15-213

"The course that gives CMU its Zip!"

System-Level I/O
November 4, 2003

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

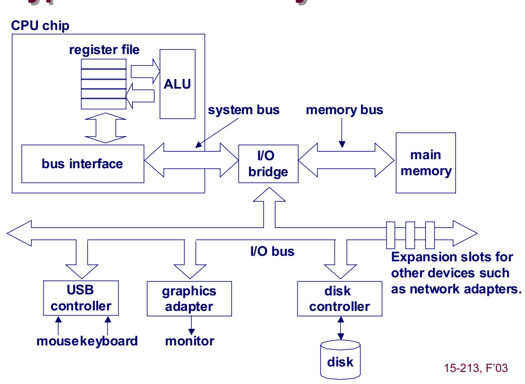
Mainframe I/O:

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

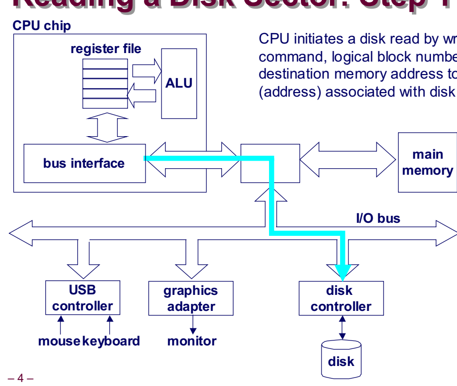
Coarse grained I/O
- Process writes "channel programs" to be executed by the I/O hardware
- Many I/O operations are performed autonomously with one interrupt at completion

A Typical Hardware System



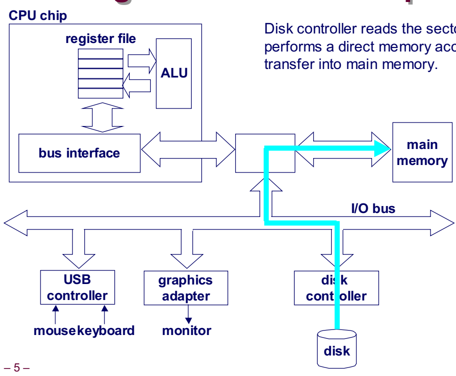
Reading a Disk Sector: Step 1

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



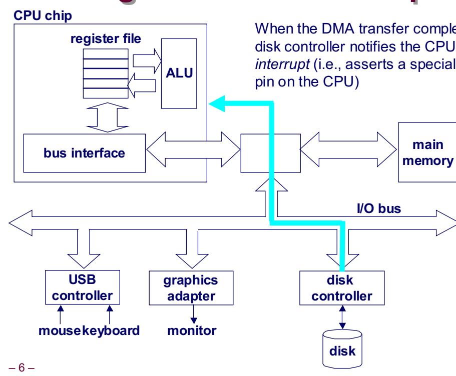
Reading a Disk Sector: Step 2

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 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)) /* 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
```


Metadata as File (Plan 9, ReiserFS 4)

Access to metadata requires a different API and is not easily extensible. The file notation can be used as a uniform assess mechanism in future file systems:

- **Files as directories:**

```
Bass> ls -l
-rw-r--r--    1 bovik    users     120 Nov  3 04:33 bar.c
-rw-r--r--    1 agn      users     727 Nov  3 04:35 foo.c
Bass> cat bar.c/..rwx
-rw-r--r--
Bass> echo 0777 > bar.c/..rwx
Bass> ls -l bar.c
-rwxrwxrwx    1 bovik    users     120 Nov  3 04:33 bar.c
Bass> cp bar.c/..uid foo.c/..uid
Bass> ls -l
-rw-r--r--    1 bovik    users     120 Nov  3 04:33 bar.c
-rwxrwxrwx    1 bovik    users     727 Nov  3 04:35 foo.c
Bass>
```


Accessing Directories

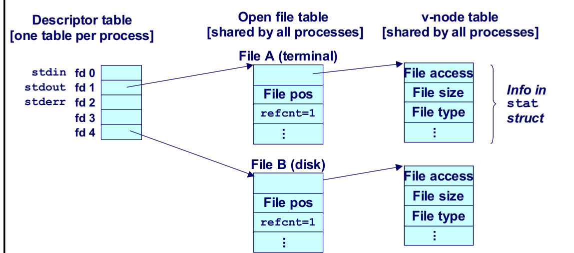
The only recommended operation on directories is to read its entries.

