COMP1521 25T1

Week 7 Lecture 1

File Systems

Adapted from Hammond Pearce,
Andrew Taylor and John Shepherd's slides

Announcements

Test 5 and Test 6 are due thursday 9pm

Assignment 2 coming out later this week!

Today's Lecture

- Recap Operating Systems
  - syscall, libc wrappers, stdio
- File Operations
  - open, close, read, write, seek

Operating Systems: Privileged Mode

- Needs hardware to provide a **privileged** mode
  - OS kernel runs in this mode
  - code can access all hardware, memory and CPU instructions
- Needs hardware to provide a **non-privileged** mode which
  - code can not access hardware directly
  - code can only access the memory it was allocated
  - user code runs in this mode

Operating Systems: System Calls

- System calls allow user level code to request hardware operations
- System calls transfer execution to OS kernel code in **privileged** mode
  - includes arguments specifying details of request being made
  - OS checks operation is valid & permitted
  - OS carries out operation
  - transfers execution back to user code in **non-privileged** mode

Experimenting with Linux System Calls

- Linux system calls also have a number
  - e.g system call **1** is **write** bytes to a file
- Linux provides 400+ system calls

```
$ cat /usr/include/x86_64-linux-gnu/asm/unistd_64.h
...
#define __NR_read 0
#define __NR_write 1
#define __NR_open 2
#define __NR_close 3
...
#define __NR_set_mempolicy_home_node 450
```

System Calls in Linux

syscall command

- not usually used in practice
- syscalls vary between operating system code is less portable
- hard to understand

Libc syscall wrapper:

- more meaningful names
- does syscall for you and helps with error checking
- more portable than syscall but not portable
    - some work on POSIX compliant systems (like linux and MacOS)

System Calls in Linux

Higher level library functions like **stdio.h:**

- useful most of the time
- calls syscall wrapper for you
- portable
- does other cool stuff to make thing easier
- you have been using these to indirectly do your system calls the whole time!

System Calls to Manipulate Files

Important file related system calls

Id	Name	Function
0	read	read some bytes from a file **descriptor**
1	write	write some bytes to a file **descriptor**
2	open	open a file system object, returning a file **descriptor**
3	close	close a file **descriptor**
4	stat	get file system metadata for a pathname
8	lseek	move file **descriptor** to a specified offset within a file

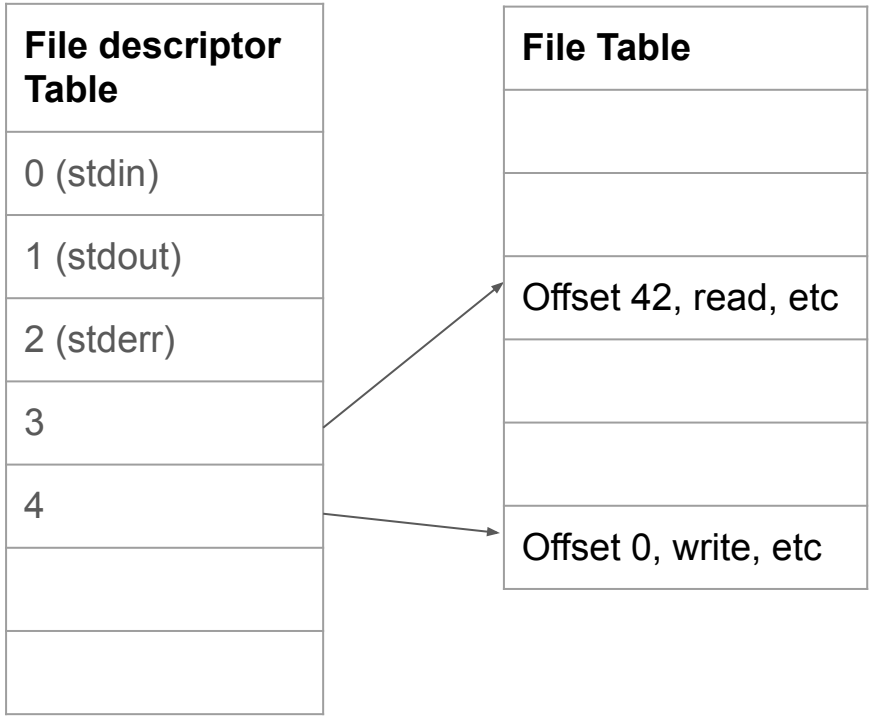
File Descriptors

Every process starts with the 3 standard streams, 0, 1, 2.

