Running Programs on a System

System-Level I/O

System-Level I/O

- **Unix I/O**
- Metadata, sharing, and redirection
- Standard I/O
- Conclusions and examples

Acknowledgement: slides based on the cs:app2e material

Unix Files

- A Unix file is a sequence of m bytes:
  - B0 , B1 , ... , Bk , ... , Bm-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)

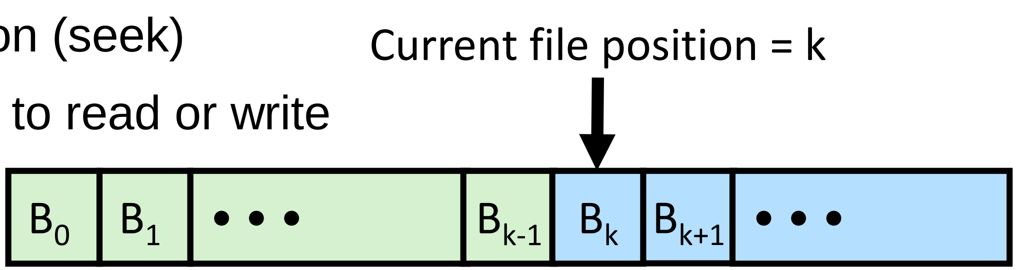
Unix File Types

- Regular file
  - File containing user/app data (binary, text, whatever)
  - OS does not know anything about the format
    - other than “sequence of bytes”, akin to main memory
- 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 inter-process communication
- Socket
  - A file type used for network communication between processes

Unix I/O

- Key Features
  - Elegant mapping of files to devices allows kernel to export simple interface called Unix I/O
  - Important 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()
  - Reading and writing a file
    - read() and write()
  - Changing the current file position (seek)
    - indicates next offset into file to read or write
    - lseek()



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
  - 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 standard in to standard out, 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);
}                                          cpstdin.c
```

Note the use of error handling wrappers for read and write (textbook, Appendix A).

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

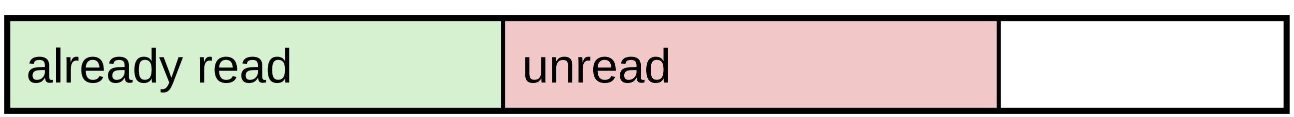
- Short counts never occur in these situations:
  - Reading from disk files (except for EOF)
  - Writing to disk files

- One way to deal with short counts in your code:
  - Use the RIO (Robust I/O) package from your textbook's csapp.c file (eTL → System Programming → Additional Material and Resources)

Buffered I/O

- Applications often read/write one character at a time
  - getc, putc, ungetc
  - gets, fgets
    - Read line of text on 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



System-Level I/O

- Unix I/O
- **Metadata, sharing, and redirection**
- Standard I/O
- Conclusions and examples

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 - 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))
        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);
}
```

```
unix> ./statcheck statcheck.c
type: regular, read: yes
unix> chmod 000 statcheck.c
unix> ./statcheck statcheck.c
type: regular, read: no
unix> ./statcheck ..
type: directory, read: yes
unix> ./statcheck /dev/kmem
type: other, read: yes
```

