15-213

System-Level I/O
November 12, 2007

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

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

- 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!

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`
  - 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(int 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.
  - Only use it when you know how many bytes to read
- `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 */
}
```

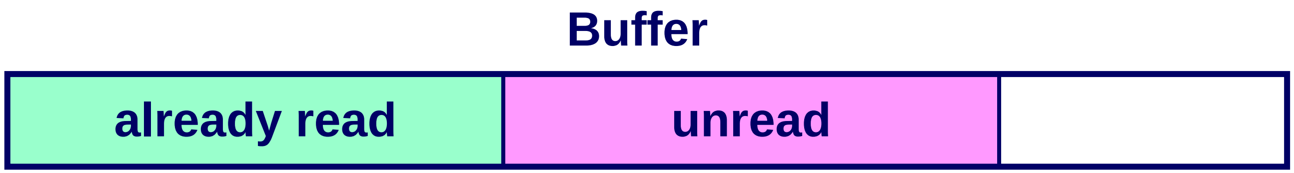
Buffered I/O: Motivation

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

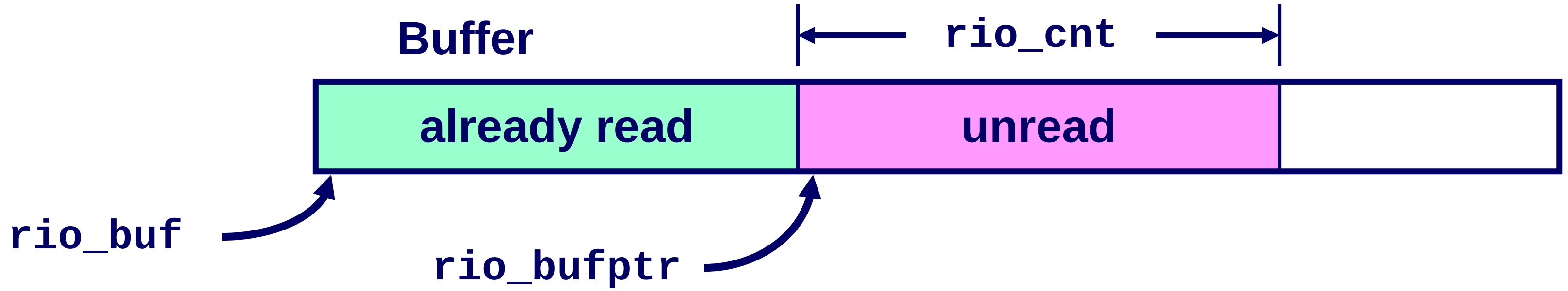


Buffered Read

- 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);
}
```

