System-Level I/O

15-213 / 18-213: Introduction to Computer Systems
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Today

■ Unix I/O
■ Metadata, sharing, and redirection
■ Standard I/O
■ RIO (robust I/O) package
■ Closing remarks
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**
  - 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

```c
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

```c
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

```c
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

```c
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

```c
int main(void)
{
    char c;
    int len;

    while ((len = read(0 /*stdin*/, &c, 1)) == 1) {
        if (write(1 /*stdout*/, &c, 1) != 1) {
            exit(20);
        }
    }
    if (len < 0) {
        printf ("read from stdin failed");
        exit (10);
    }
    exit(0);
}
```
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 or Unix pipes

Short counts never occur in these situations:

- Reading from disk files (except for EOF)
- Writing to disk files
Today

- Unix I/O
- Metadata, sharing, and redirection
- Standard I/O
- RIO (robust I/O) package
- Closing remarks
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

```c
/* 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
Repeated Slide: Opening Files

- Opening a file informs the kernel that you are getting ready to access that file

```c
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
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.

Descriptor table
[one table per process]

Open file table
[shared by all processes]

v-node table
[shared by all processes]

Info in stat struct
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

Descriptor table
[one table per process]

Open file table
[shared by all processes]

v-node table
[shared by all processes]

stdin  fd 0
stdout fd 1
stderr fd 2
fd 3
fd 4

File A (disk)
File pos
refcnt=1
...

File access
File size
File type
...

File B (disk)
File pos
refcnt=1
...

File access
File size
File type
...
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:

  **Descriptor table**
  [one table per process]

  **Open file table**
  [shared by all processes]

  **v-node table**
  [shared by all processes]

  ![Diagram showing file descriptors and tables](diagram.png)
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

Descriptor table
[one table per process]

Open file table
[shared by all processes]

v-node table
[shared by all processes]

Parent

Child

File A (terminal)

File B (disk)
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)`

<table>
<thead>
<tr>
<th>fd 0</th>
<th>fd 1</th>
<th>fd 2</th>
<th>fd 3</th>
<th>fd 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>a</strong></td>
<td></td>
<td></td>
<td><strong>b</strong></td>
</tr>
</tbody>
</table>

*after* `dup2(4,1)`

<table>
<thead>
<tr>
<th>fd 0</th>
<th>fd 1</th>
<th>fd 2</th>
<th>fd 3</th>
<th>fd 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>b</strong></td>
<td></td>
<td></td>
<td><strong>b</strong></td>
</tr>
</tbody>
</table>
I/O Redirection Example

- **Step #1: open file to which stdout should be redirected**
  - Happens in child executing shell code, before `exec`

---

### Diagram

- **Descriptor table**
  - [one table per process]

- **Open file table**
  - [shared by all processes]

- **v-node table**
  - [shared by all processes]

---

<table>
<thead>
<tr>
<th>stdin</th>
<th>fd 0</th>
<th>File A</th>
</tr>
</thead>
<tbody>
<tr>
<td>stdout</td>
<td>fd 1</td>
<td>File pos</td>
</tr>
<tr>
<td>stderr</td>
<td>fd 2</td>
<td>refcnt=1</td>
</tr>
<tr>
<td></td>
<td>fd 3</td>
<td>:</td>
</tr>
<tr>
<td></td>
<td>fd 4</td>
<td>:</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>File B</th>
</tr>
</thead>
<tbody>
<tr>
<td>File pos</td>
</tr>
<tr>
<td>refcnt=1</td>
</tr>
<tr>
<td>:</td>
</tr>
</tbody>
</table>

| File access |
| File size |
| File type |
|     :   |

| File access |
| File size |
| File type |
|     :   |
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
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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)

```c
#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");
}
```
Buffered I/O: Motivation

- 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
Buffering in Standard I/O

- Standard I/O functions use buffered I/O

```c
printf("h");
printf("e");
printf("l");
printf("l");
printf("o");
printf("\n");
```

```c
buf = write(1, buf, 6);
```

- 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:

```c
#include <stdio.h>

int main()
{
    printf("h");
    printf("e");
    printf("l");
    printf("l");
    printf("o");
    printf("\n");
    fflush(stdout);
    exit(0);
}
```

```shell
linux> strace ./hello
execve("./hello", ["hello"], [/* ... */]).
...
write(1, "hello\n", 6) = 6
...
exit_group(0) = ?
```
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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
    - \texttt{rio_readn} and \texttt{rio_writen}
  - Buffered input of binary data and text lines
    - \texttt{rio_readlineb} and \texttt{rio_readnb}
    - Buffered RIO routines are thread-safe and can be interleaved arbitrarily on the same descriptor

- Download from \url{http://csapp.cs.cmu.edu/public/code.html}
  \texttt{src/csapp.c} and \texttt{include/csapp.h}
Implementation of \texttt{rio_readn}

```c
/*
 * \texttt{rio_readn} - robustly read \textit{n} bytes (unbuffered)
 */
ssize_t \texttt{rio_readn}(int \texttt{fd}, \texttt{void *}\texttt{usrbuf}, \texttt{size_t} \texttt{n})
{
    \texttt{size_t} \texttt{nleft} = \texttt{n};
    \texttt{ssize_t} \texttt{nread};
    \texttt{char} *\texttt{bufp} = \texttt{usrbuf};

    \texttt{while (nleft > 0)} { \texttt{
    if ((nread = \texttt{read}(\texttt{fd}, \texttt{bufp}, \texttt{nleft})) < 0) { \texttt{
        if (errno == \texttt{EINTR}) /* interrupted by sig handler return */
            \texttt{nread} = \texttt{0}; /* and call \texttt{read()} again */
        \texttt{else} \texttt{
            return -1; /* errno set by \texttt{read()} */
        } \texttt{
    } \texttt{
    } \texttt{else if (nread == 0) \texttt{
        break; /* EOF */
        \texttt{nleft} -= \texttt{nread};
        \texttt{bufp} += \texttt{nread};
    } \texttt{
    return (\texttt{n} - \texttt{nleft}); /* return \texttt{\geq 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?
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 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 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
  - But, be sure to understand the functions you use!

- **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

- **When to use RIO**
  - 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 things like `rio_readn` or `rio_readnb` instead

- **String functions**
  - `strlen`, `strncpy`
  - Interprets byte value 0 (end of string) as special
For Further Information

■ The Unix bible:
    ▪ Updated from Stevens’s 1993 classic text.

■ 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
Fun with File Descriptors (1)

```c
#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”?
What would this program print for file containing “abcde”? 

```c
#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
```
Fun with File Descriptors (3)

```c
#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 the contents of the resulting file?
# 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

```c
#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);
}
```
Backup Slides
Unbuffered RIO Input and Output

- Same interface as Unix read and write
- Especially useful for transferring data on network sockets

```c
#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
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:

```
<table>
<thead>
<tr>
<th>not in buffer</th>
<th>already read</th>
<th>unread</th>
<th>unseen</th>
</tr>
</thead>
</table>
```

```
Buffer
```

```
rio_buf
```

```
rio_bufptr
```

```
rio_cnt
```

```
Current File Position
```

```
Buffered Portion
```
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;
```
Buffered RIO Input Functions

- Efficiently read text lines and binary data from a file partially cached in an internal memory buffer

```c
#include "csapp.h"

void rio_readinitb(rio_t *rp, int fd);
ssize_t rio_readlineb(rio_t *rp, void *usrbuf, size_t maxlen);
```

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)

```c
#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`
RIO Example

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

```c
#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