statcheck.c

Accessing Directories

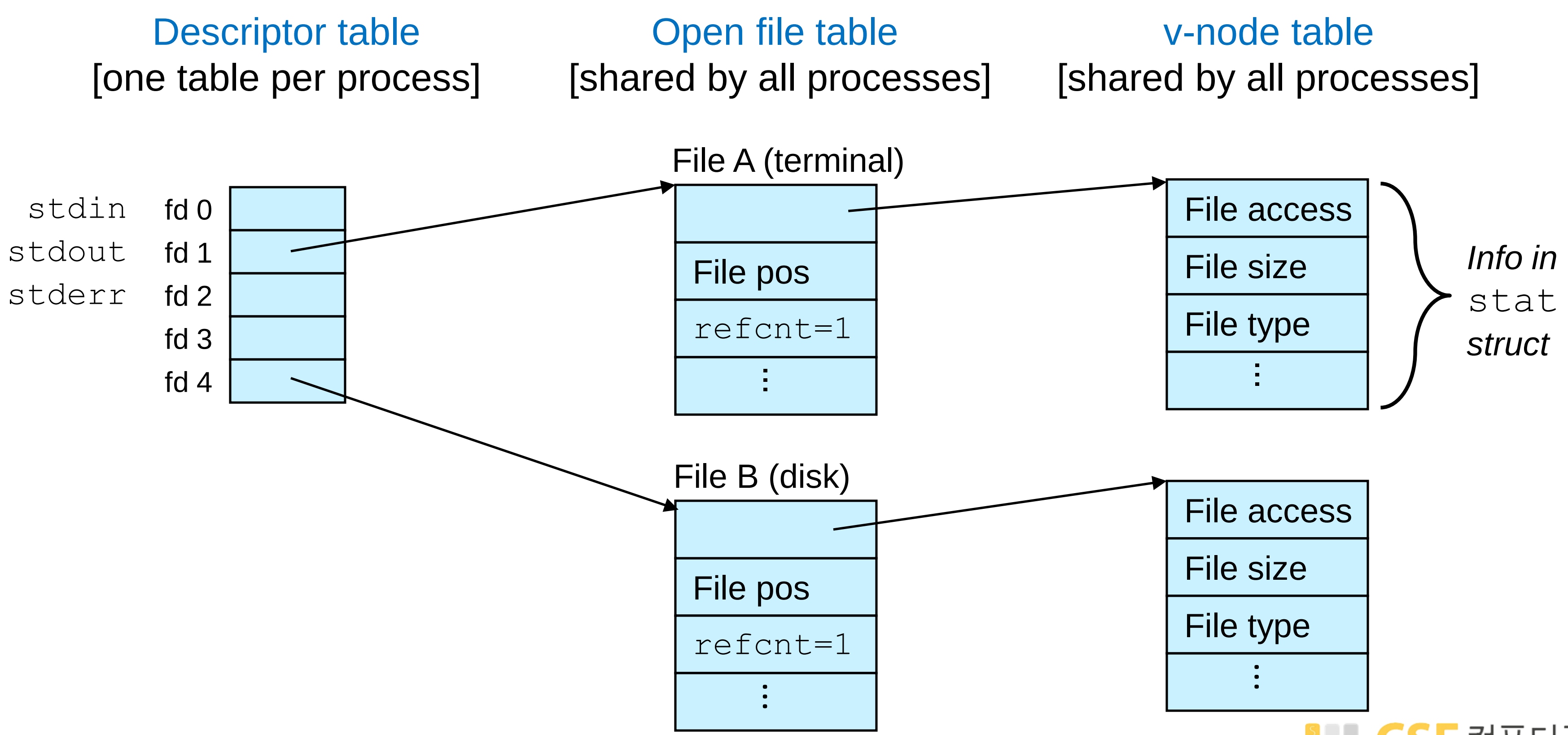
- Only recommended operation on a directory: read its entries
  - dirent structure contains information about a directory entry
  - DIR structure contains information about directory while stepping through its entries

```
#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);
}
```