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))
        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
```

Accessing Directories

The only recommended operation on directories is to read its entries

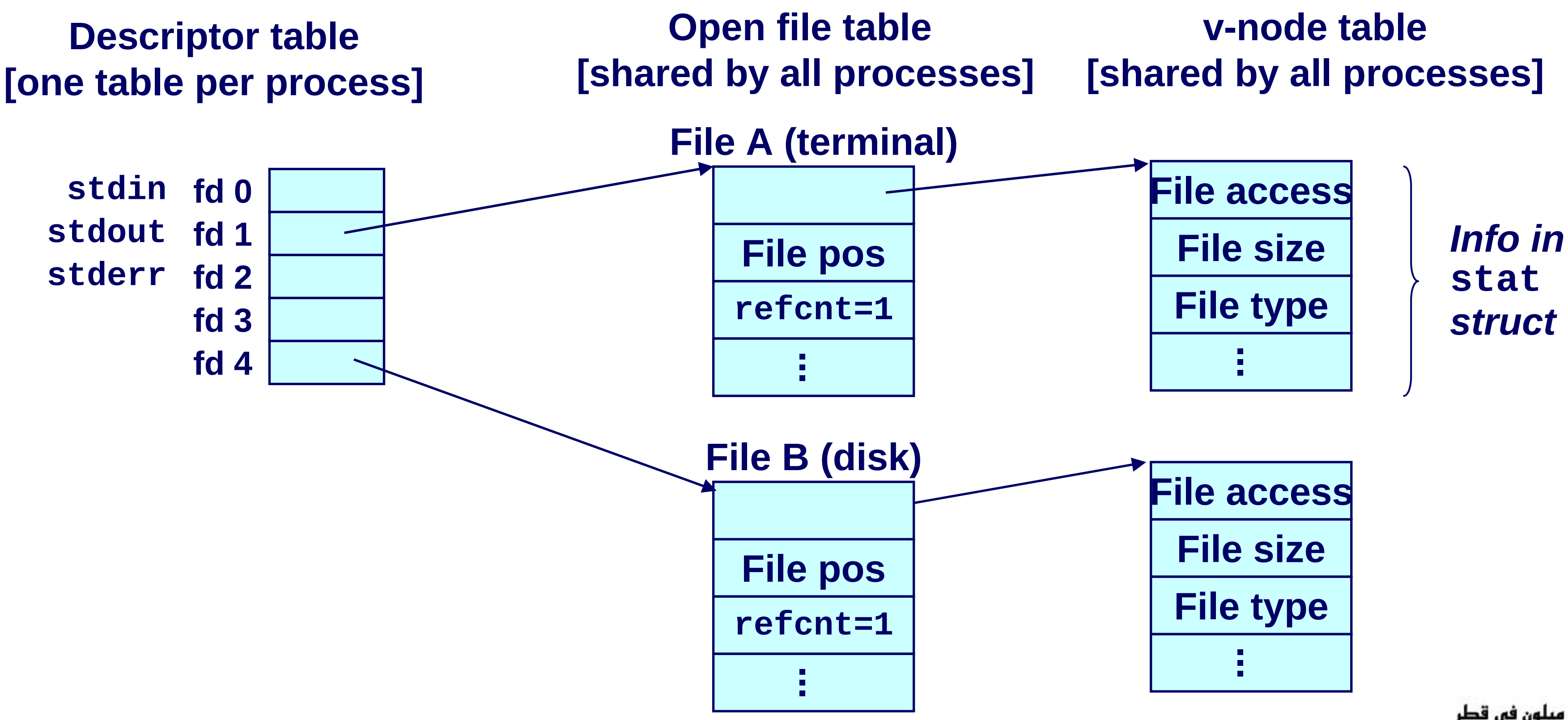
- dirent structure contains information about directory
- DIR structure contains information about directory while stepping through its entries

