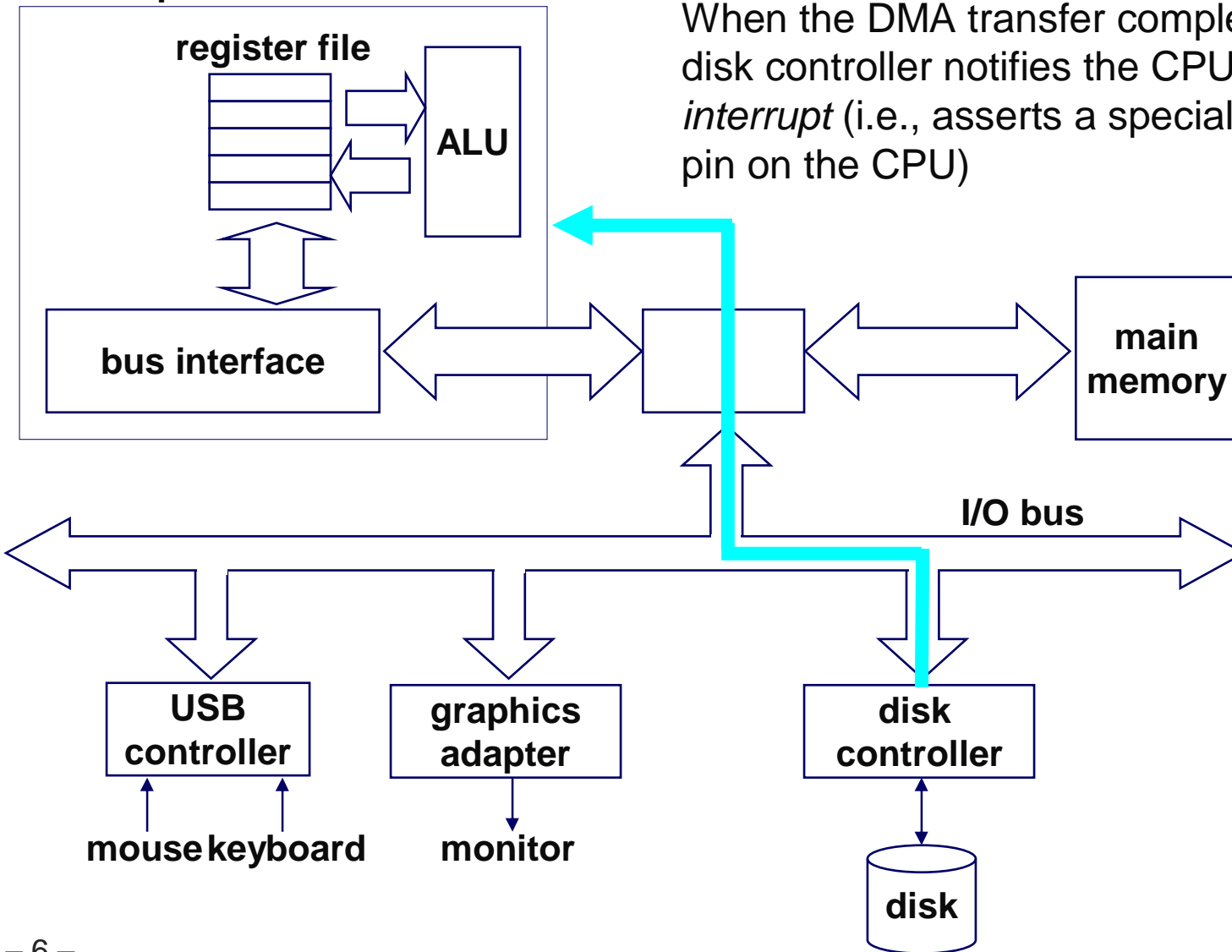
main memory

I/O bus

USB controller

graphics adapter

disk controller

mouse keyboard

monitor

disk

– 4 –

Reading a Disk Sector: Step 2

CPU chip

register file

ALU

bus interface

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

main memory

I/O bus

USB controller

graphics adapter

disk controller

mouse **keyboard**

monitor

disk

Reading a Disk Sector: Step 3

CPU chip

register file

ALU

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

bus interface

main memory

I/O bus

USB controller

graphics adapter

disk controller

mouse **keyboard**

monitor

disk

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.

```c
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.