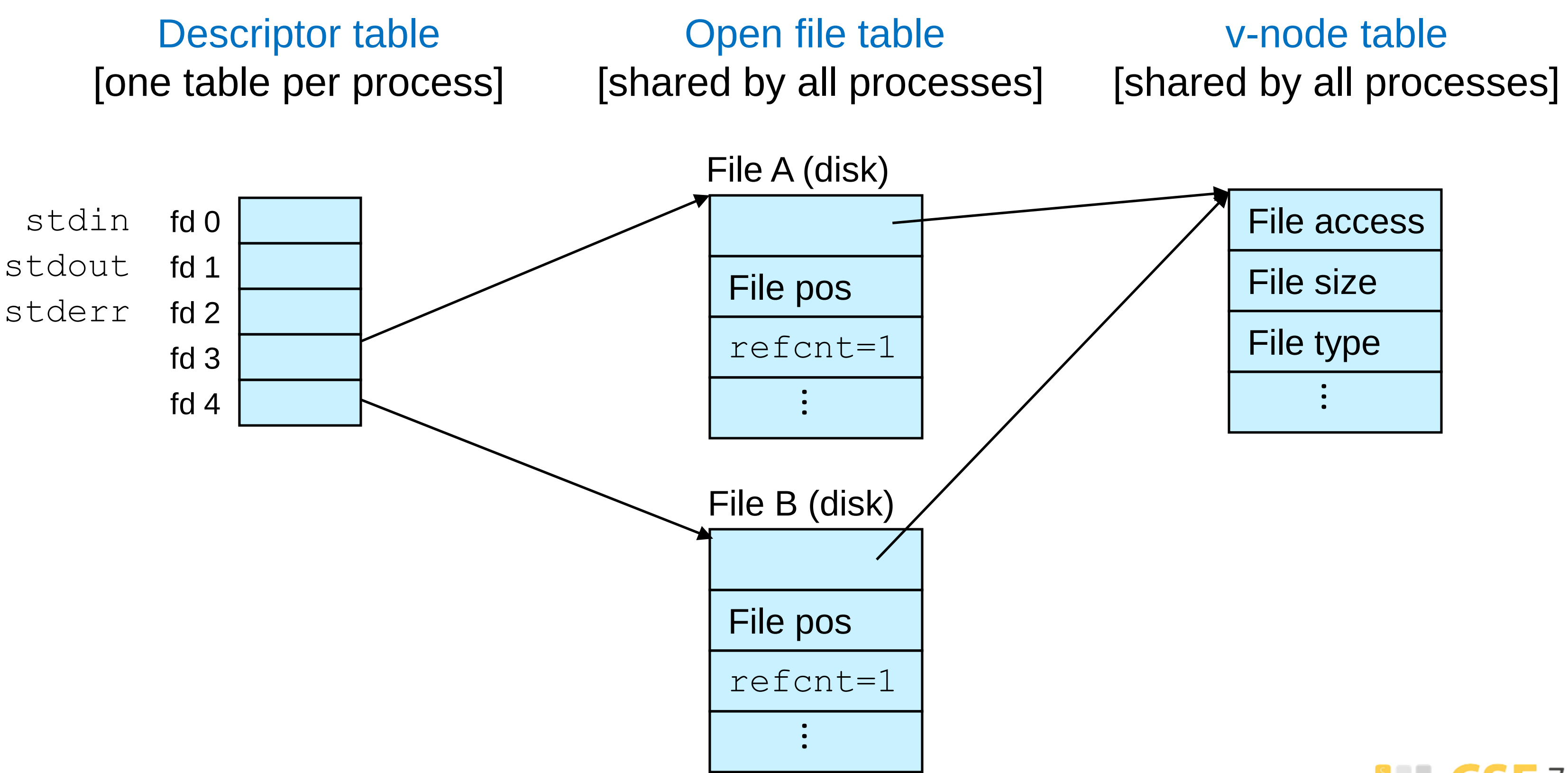
How the Unix Kernel Represents Open Files