```
#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

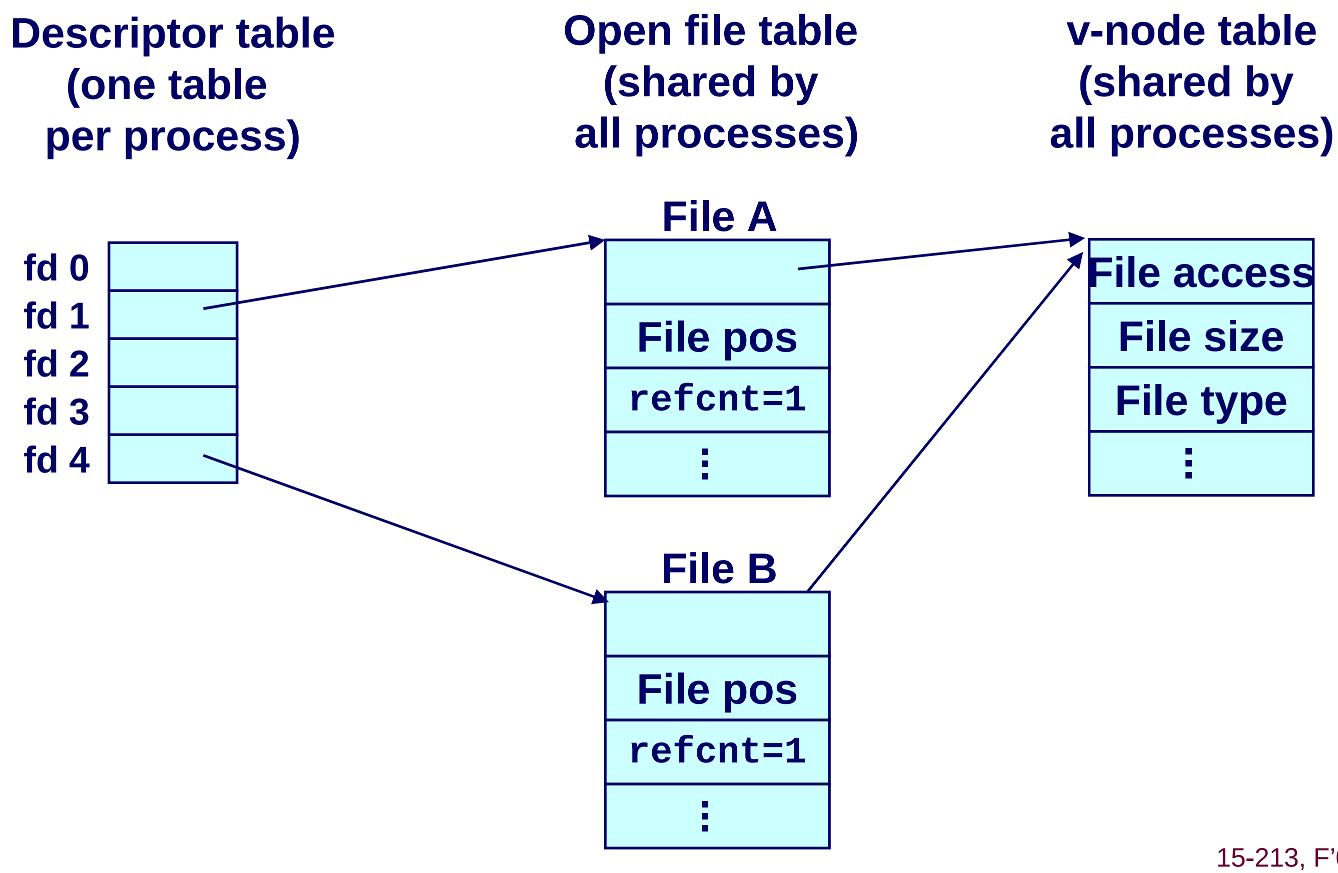
Two descriptors referencing two distinct open disk files. Descriptor 1 (stdout) points to terminal, and descriptor 4 points to open disk file.



File Sharing

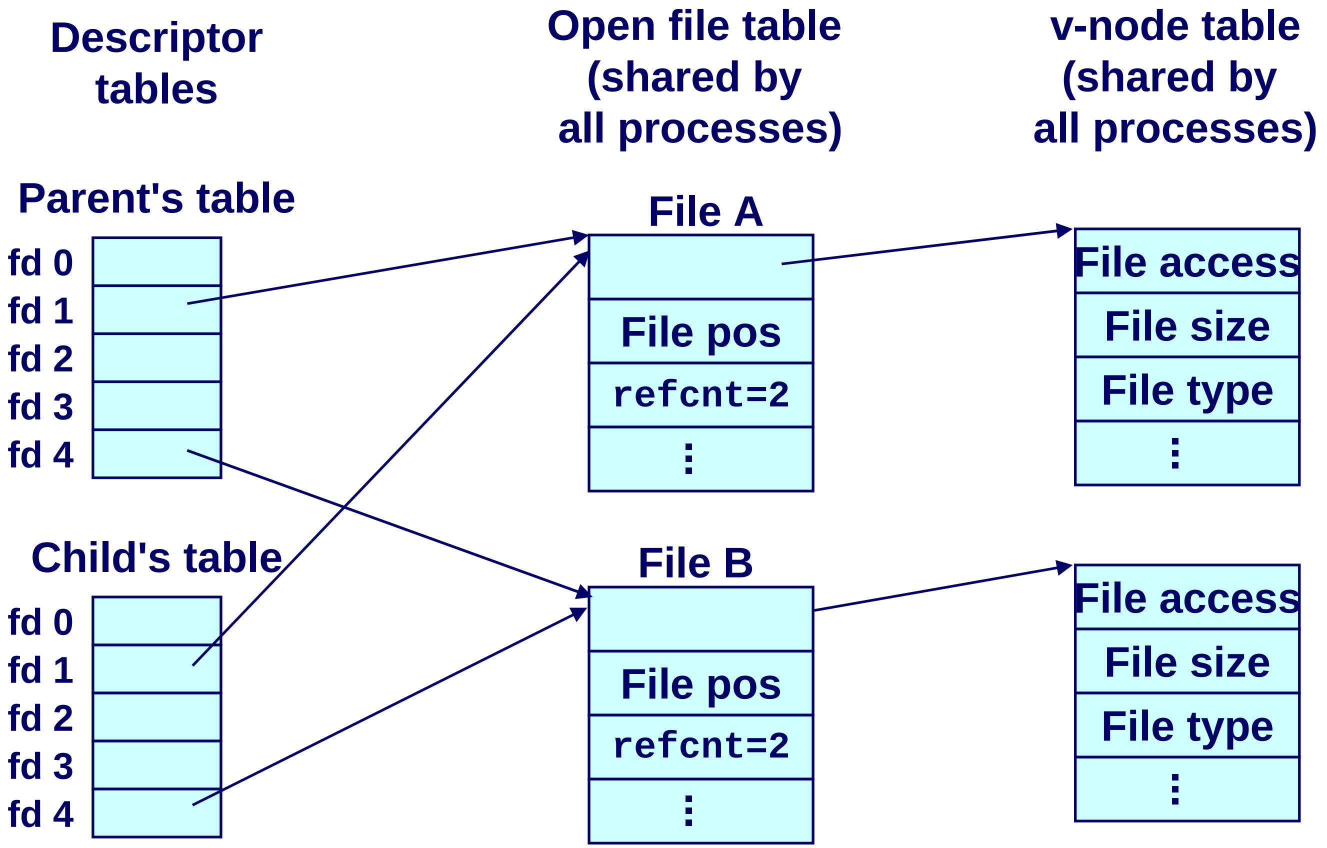
Two distinct descriptors sharing the same disk file through two distinct open file table entries