```c
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.

```c
#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`

```c
/*
 * 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 */
}
```
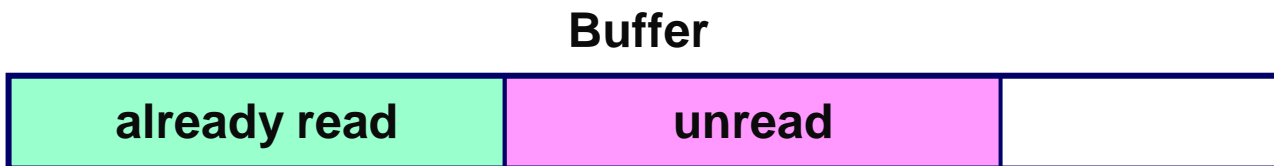
Buffered I/O: Motivation

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
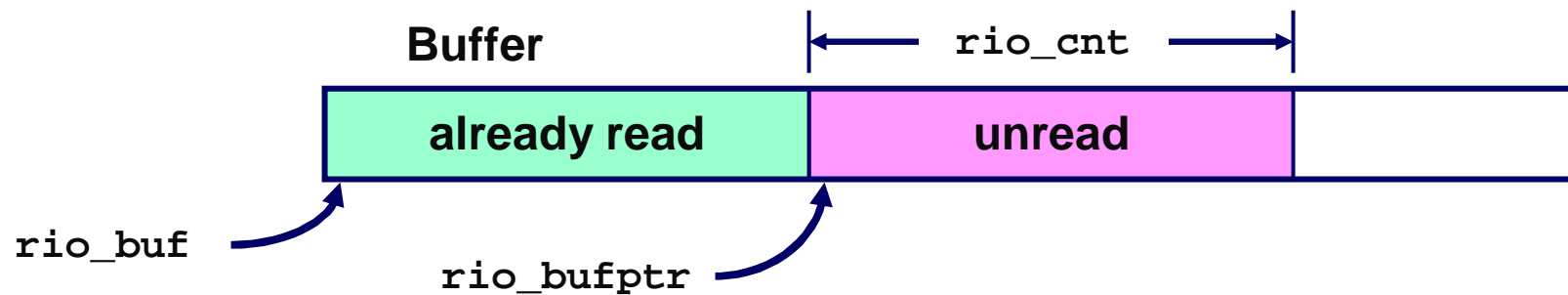 - > 10,000 clock cycles

Buffer

already read	unread	

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.

```c
#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);
}
```

File Metadata

Metadata is data about data, in this case file data.

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 - Querying and manipulating a file's meta data */
#include "csapp.h"

int main (int argc, char **argv)
{
    struct stat stat;
    char *type, *readok;

    Stat(argv[1], &stat);
    if (S_ISREG(stat.st_mode)) /* file type*/
        type = "regular";
    else if (S_ISDIR(stat.st_mode))
        type = "directory";
    else
        type = "other";
    if ((stat.st_mode & S_IRUSR)) /* OK to read?*/
        readok = "yes";
    else
        readok = "no";

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