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



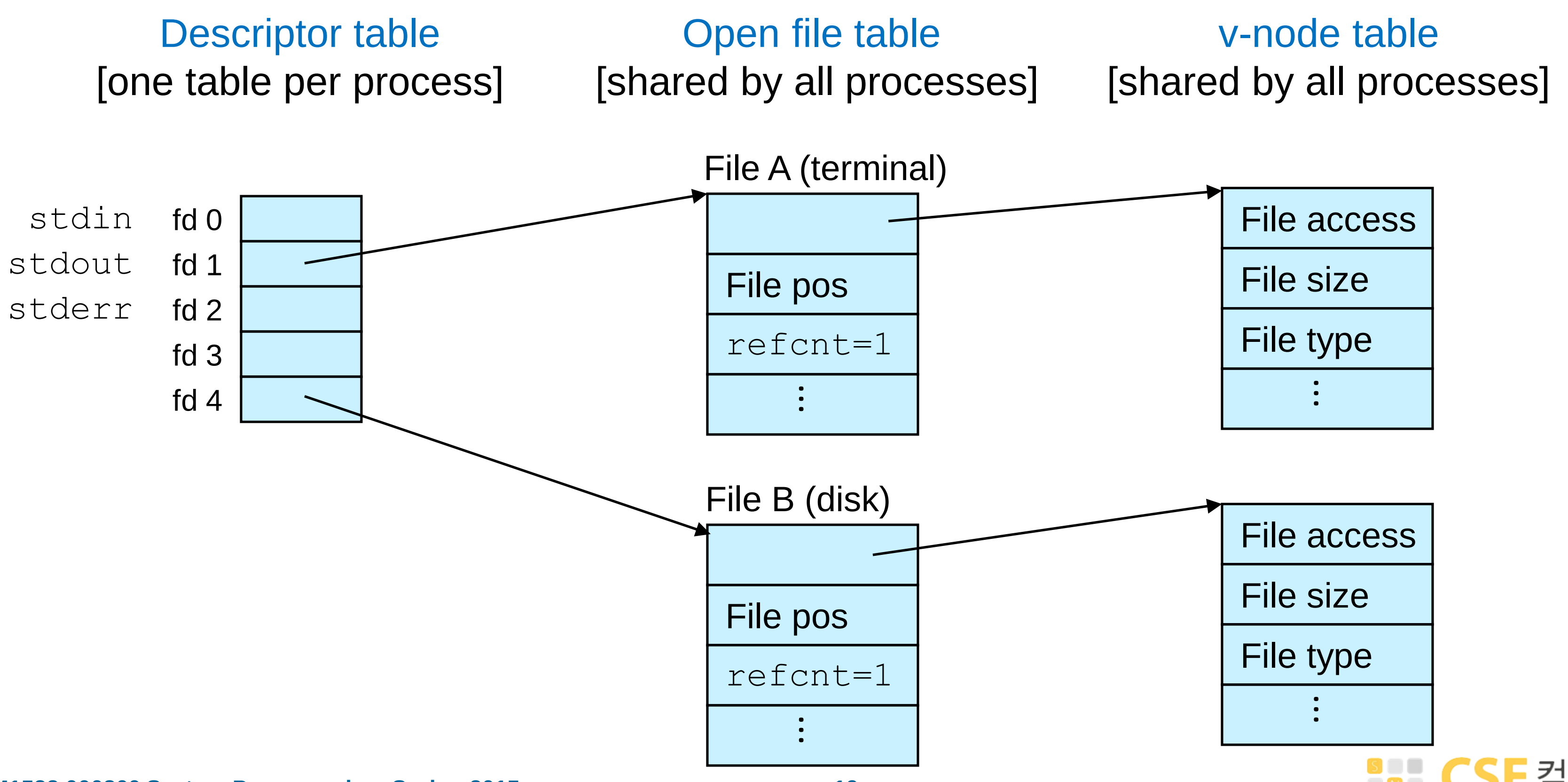
File Sharing