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



How Processes Share Files

- 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?

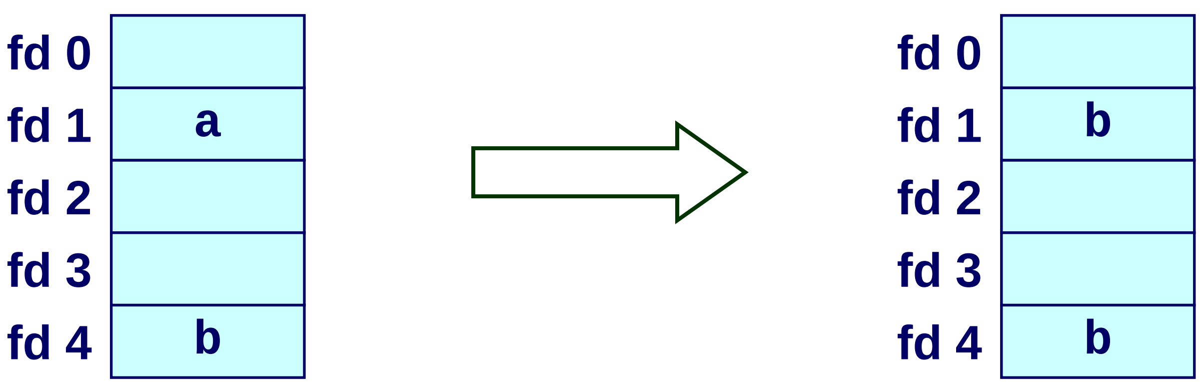
```
unix> ls > foo.txt
```

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

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

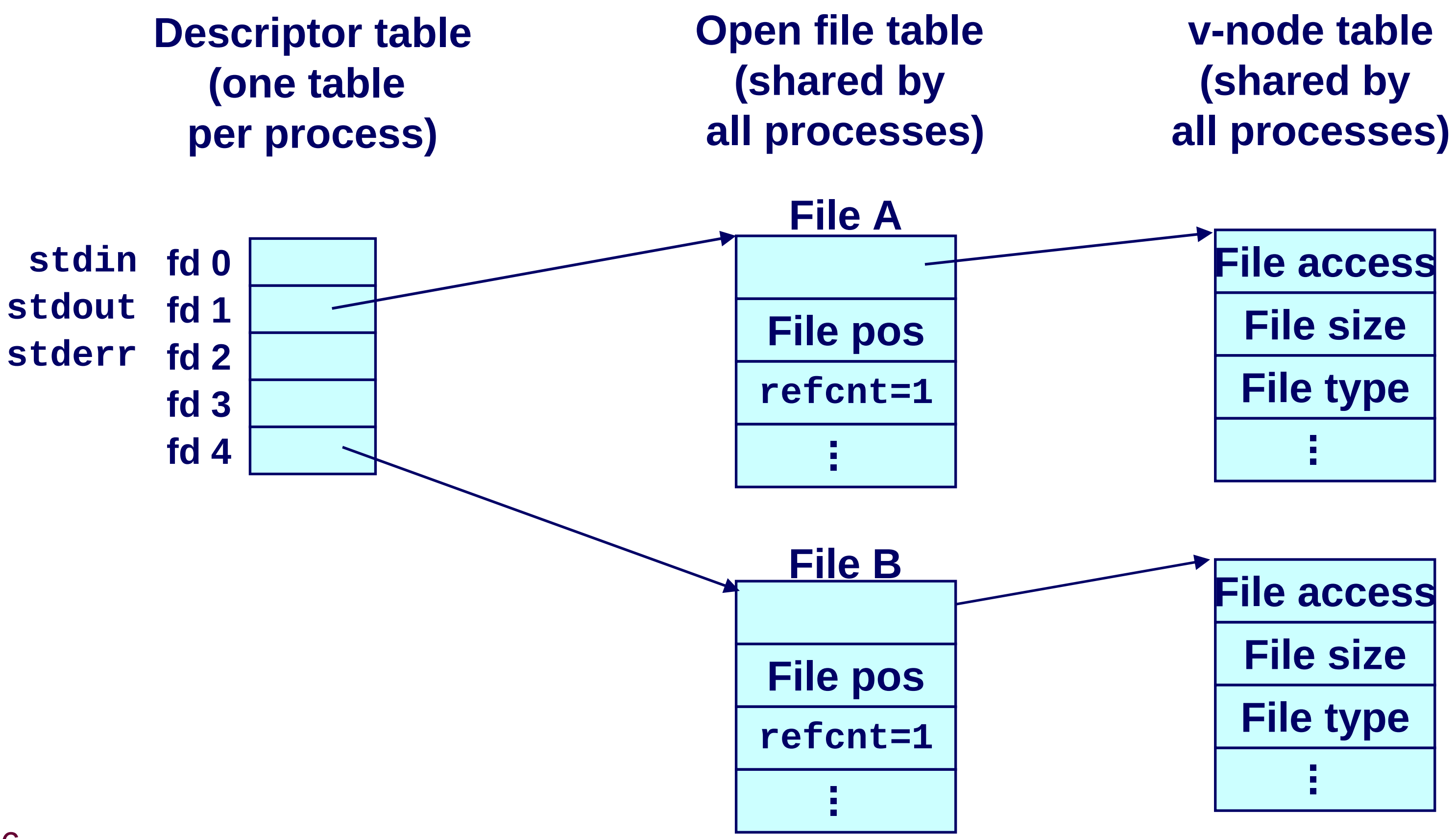