```
bass> ./statcheck statcheck.c
type: regular, read: yes
bass> chmod 000 statcheck.c
bass> ./statcheck statcheck.c
type: regular, read: no
```
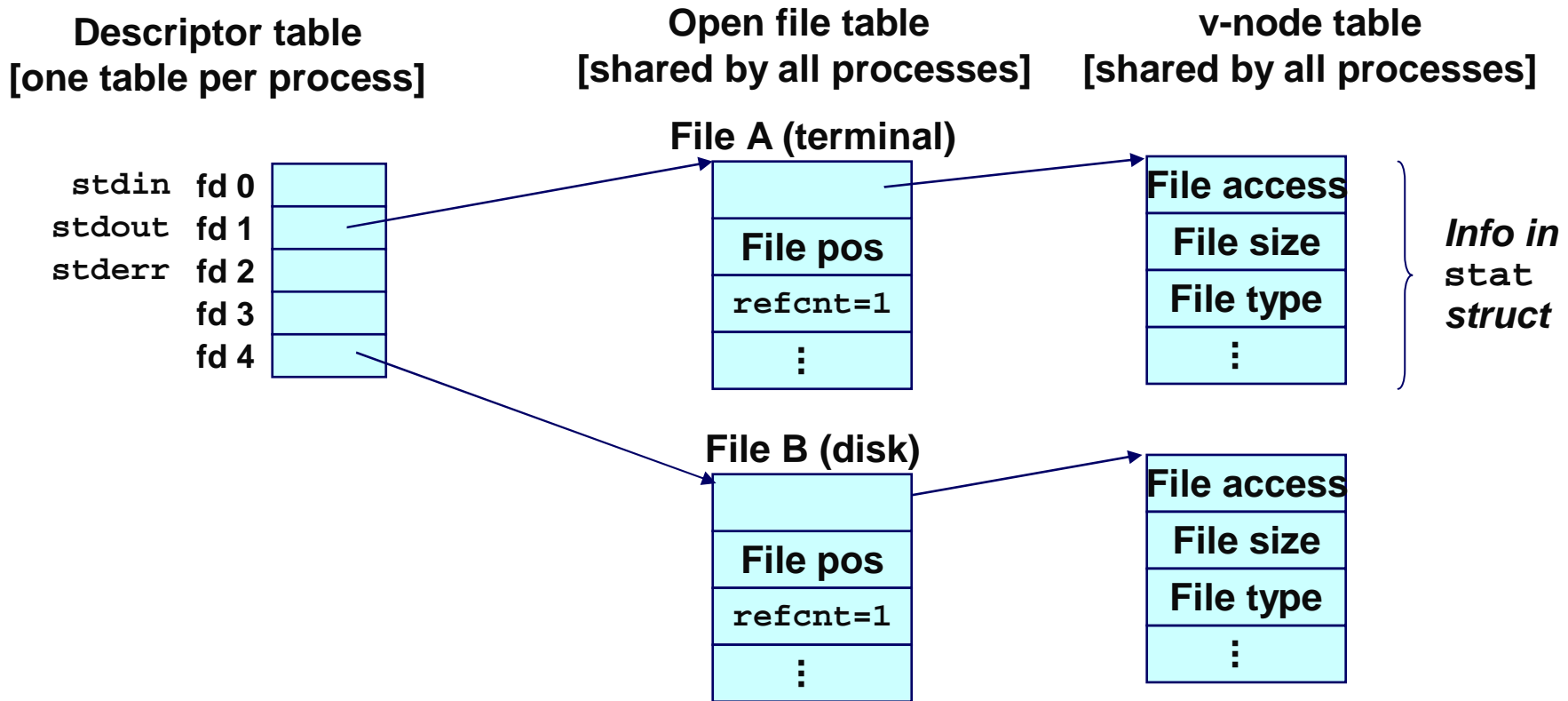
Accessing Directories

The only recommended operation on directories is to read its entries.