- 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



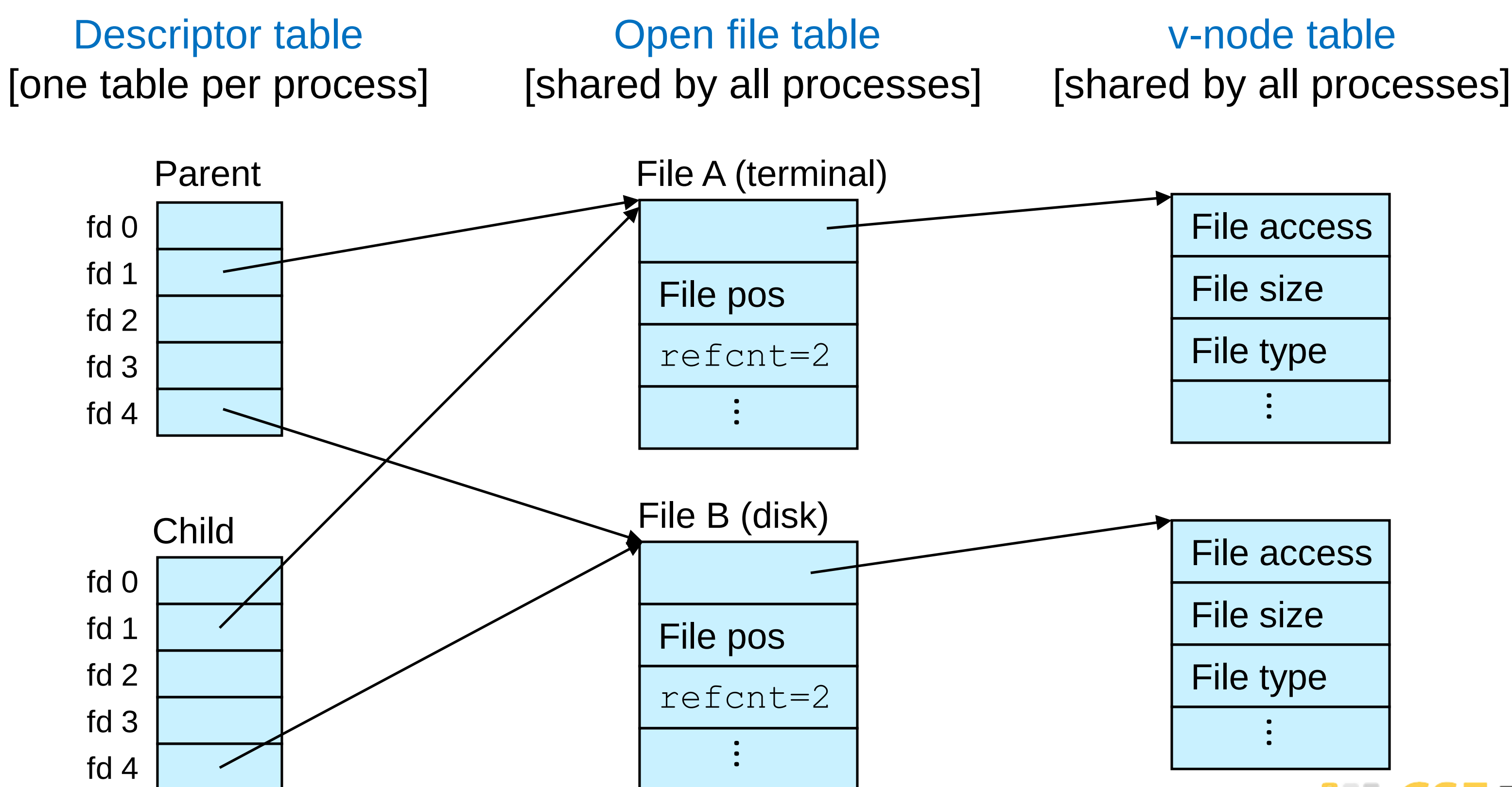
How Processes Share Files: Fork()

