15-213

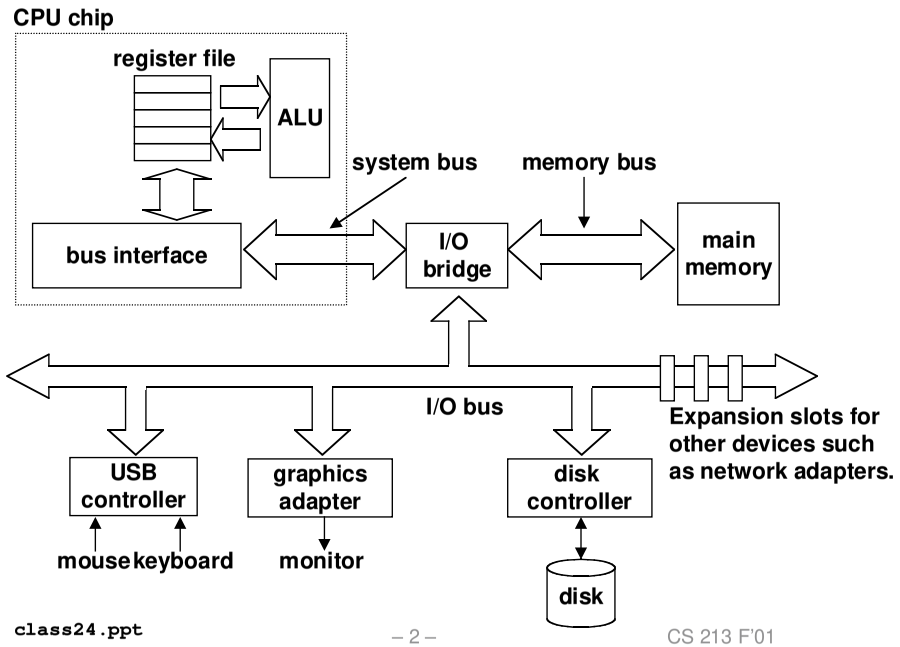
"The course that gives CMU its Zip!"