Descriptor table before `dup2(4,1)`

Descriptor table after `dup2(4,1)`



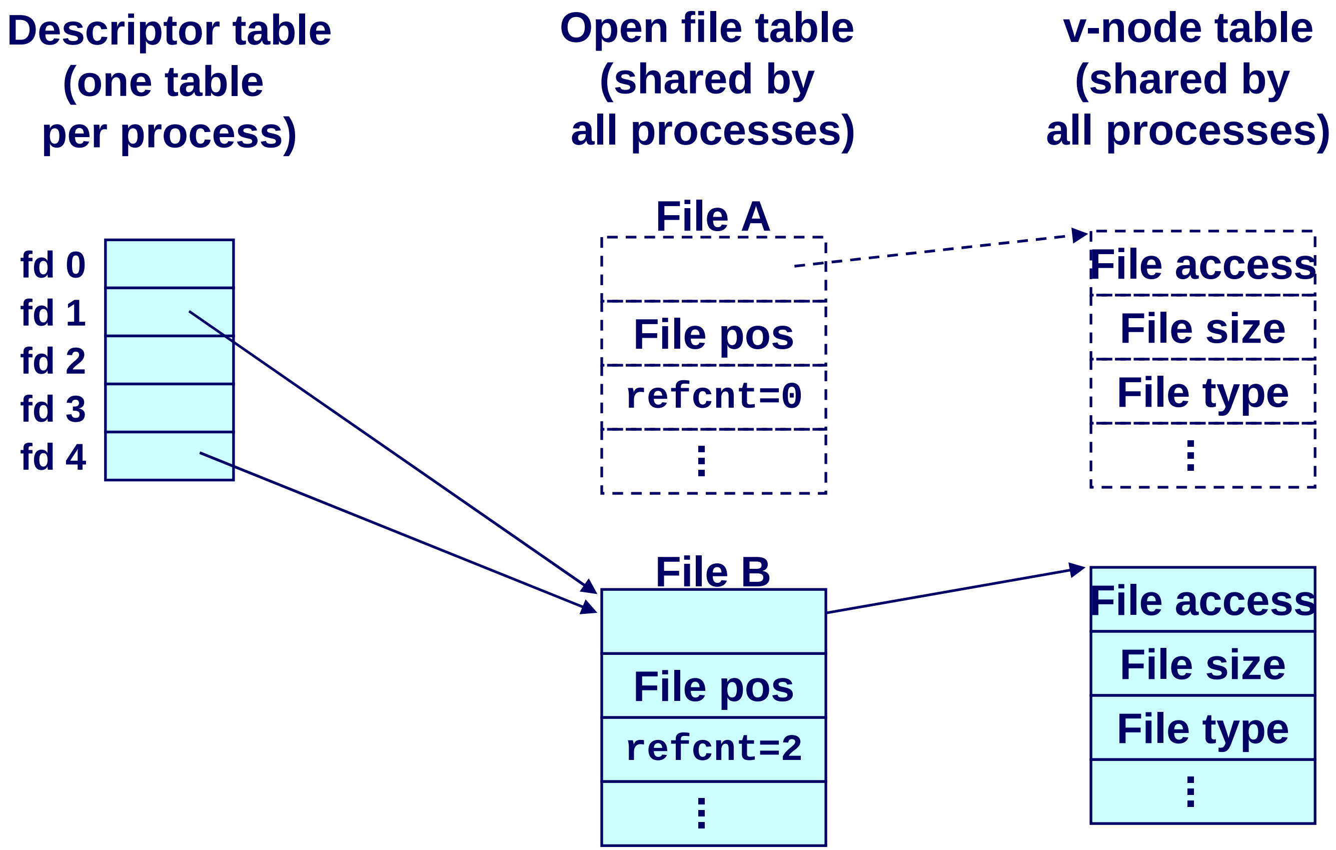
I/O Redirection Example

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.



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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;
}
```

- **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;
}
```