- 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



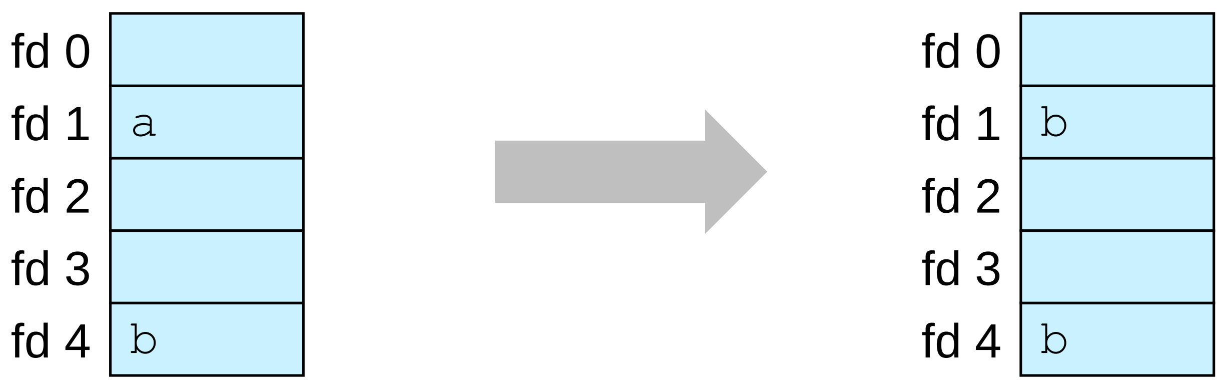
I/O Redirection

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

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

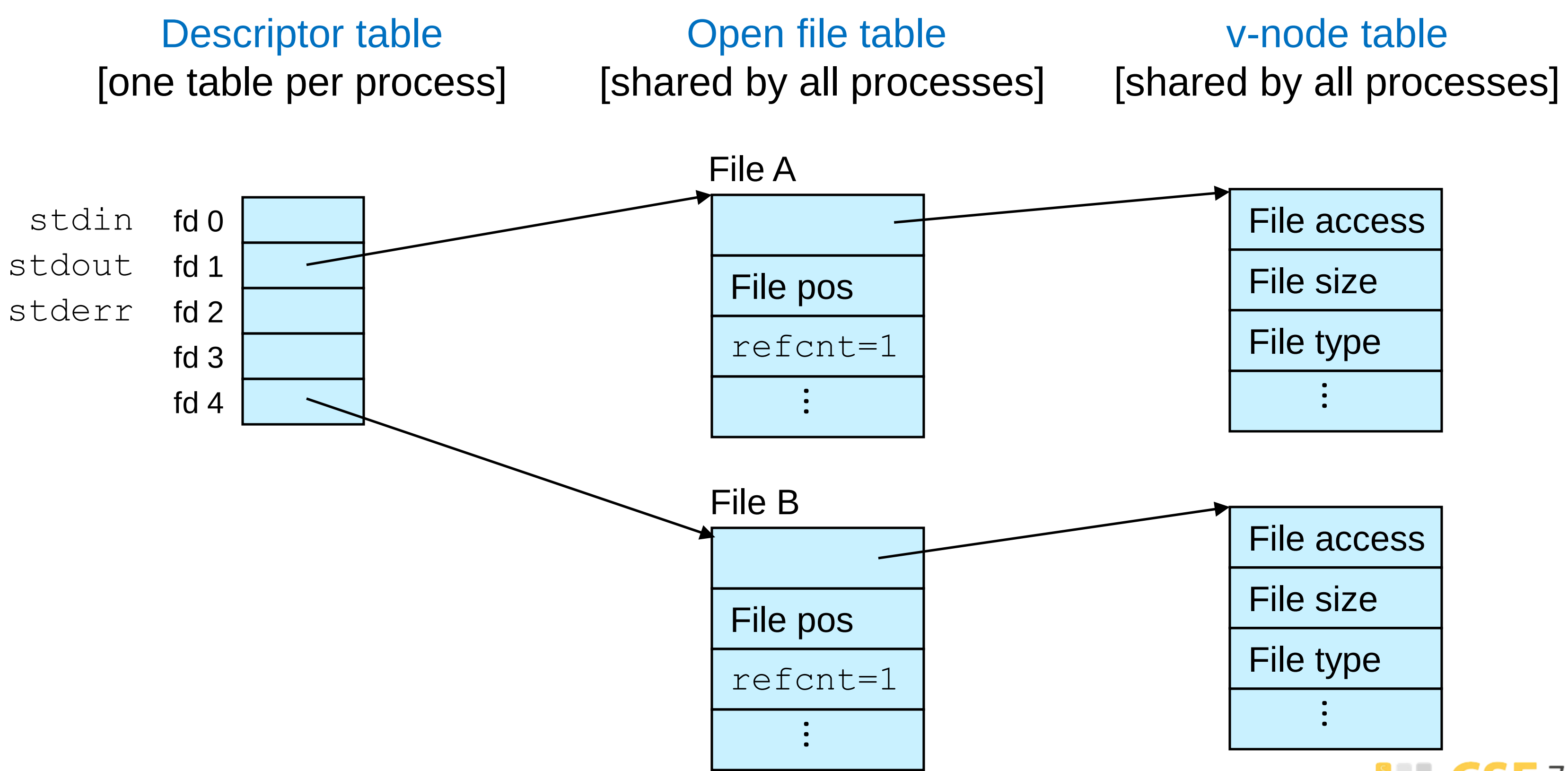
Descriptor table *before* `dup2(4,1)`

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



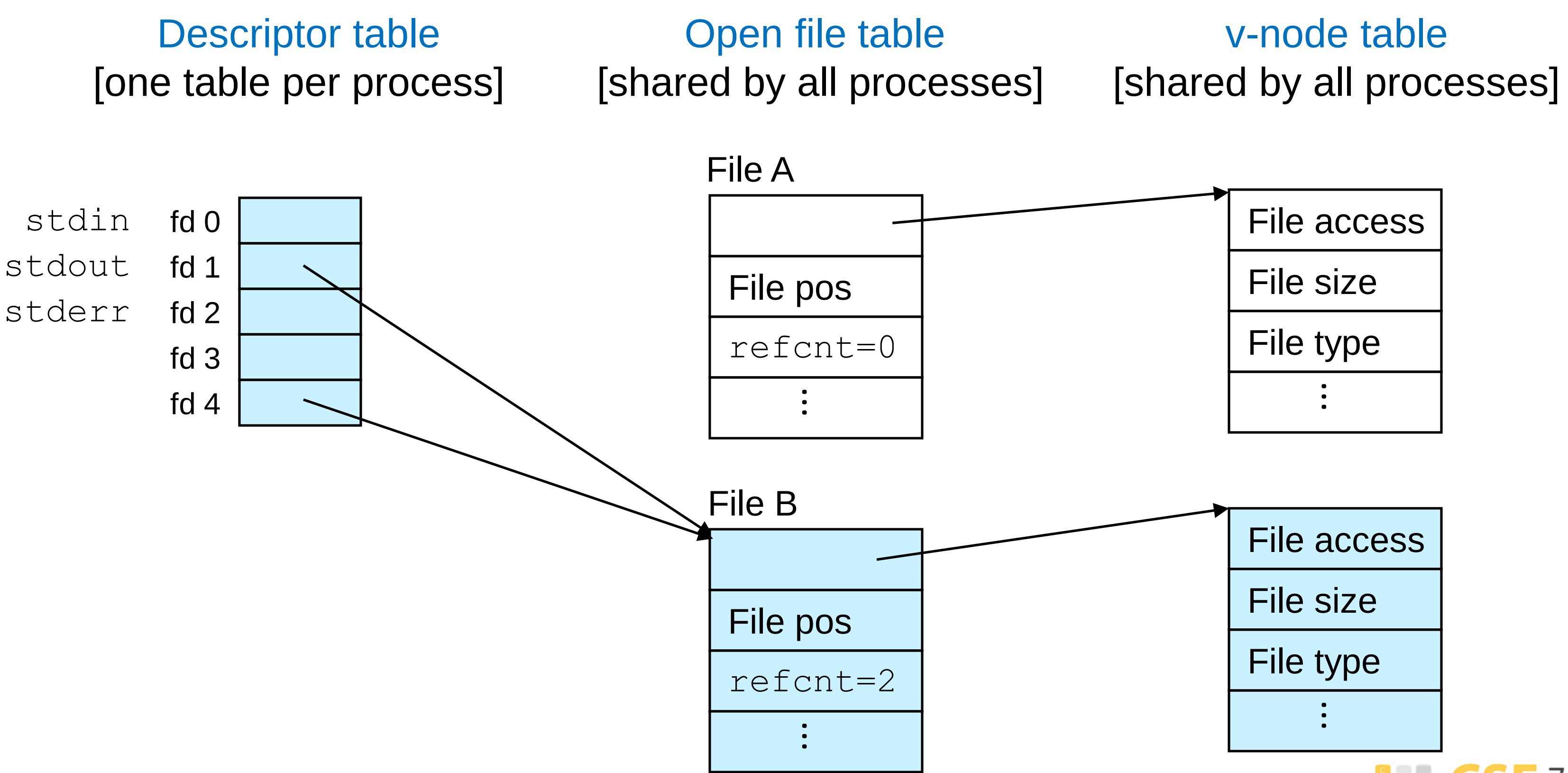
I/O Redirection Example

- 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



Fun with File Descriptors (1)

```
#include "csapp.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 "csapp.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 "csapp.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?

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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.

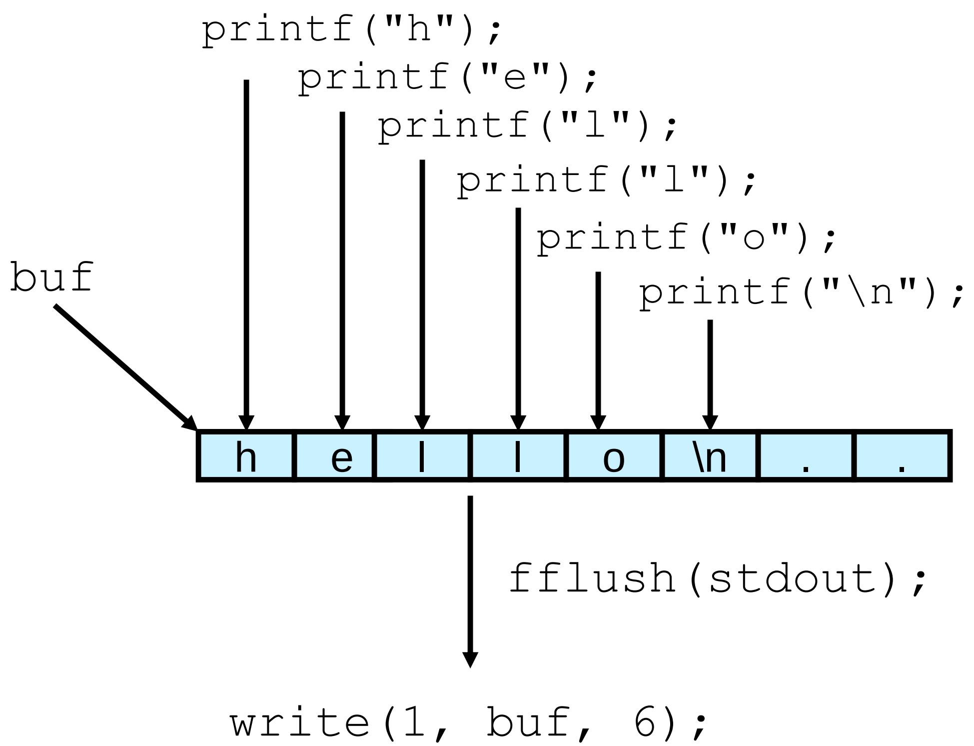
- C programs begin life with three open streams (defined in stdio.h)
  - stdin (standard input)
  - stdout (standard output)
  - stderr (standard error)

```
#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");
}
```

Buffering in Standard I/O