```
#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

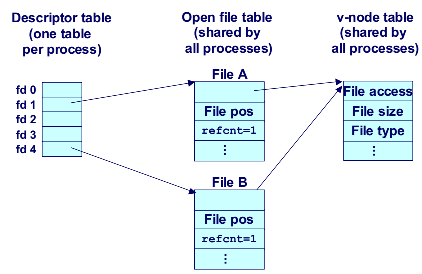
Two descriptors referencing two distinct open disk files. Descriptor 1 (stdout) points to terminal, and descriptor 4 points to open disk file.



File Sharing

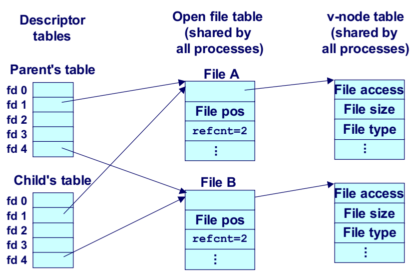
Two distinct descriptors sharing the same disk file through two distinct open file table entries

- 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`



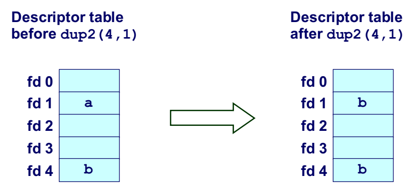
I/O Redirection

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

`unix> ls > foo.txt`

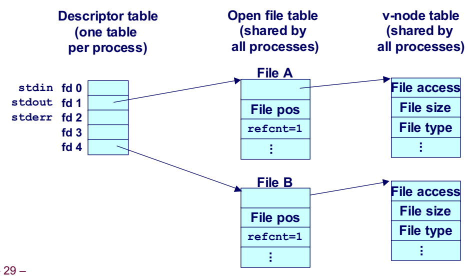
Answer: By calling the `dup2(oldfd, newfd)` function

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



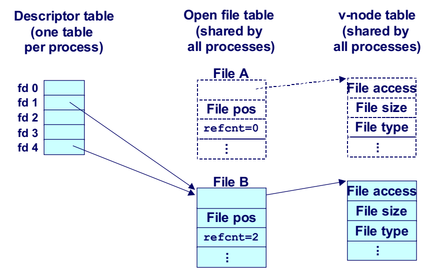
I/O Redirection Example

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`)

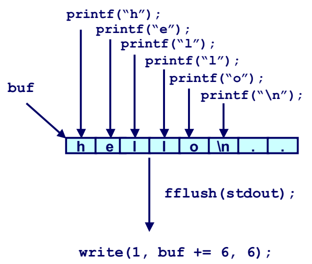
- `stdin` (standard input)
- `stdout` (standard output)
- `stderr` (standard error)

```
#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:

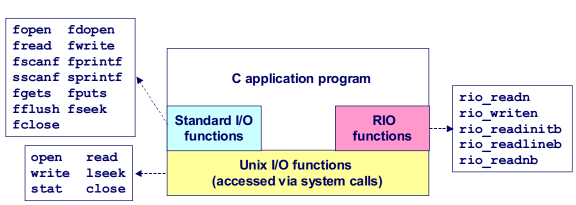
```
#include <stdio.h>

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.

Asynchronous I/O

How to deal with multiple I/O operations concurrently?

For example: wait for a keyboard input, a mouse click and input from a network connection.

- Select system call

```
int select(int n, fd_set *readfds, fd_set *writefds,
           fd_set *exceptfds, struct timeval *timeout);
```

- Poll system call (same idea, different implementation)

```
int poll(struct pollfd *ufds, unsigned int nfds, int timeout);

struct pollfd { int fd;           /* file descriptor */
                short events;     /* requested events */
                short revents;    /* returned events */
              };
```

- /dev/poll (Solaris, being considered for Linux)
- Posix real-time signals + `sigtimedwait()`
- Native Posix Threads Library (NPTL)

For more info see http://www.kegel.com/c10k.html

Asynchronous I/O (cont.)

POSIX P1003.4 Asynchronous I/O interface functions:
(available in Solaris, AIX, Tru64 Unix,…)

- `aio_cancel`
  cancel asynchronous read and/or write requests
- `aio_error`
  retrieve Asynchronous I/O error status
- `aio_fsync`
  asynchronously force I/O completion, and sets errno to ENOSYS
- `aio_read`
  begin asynchronous read
- `aio_return`
  retrieve return status of Asynchronous I/O operation
- `aio_suspend`
  suspend until Asynchronous I/O Completes
- `aio_write`
  begin asynchronous write
- `lio_listio`
  issue list of I/O requests

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.