- **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;
}
```

- **What would be contents of resulting file?**

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.
- Similar to buffered RIO

C programs begin life with three open streams (defined in `stdio.h`)

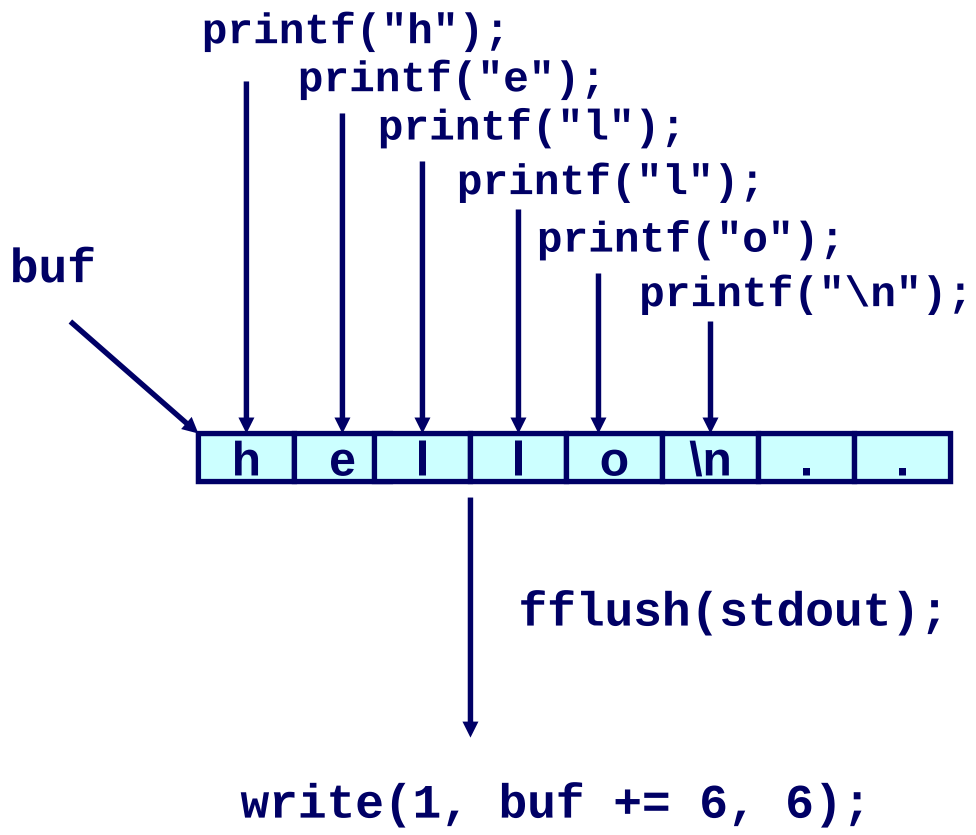
- `stdin` (standard input)
- `stdout` (standard output)
- `stderr` (standard error)