- Standard I/O functions use buffered I/O



- Buffer flushed to output fd on “\n” or fflush() call

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_group(0)                           = ?
```

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- **Conclusions and examples**

Unix I/O System Calls

$ man –S 2 <syscall>

```
#include <unistd.h>
#include <fcntl.h>
#include <sys/types.h>
#include <sys/stat.h>

int     open(const char *pathname, int flags[, mode_t mode]);
int     creat(const char *pathname, mode_t mode);

ssize_t read(int fd, void *buf, size_t count);
ssize_t write(int fd, const void *buf, size_t count);

off_t   lseek(int fd, off_t offset, int whence);
int     stat(const char *path, struct stat *buf);

int     close(int fd);
```

Standard I/O System Calls

$ man –S 3 <syscall>

```
#include <stdio.h>

FILE*   fopen(const char *pathname, const char *mode);

size_t fread(void *ptr, size_t size, size_t nmemb, FILE *stream);
size_t fwrite(const void *ptr, size_t size, size_t nmemb,
              FILE *stream);
int    fflush(FILE *stream);

int    feof(FILE *stream);
int    ferror(FILE *stream);

off_t   fseek(FILE *stream, long offset, int whence);
int     f[get/set]pos(FILE *stream, fpos_t *pos);

int     fclose(FILE *fp);
```

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 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:APP2e, Sec 10.9)

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
  - Inside signal handlers, because Unix I/O is async-signal-safe.
  - In rare cases when you need absolute highest performance.

- alternative: RIO (see textbook)
  - When you are reading and writing network sockets.
  - Avoid using standard I/O on sockets.

Aside: Working with Binary Files

- Binary File Examples
  - Object code, Images (JPEG, GIF)

- Functions you shouldn't use on binary files
  - Line-oriented I/O such as fgets, scanf, printf, rio_readlineb
    - Different systems interpret 0x0A ('\n') (newline) differently:
      - Linux and Mac OS X: LF(0x0a) ['\n']
      - HTTP servers & Windoes: CR+LF(0x0d 0x0a) ['\r\n']
    - Use rio_readn or rio_readnb instead

  - String functions
    - strlen, strcpy
    - 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.