```c
#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);
}
```
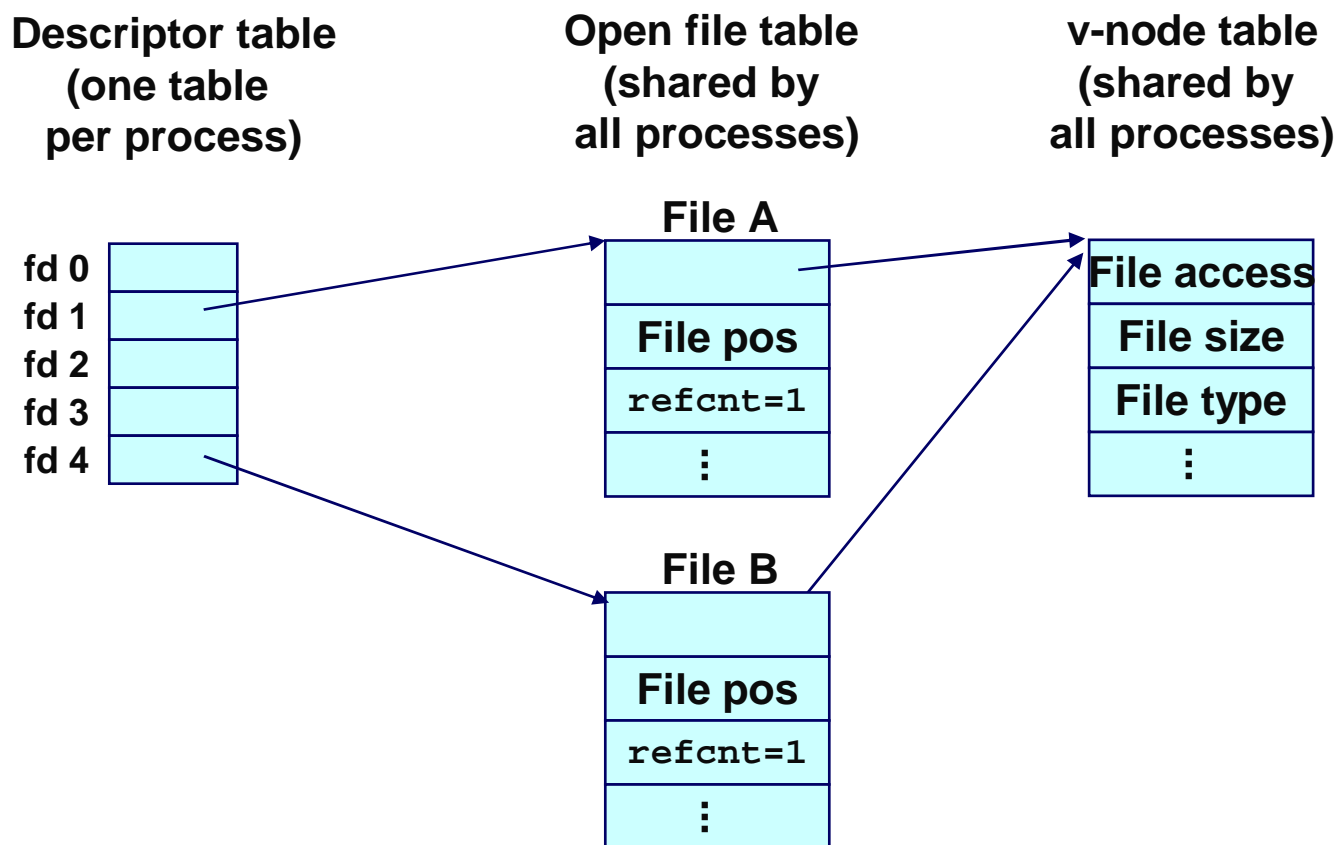
How the Unix Kernel Represents Open Files

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

Descriptor table
[one table per process]

Open file table
[shared by all processes]

v-node table
[shared by all processes]

File A (terminal)

stdin	fd 0
stdout	fd 1
stderr	fd 2
	fd 3
	fd 4

File pos
refcnt=1
⋮

File access
File size
File type
⋮

Info in `stat` *struct*

File B (disk)

File pos
refcnt=1
⋮

File access