```
#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:

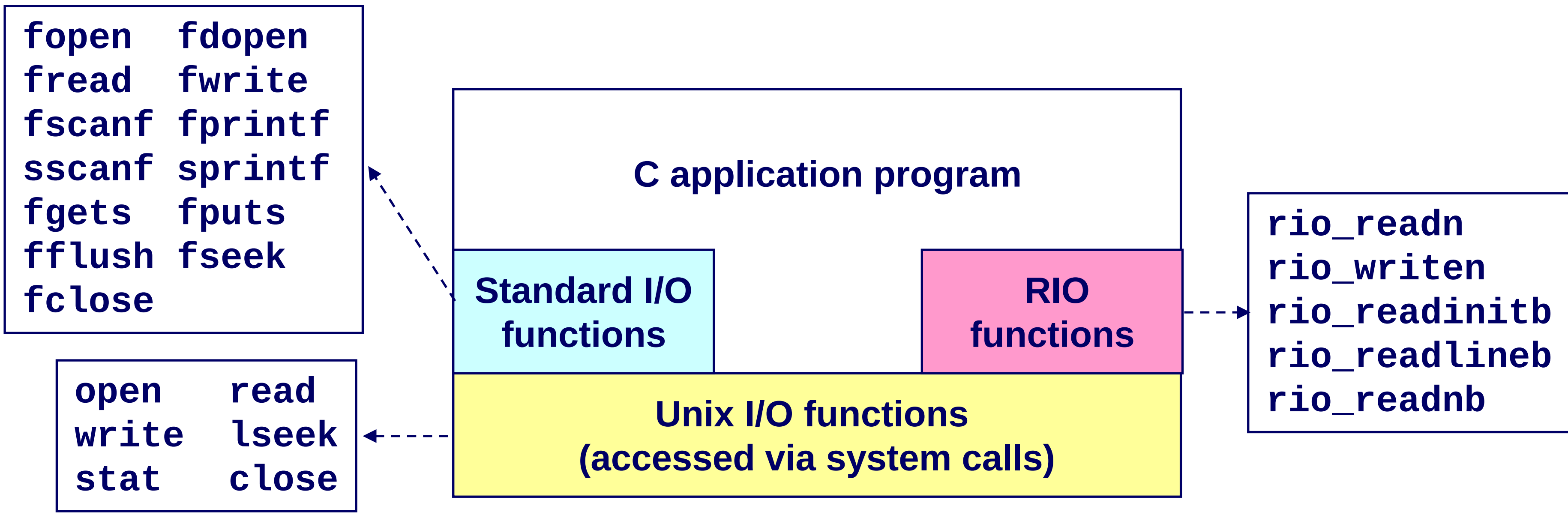
```
#include <stdio.h>

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

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 & Stephen A. Rago, Advanced Programming in the Unix Environment, 2nd Edition, Addison Wesley, 2005.
  - Updated from Stevens' 1993 book

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

- But others have taken up his legacy