I/O
Nov 15, 2001

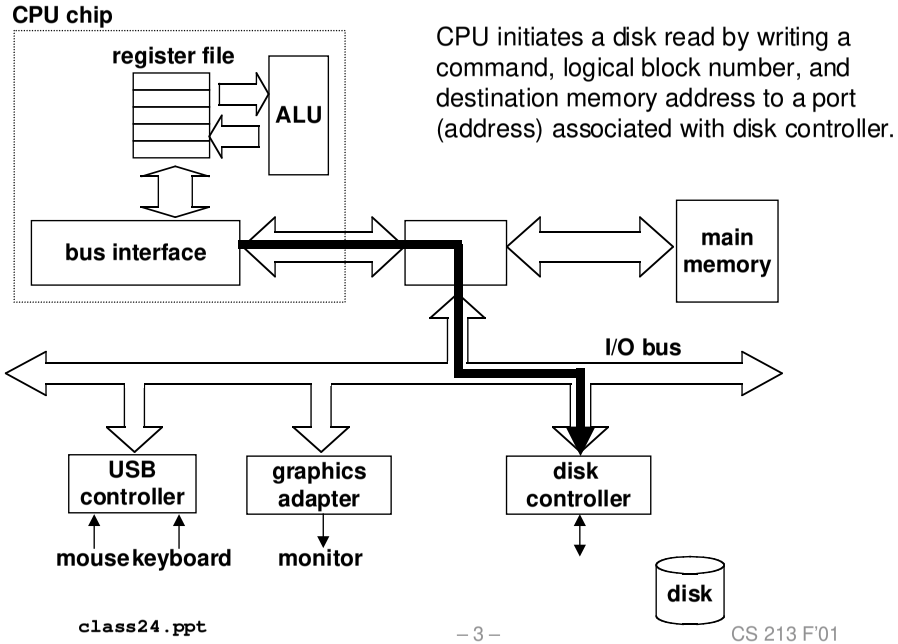
Topics

- Files
- Unix I/O
- Standard I/O

A typical hardware system

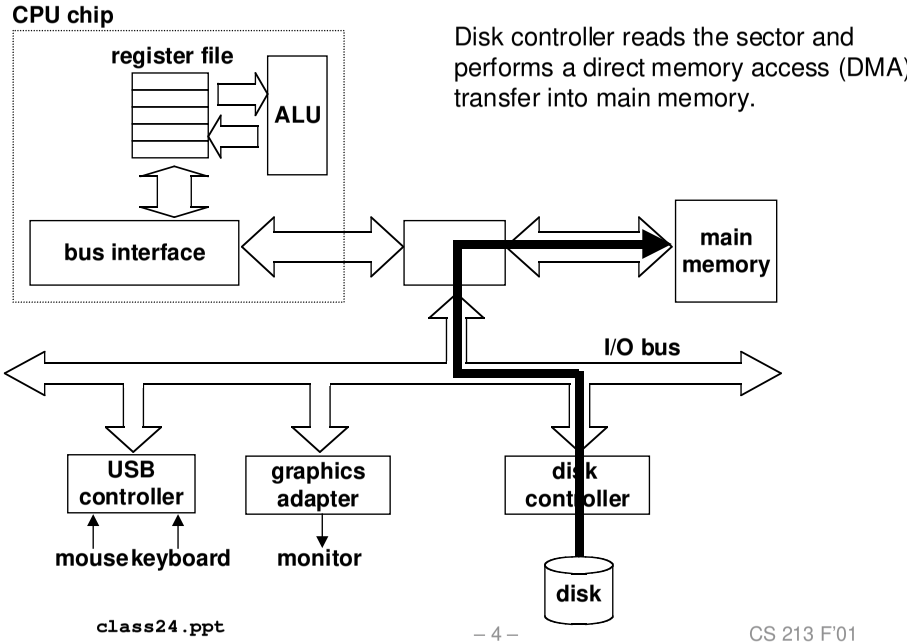


Reading a disk sector (1)



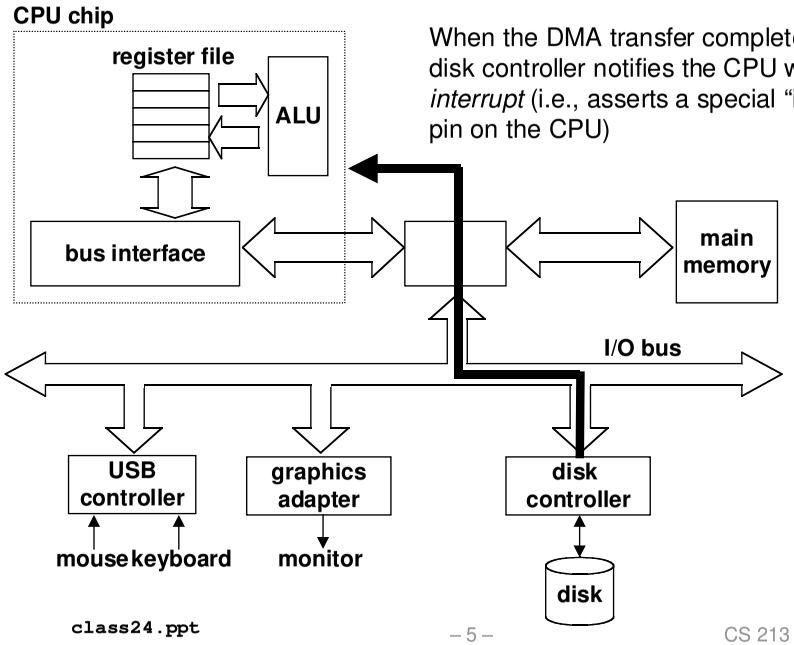
CPU initiates a disk read by writing a command, logical block number, and destination memory address to a port (address) associated with disk controller.

Reading a disk sector (2)



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

Reading a disk sector (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 *n* bytes:

- $B_0, B_1, \ldots, B_k, \ldots, B_{n-1}$

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)

Kernel identifies each file by a small integer *descriptor:*

- 0: standard input
- 1: standard output
- 2: standard error

Unix file types

Regular file

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

Directory file

- A file that contains names and locations of other files.

Character special file

- For certain types of streaming devices (e.g., terminals)

Block special file

- A file type typically used for disks.

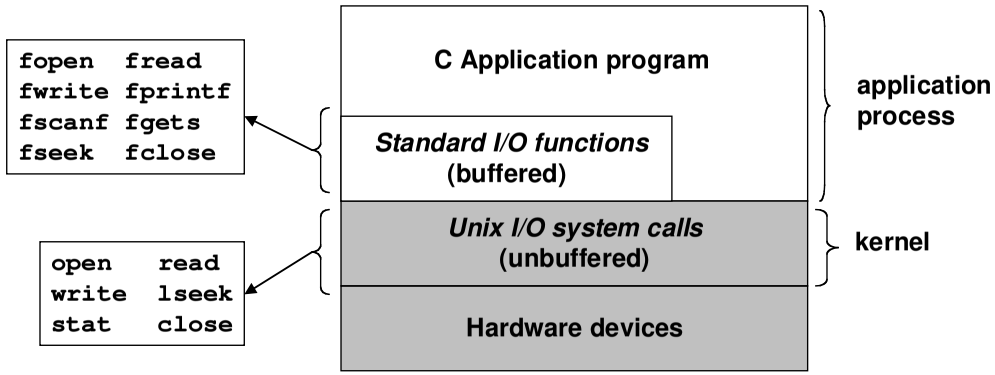
FIFO (named pipe)