**File size**
File type
⋮

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

Descriptor table (one table per process)	Open file table (shared by all processes)	v-node table (shared by all processes)

File A

File pos
`refcnt=1`
⋮

File access

File access
File size
File type
⋮

fd 0
fd 1
fd 2
fd 3
fd 4

File B

File pos
`refcnt=1`
⋮

How Processes Share Files

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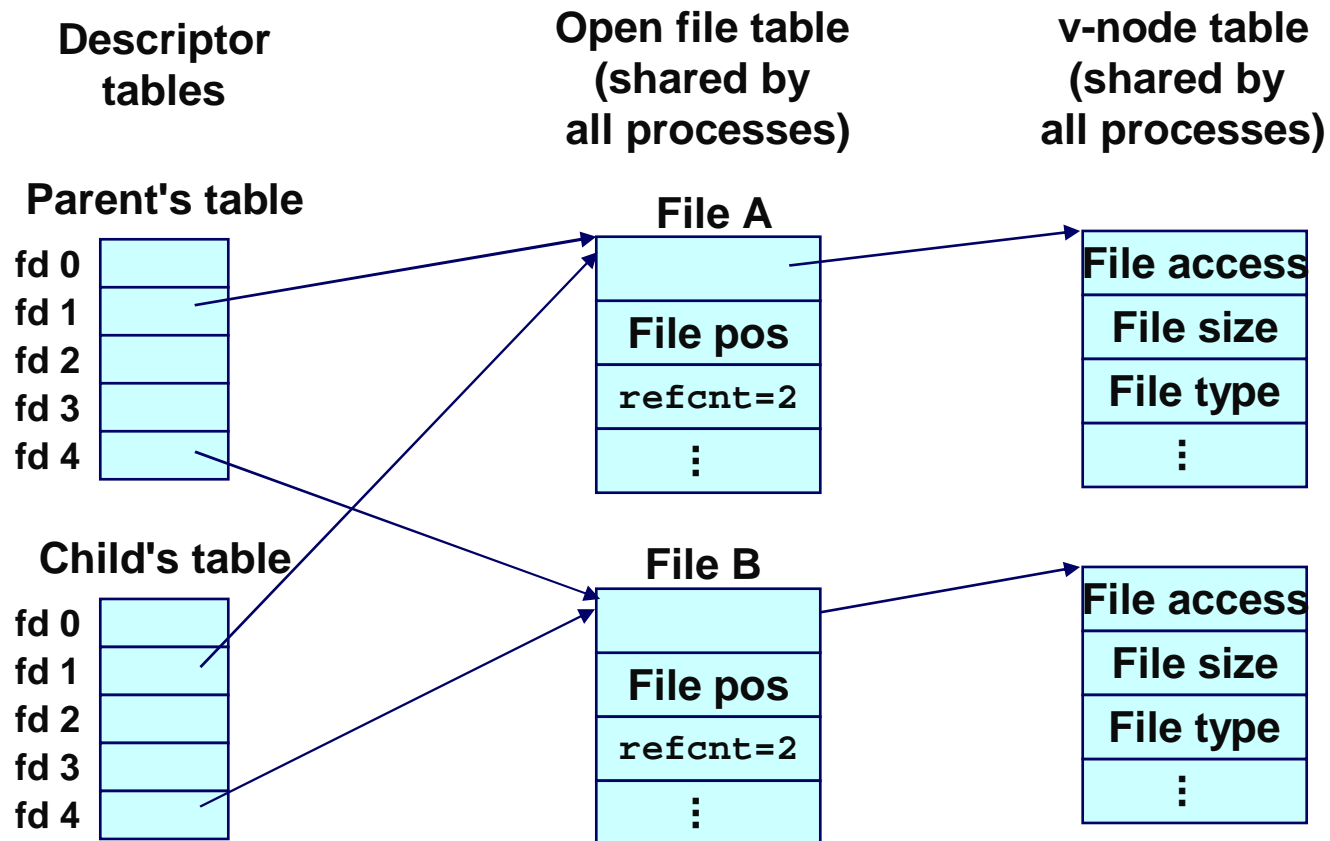
I/O Redirection

Question: How does a shell implement I/O redirection?
