System-Level I/O

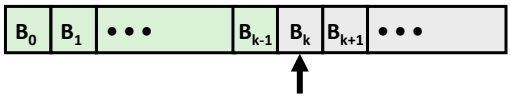
CS 475

Unix I/O Overview

- **A Linux *file* is a sequence of *m* bytes:**
  - $B_0, B_1, \ldots, B_k, \ldots, B_{m-1}$
- **Cool fact: All I/O devices are represented as files:**
  - `/dev/sda2` (`/usr` disk partition)
  - `/dev/tty2` (terminal)
- **Even the kernel is represented as a file:**
  - `/boot/vmlinuz-3.13.0-55-generic` (kernel image)
  - `/proc` (kernel data structures)

Unix I/O Overview

- **Elegant mapping of files to devices allows kernel to export simple interface called *Unix I/O:***
  - 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()`



Current file position = k

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File Types

- **Each file has a *type* indicating its role in the system**
  - *Regular file:* Contains arbitrary data
  - *Directory:* Index for a related group of files
  - *Socket:* For communicating with a process on another machine
- **Other file types beyond our scope**
  - *Named pipes (FIFOs)*
  - *Symbolic links*
  - *Character and block devices*

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Regular Files

- **A regular file contains arbitrary data**
- **Applications often distinguish between *text files* and *binary files***
  - Text files are regular files with only ASCII or Unicode characters
  - Binary files are everything else
    - e.g., object files, JPEG images
  - Kernel doesn't know the difference!
- **Text file is sequence of *text lines***
  - Text line is sequence of chars terminated by *newline char* ('`\n`')
    - Newline is `0xa`, same as ASCII line feed character (LF)
- **End of line (EOL) indicators in other systems**
  - Linux and Mac OS: '`\n`' (`0xa`)
    - line feed (LF)
  - Windows and Internet protocols: '`\r\n`' (`0xd 0xa`)
    - Carriage return (CR) followed by line feed (LF)

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Directories

- **Directory consists of an array of *links***
  - Each link maps a *filename* to a file
- **Each directory contains at least two entries**
  - `.` (dot) is a link to itself
  - `..` (dot dot) is a link to *the parent directory* in the *directory hierarchy* (next slide)
- **Commands for manipulating directories**
  - `mkdir`: create empty directory
  - `ls`: view directory contents
  - `rmdir`: delete empty directory

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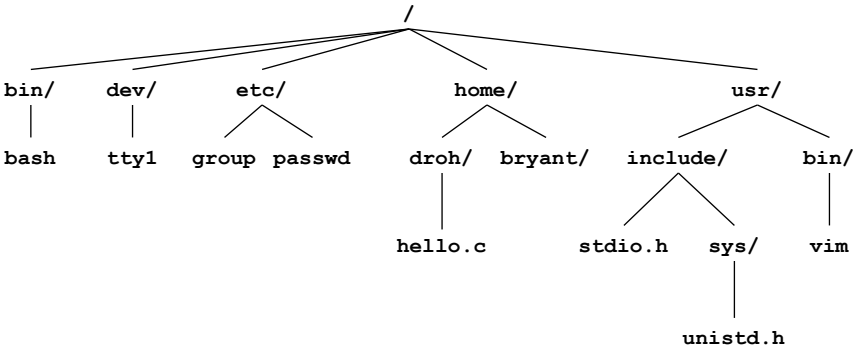
Directory Hierarchy

- **All files are organized as a hierarchy anchored by root directory named / (slash)**



- **Kernel maintains *current working directory (cwd)* for each process**
  - Modified using the `cd` command

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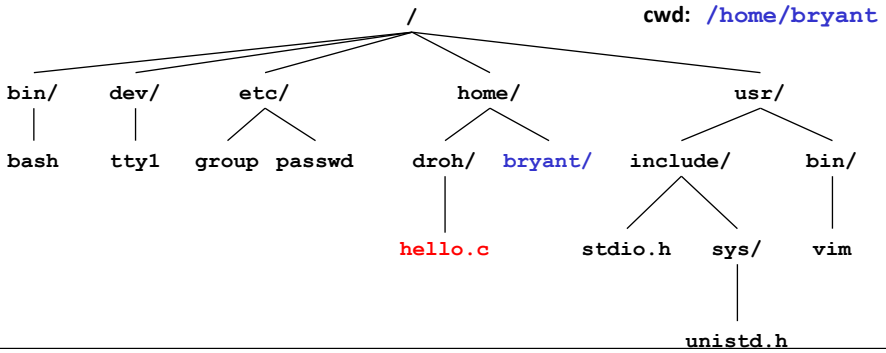
Pathnames

- **Locations of files in the hierarchy denoted by *pathnames***
  - *Absolute pathname* starts with '/' and denotes path from root
    - `/home/droh/hello.c`
  - *Relative pathname* denotes path from current working directory
    - `../home/droh/hello.c`



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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 Linux shell begins life with three open files associated with a terminal:**
  - 0: standard input (stdin)
  - 1: standard output (stdout)
  - 2: standard error (stderr)

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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()`**

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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!

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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!