- A file type used for interprocess comunication

Socket

- A file type used for network communication between processes

I/O functions



Standard I/O vs Unix I/O

When should I use the Standard I/O functions?

- Whenever possible!
- Many C programmers are able to do all of their work using the standard I/O functions.

Why would I ever need to use the lower level Unix I/O functions?

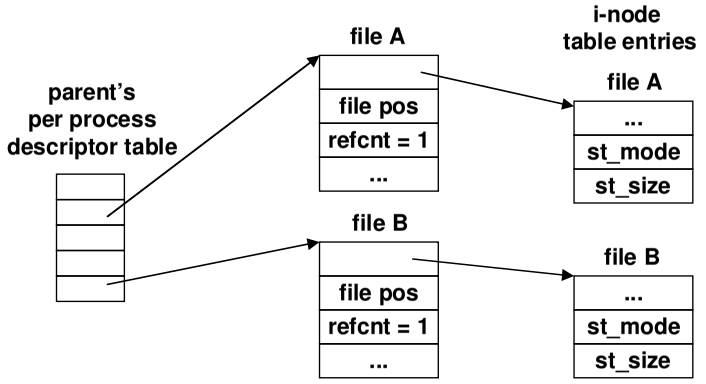
- Fetching file metadata (e.g., size, modification date)
  - must use lower level `stat` function
- Doing network programming
  - there are some bad interactions between sockets and the standard library functions.
- Needing high performance.

Meta-data returned by `stat()`

```
/*
 * file info returned by the stat function
 */
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 */
};
```

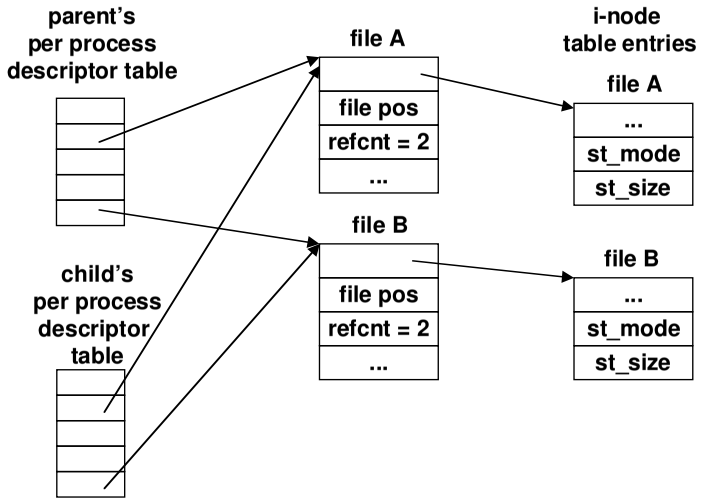

Kernel's file representation

Before fork:



Kernel's file representation (cont)

After fork (processes inherit open file tables):



Unix file I/O: `open()`

Must `open()` a file before you can do anything else.

```
int fd;   /* file descriptor */

if ((fd = open("/etc/hosts", O_RDONLY)) < 0) {
   perror("open");
   exit(1);
}
```

`open()` returns a small integer (file descriptor)

- `fd` < 0 indicates that an error occurred

predefined file descriptors:

- 0: stdin
- 1: stdout
- 2: stderr

Unix file I/O: `read()`

`read()` allows a program to fetch the contents of a file from the current *file position*.

```
char buf[512];
int fd;       /* file descriptor */
int nbytes;   /* number of bytes read */

/* open the file */
...
/* read up to 512 bytes from file fd */
if ((nbytes = read(fd, buf, sizeof(buf))) < 0) {
   perror("read");
   exit(1);
}
```

`read()` returns the number of bytes read from file `fd`.

- `nbytes` < 0 indicates that an error occurred.
- short counts (nbytes < sizeof(buf)) are possible and not errors!