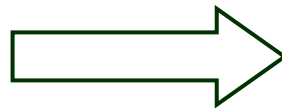
```
unix> ls > foo.txt
```

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

- Copies (per-process) descriptor table entry `oldfd` to entry `newfd`
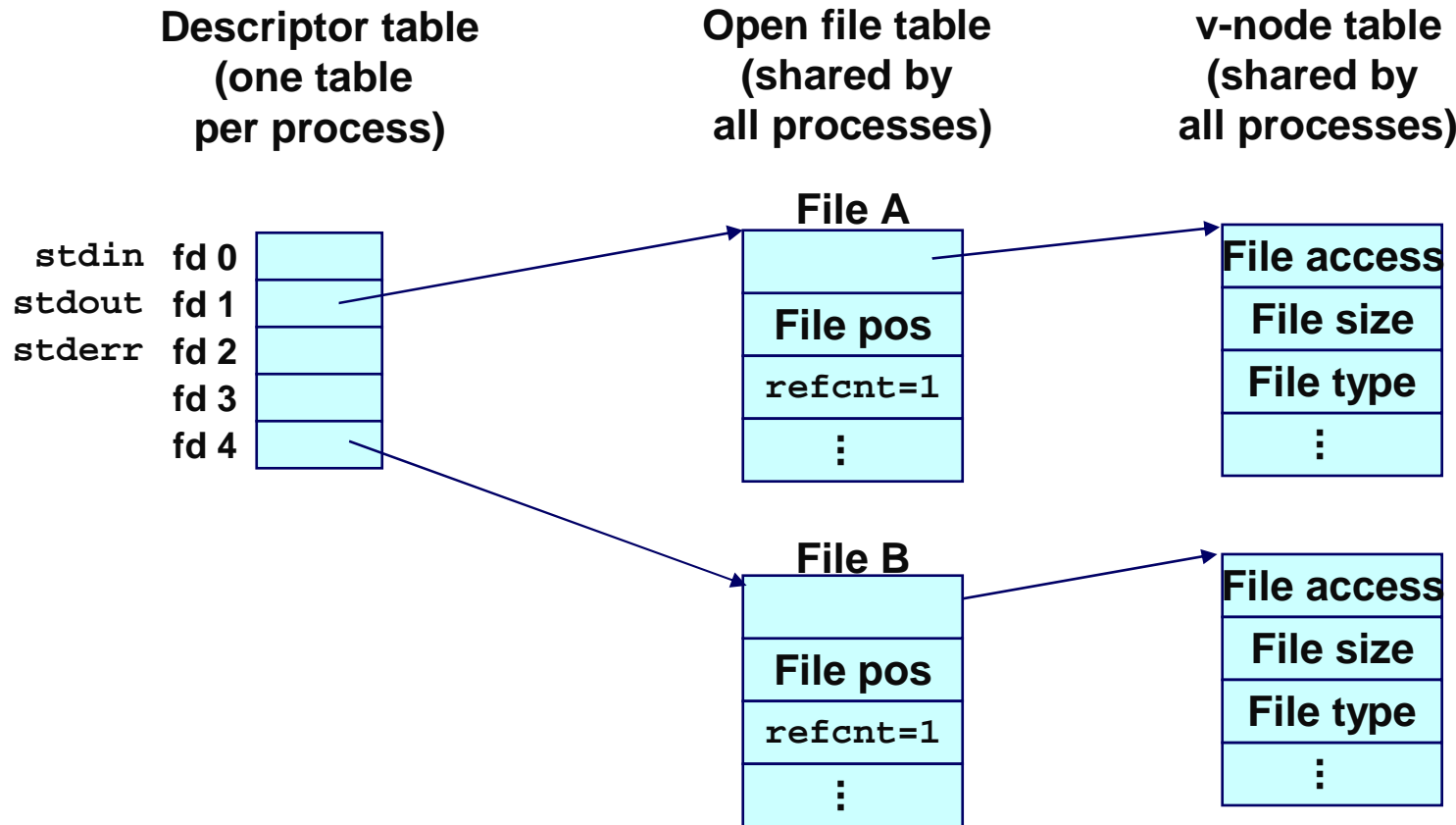
Descriptor table
before `dup2(4,1)`

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

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

Descriptor table (one table per process)	Open file table (shared by all processes)	v-node table (shared by all processes)

File A