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Simple Unix I/O example

- **Copying stdin to stdout, 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);
}
```

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On 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
- **Short counts never occur in these situations:**
  - Reading from disk files (except for EOF)
  - Writing to disk files
- **Best practice is to always allow for short counts.**

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The RIO Package

- **RIO is a set of wrappers that provide efficient and robust I/O in apps, 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 text lines and binary data
    - **`rio_readlineb`** and **`rio_readnb`**
    - Buffered RIO routines are thread-safe and can be interleaved arbitrarily on the same descriptor

- **Download from http://csapp.cs.cmu.edu/3e/code.html**
  → **`src/csapp.c`** and **`include/csapp.h`**

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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 if 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

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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 */
}
```

csapp.c

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
- Stopping conditions
  - **`maxlen`** bytes read
  - EOF encountered
  - Newline (‘**`\n`**’) encountered

Buffered RIO Input Functions (cont)

```
#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_readnb`** reads up to **`n`** bytes from file **`fd`**
- Stopping conditions
  - **`maxlen`** bytes read
  - EOF encountered
- Calls to **`rio_readlineb`** and **`rio_readnb`** can be interleaved arbitrarily on the same descriptor
  - Warning: Don't interleave with calls to **`rio_readn`**

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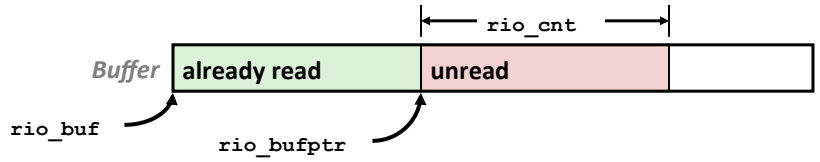
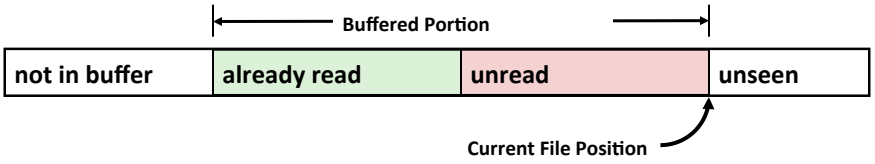
Buffered I/O: Implementation

- **For reading from file**
- **File has associated buffer to hold bytes that have been read from file but not yet read by user code**



- **Layered on Unix file:**



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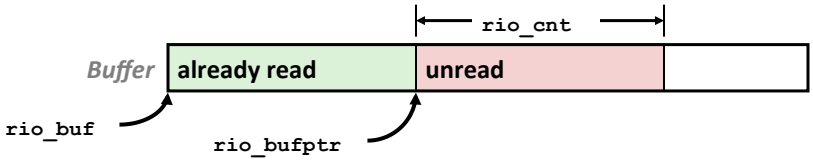
Buffered I/O: Declaration

- All information contained in `struct`




```
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;
```


RIO Example

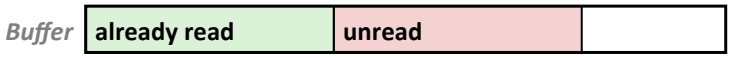
- Copying the lines of a text file from standard input to standard output

```
#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);
}
```

cpfile.c

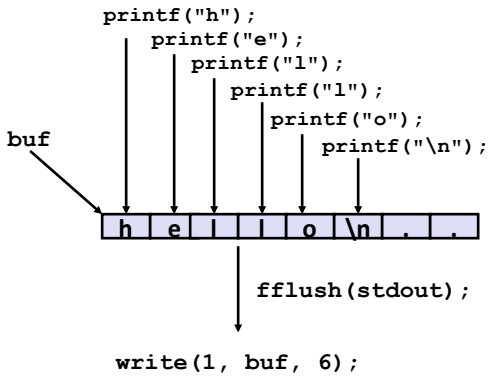
Buffered I/O: Motivation

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



Buffering in Standard I/O

- **Standard I/O functions use buffered I/O**



- **Buffer flushed to output fd on "\n", call to `fflush` or `exit`, or return from `main`.**

Standard I/O Buffering in Action

- You can see this buffering in action for yourself, using the always fascinating Linux `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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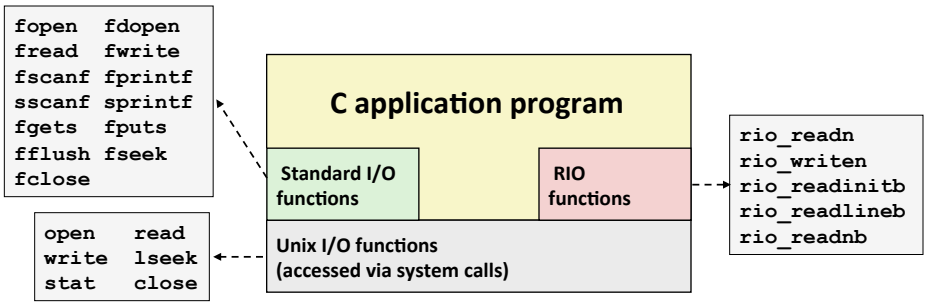
Unix I/O vs. Standard I/O vs. RIO

- Standard I/O and RIO are implemented using low-level Unix I/O



- Which ones should you use in your programs?

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