- places `nbytes` bytes into memory address `buf`

Unix file I/O: `write()`

`write()` allows a program to modify the file contents starting at the current file position.

```
char buf[512];
int fd;       /* file descriptor */
int nbytes;   /* number of bytes read */

/* open the file */
...
/* write up to 512 bytes from buf to file fd */
if ((nbytes = write(fd, buf, sizeof(buf)) < 0) {
   perror("write");
   exit(1);
}
```

`write()` returns the number of bytes written from `buf` to file `fd`.

- `nbytes` < 0 indicates that an error occurred.
- short counts are possible and are not errors.

Robustly dealing with read short counts (adapted from Stevens)

```
ssize_t readn(int fd, void *buf, size_t count)
{
    size_t nleft = count;
    ssize_t nread;
    char *ptr = buf;
    while (nleft > 0) {
        if ((nread = read(fd, ptr, nleft)) < 0) {
            if (errno == EINTR)
                nread = 0;      /* and call read() again */
            else
                return -1;      /* errno set by read() */
        }
        else if (nread == 0)
            break;              /* EOF */
        nleft -= nread;
        ptr += nread;
    }
    return (count - nleft);     /* return >= 0 */
}
```

Robustly dealing with write short counts (adapted from Stevens)

```
ssize_t writen(int fd, const void *buf, size_t count)
{
    size_t nleft = count;
    ssize_t nwritten;
    const char *ptr = buf;

    while (nleft > 0) {
        if ((nwritten = write(fd, ptr, nleft)) <= 0) {
            if (errno == EINTR)
                nwritten = 0;    /* and call write() again */
            else
                return -1;       /* errorno set by write() */
        }
        nleft -= nwritten;
        ptr += nwritten;
    }
    return count;
}
```


Unix file I/O: `lseek()`

`lseek()` changes the current *file position*

```
int fd;       /* file descriptor */

/* open the file */
...
/* Move the file position to byte offset 100 */
if ((lseek(fd, 100, SEEK_SET) < 0) {
   perror("lseek");
   exit(1);
}
```

`lseek()` changes the current file position.

Unix file I/O: `dup2()`

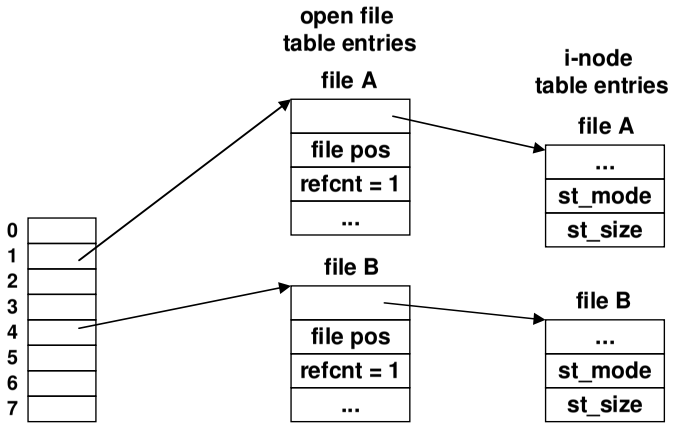
`dup2()` copies entries in the per-process file descriptor table.

```
/* Redirect stderr to stdout (so that driver will get all output
   on the pipe connected to stdout) */
   dup2(1, 2);  /* copies fd 1 (stdout) to fd 2 (stderr) */
```

`lseek(oldfd, newfd)` overwrites the entry in the per-process file table for `newfd` with the entry for `oldfd`.

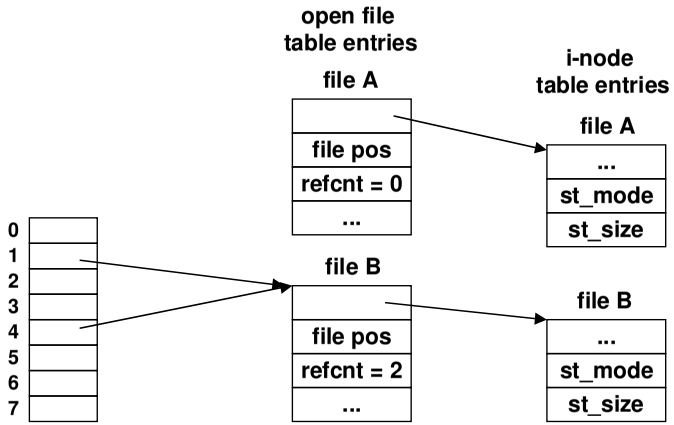
`dup2()` example

Before calling `dup2(4,1)`:



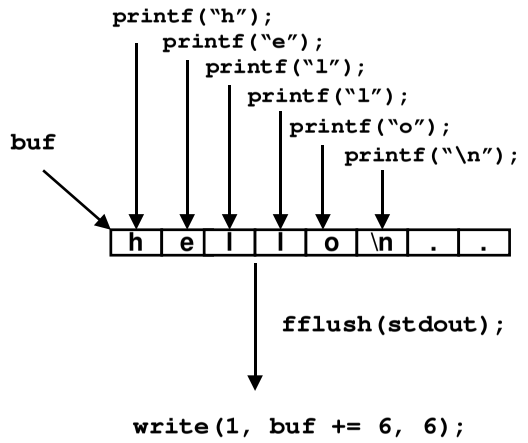
dup2() example

After calling `dup2(4,1)`:



Buffering in Standard I/O

Standard library functions use *buffered I/O*



Buffering in action

You can see this buffering 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);
}
```

```
bass> strace hello
execve("./hello", ["hello"], [/* ... */]).
...
write(1, "hello\n", 6)                  = 6
munmap(0x40000000, 4096)                = 0
_exit(0)                                = ?
```


Using buffering to robustly read text lines (Stevens)

```
static ssize_t my_read(int fd, char *ptr)
{
    static int read_cnt = 0;
    static char *read_ptr, read_buf[MAXLINE];

    if (read_cnt <= 0) {
    again:
        if ( (read_cnt = read(fd, read_buf, sizeof(read_buf))) < 0) {
            if (errno == EINTR)
                goto again;
            return -1;
        }
        else if (read_cnt == 0)
            return 0;
        read_ptr = read_buf;
    }
    read_cnt--;
    *ptr = *read_ptr++;
    return 1;
}
```

Robustly reading text lines (cont)

```
ssize_t readline(int fd, void *buf, size_t maxlen) {
    int n, rc;
    char c, *ptr = buf;
    for (n = 1; n < maxlen; n++) {  /* notice that loop starts at 1 */
        if ( (rc = my_read(fd, &c)) == 1) {
            *ptr++ = c;
            if (c == '\n')
                break;          /* newline is stored, like fgets() */
        }
        else if (rc == 0) {
            if (n == 1)
                return 0;       /* EOF, no data read */
            else
                break;          /* EOF, some data was read */
        }
        else
            return -1;  /* error, errno set by read() */
    }
    *ptr = 0;   /* null terminate like fgets() */
    return n;
}
```


`mmap()` revisited

```
void *mmap(void *start, int len, int prot,
           int flags, int fd, int offset)
```

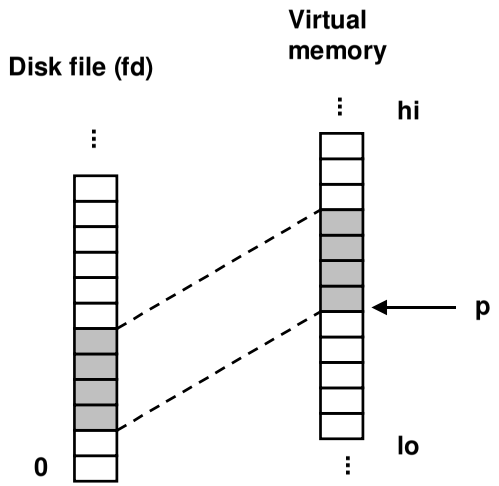
Map `len` bytes starting at offset `offset` of the file specified by file description `fd`, preferably at address `start` (usually 0 for don't care).

- `prot`: `MAP_READ`, `MAP_WRITE`
- `flags`: `MAP_PRIVATE`, `MAP_SHARED`

Return a pointer to the mapped area

Visualizing `mmap()`

```
p = mmap(NULL, 4, PROT_READ, MAP_PRIVATE, fd, 2);
```



`mmap()` example

```
/* mmapcopy - uses mmap to copy file fd to stdout */
void mmapcopy(int fd, int size)
{
    char *bufp; /* ptr to memory mapped VM area */
    bufp = Mmap(NULL, size, PROT_READ, MAP_PRIVATE, fd, 0);
    Write(1, bufp, size);
    return;
}

/* mmapcopy driver */
int main(int argc, char **argv)
{
    struct stat stat;
    int fd;

    fd = Open(argv[1], O_RDONLY, 0);
    Fstat(fd, &stat);
    mmapcopy(fd, stat.st_size);
    exit(0);
}
```

For further information

The Unix bible:

- W. Richard Stevens, *Advanced Programming in the Unix Environment,* Addison Wesley, 1993.

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.