```
stdin   fd 0
stdout  fd 1
stderr  fd 2
        fd 3
        fd 4
```

File A:
File pos
refcnt=1
⋮

File access
File size
File type
⋮

File B
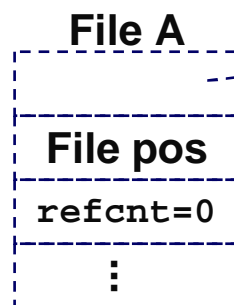
File pos
refcnt=1
⋮

File access
File size
File type
⋮

I/O Redirection Example (cont)

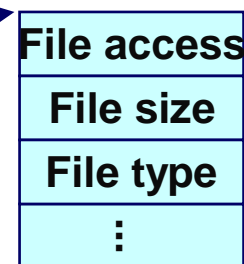**After calling `dup2(4,1)`, stdout is now redirected to the disk file pointed at by descriptor 4.**
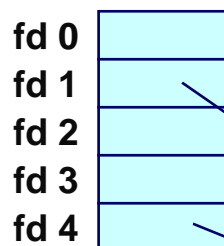
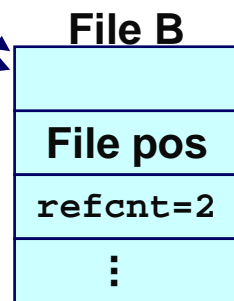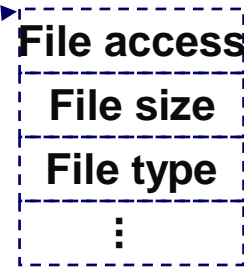|	Descriptor table (one table per process)	Open file table (shared by all processes)	v-node table (shared by all processes)

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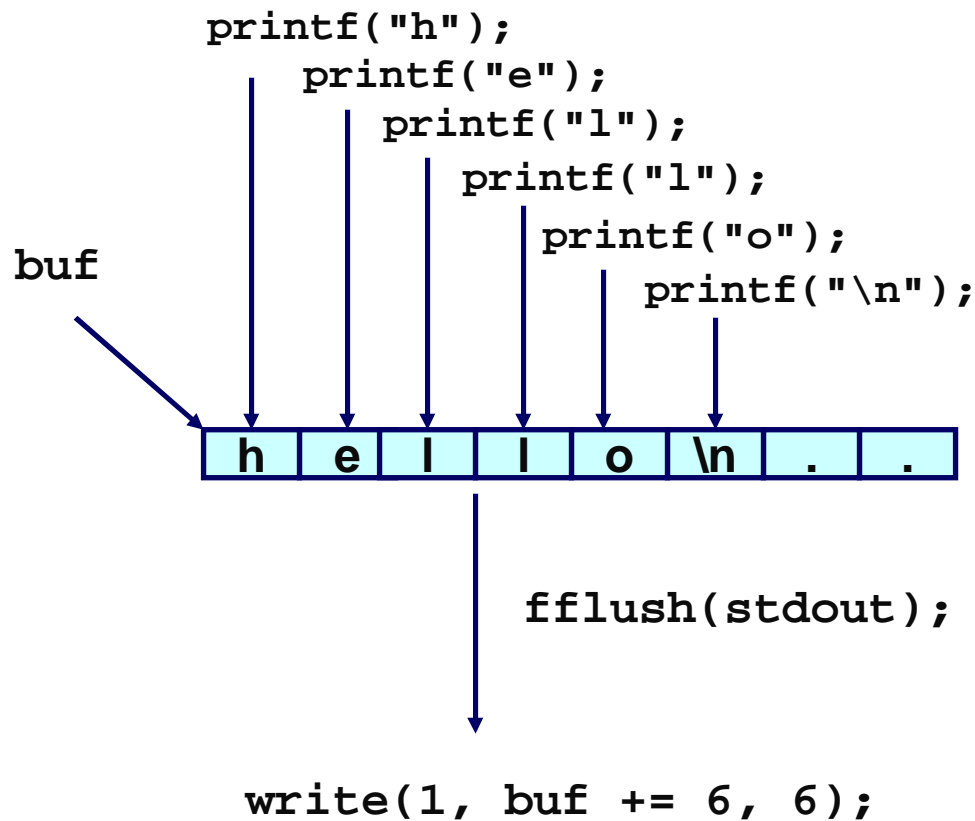
- `stdin` (standard input)
- `stdout` (standard output)
- `stderr` (standard error)

