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

- 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()`

```
 B_0  B_1  \cdots  B_{k-1}  B_k  B_{k+1}  \cdots

\text{Current file position} = k
```
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

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- 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);
}
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.
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]

---

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

---

```plaintext
File A (disk)

File pos
refcnt=1
::

File B (disk)

File pos
refcnt=1
::
```

---

```plaintext
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:

  ![Diagram of file descriptors and tables]

  - **Descriptor table**
    - [one table per process]
  
  - **Open file table**
    - [shared by all processes]
  
  - **v-node table**
    - [shared by all processes]

  - **Files**
    - `stdin` fd 0
    - `stdout` fd 1
    - `stderr` fd 2
    - fd 3
    - fd 4

  - **File A (terminal)**
    - File pos
    - refcnt=1
    - ...

  - **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
- 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

<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>
</table>

Child

<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>
</table>

File A (terminal)

<table>
<thead>
<tr>
<th>File pos</th>
<th>refcnt=2</th>
</tr>
</thead>
</table>

File B (disk)

<table>
<thead>
<tr>
<th>File pos</th>
<th>refcnt=2</th>
</tr>
</thead>
</table>

File access

File size

File type
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)`

| fd 0 |    |
| fd 1 | a  |
| fd 2 |    |
| fd 3 |    |
| fd 4 | b  |

Descriptor table after `dup2(4, 1)`

| fd 0 |    |
| fd 1 | b  |
| fd 2 |    |
| fd 3 |    |
| fd 4 | b  |
I/O Redirection Example

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

---

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

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

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

---

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

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

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

---

**Diagram:***
- **Descriptor table**:
  - stdin: fd 0
  - stdout: fd 1
  - stderr: fd 2
  - fd 3
  - fd 4

- **Open file table**:
  - File A
    - refcnt=0
    - File pos
  - File B
    - refcnt=2
    - File pos

- **v-node table**:
  - File access
  - File size
  - File type
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- Closing remarks
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("l");
printf("o");
printf("\n");
fflush(stdout);
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);
}
```

```
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
    - `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 [http://csapp.cs.cmu.edu/public/code.html](http://csapp.cs.cmu.edu/public/code.html)
  - `src/csapp.c` and `include/csapp.h`
/ *    * 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 */
}
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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 & Windows: CR+LF (0x0d 0x0a) [‘\r\n’]
    - Use things like `rio_readn` or `rio_readnb` instead

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

- **The Unix bible:**
    - Updated from Stevens’s 1993 classic text

- **The Linux bible:**
    - Encyclopedic and authoritative
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”?
Fun with File Descriptors (2)

```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

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

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);  
}
```
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 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)

```
#include "csapp.h"

def void rio_readinitb(rio_t *rp, int fd);

def ssize_t rio_readlineb(rio_t *rp, void *usrbuf, size_t maxlen);

def 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**
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:

Buffer

rio_buf

rio_bufptr

rio_cnt

already read

unread

not in buffer

already read

unread

unseen

Current File Position

Buffered Portion
Buffered I/O: Declaration

- All information contained in struct

```c
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

```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