```
#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

```
printf("h");
    printf("e");
        printf("l");
            printf("l");
                printf("o");
                    printf("\n");
```

buf

| h | e | l | l | o | \n | . | . |

fflush(stdout);

write(1, buf += 6, 6);

Standard I/O Buffering in Action

You can see this buffering in action for yourself, using the always fascinating Unix `strace` program:
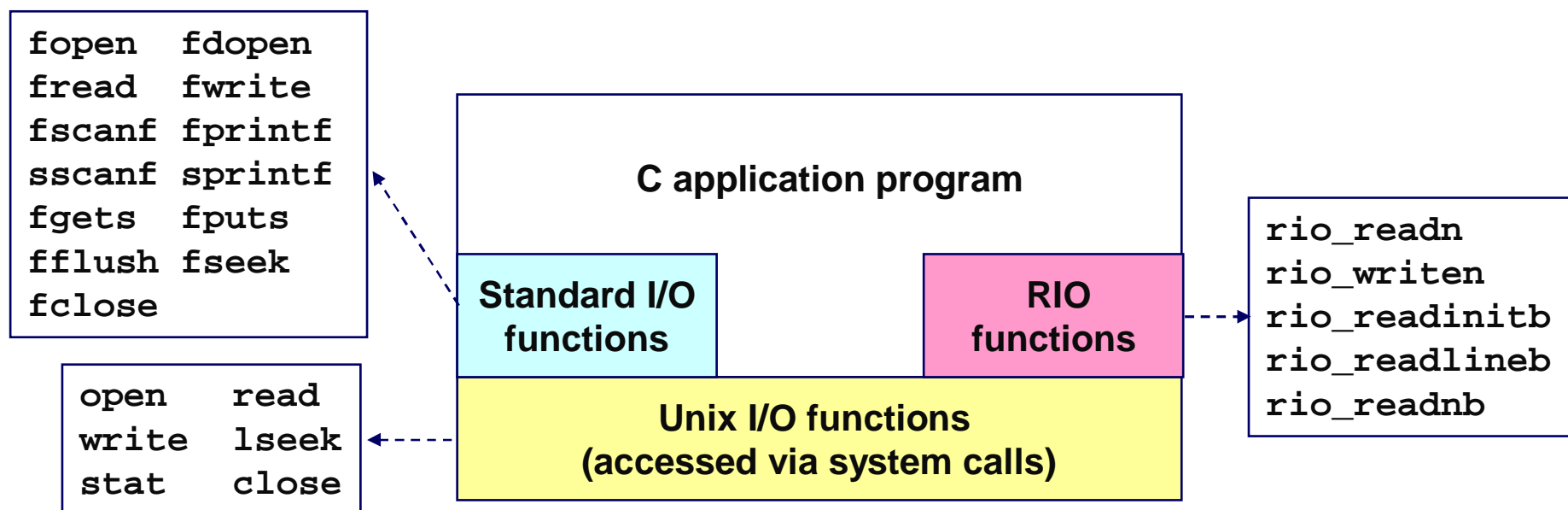
```
#include <stdio.h>

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.

```
fopen   fdopen
fread   fwrite
fscanf  fprintf
sscanf  sprintf
fgets   fputs
fflush  fseek
fclose
```

```
open    read
write   lseek
stat    close
```

C application program

Standard I/O functions

RIO functions

Unix I/O functions (accessed via system calls)

```
rio_readn
rio_writen
rio_readinitb
rio_readlineb
rio_readnb
```

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.