When a file is opened a new file descriptor is added to the table.

When a file is closed the file descriptor is removed

When a file is read to or written from, the offset is updated



System call to print a message to stdout

`syscall` : make a system call without writing assembler code

- not usually used by programmers
- use to experiment and learn

```
char bytes[13] = "Hello, Zac!\n";

// argument 1 to syscall is the system call number, 1 is write
// remaining arguments are specific to each system call

// write system call takes 3 arguments:
//   1) file descriptor, 1 == stdout
//   2) memory address of first byte to write
//   3) number of bytes to write

syscall(1, 1, bytes, 12); // prints Hello, Zac! on stdout
```

Source code for hello_syscalls.c

Libc wrapper to print message to stdout

```c
char bytes[13] = "Hello, Zac!\n";

// write takes 3 arguments:
//    1) file descriptor, 1 == stdout
//    2) memory address of first byte to write
//    3) number of bytes to write
write(1, bytes, 12); // prints Hello, Zac! on stdout
```

Source code for hello_libc.c

stdio library to print message to stdout

```
char bytes[] = "Hello, Zac!\n";
printf("%s",bytes);
```

`printf` will do the write system call for us!

See more ways to print using `stdio.h` with `hello_stdio.c`

Source code for hello_stdio.c

Libc wrapper to open a file

`int open(char *pathname, int flags);`

- open file at **`pathname`**, according to **`flags`**
- **`flags`** is a bit-mask defined in **`<fcntl.h>`**

`int open(char *pathname, int flags, mode_t mode);`

- Use this version when potentially creating a new file
- **`mode`** is an octal number to give the file sensible user access permissions

if successful they return file descriptor (small non-negative int)
if unsuccessful they return **`-1`** and set **`errno`** to value indicating reason

Libc wrapper to open a file

Flag	Use
`O_RDONLY`	open for reading
`O_WRONLY`	open for writing
`O_APPEND`	append on each write
`O_RDWR`	open object for reading and writing
`O_CREAT`	create file if doesn't exist
`O_TRUNC`	truncate to size 0

flags can be combined e.g. `(O_WRONLY|O_CREAT)`

errno

- C library has an interesting way of returning error information
  - functions typically return **-1** to indicate error
  - and set errno to integer value indicating reason for error
  - you can think of **errno** as a global integer variable

- These integer values are **#define**-d in **errno.h**
  - see man errno for more information
  - **perror()** looks at **errno** and prints message with reason
  - **strerror()** converts **errno** to string describing reason for error

- To see all error codes type **errno -l** on command line

Libc wrapper to close a file

`int close(int fd);`

- release open file descriptor **`fd`**
- if successful, return **`0`**
- if unsuccessful, return **`-1`** and set errno
  - could be unsuccessful if **`fd`** is not an open file descriptor
  - e.g. if **`fd`** has already been closed

number of file descriptors may be limited (maybe to 1024)

- limited number of file open at any time, so use **`close()`**

Libc library wrapper for read system call

```
ssize_t read(int fd, void *buf, size_t count);
```

- read (up to) **`count`** bytes from **`fd`** into **`buf`**
  - **`buf`** should point to array of at least **`count`** bytes
  - read cannot check **`buf`** points to enough space
- if successful, number of bytes actually read is returned
- if no more bytes to read, **`0`** returned
- if error, **`-1`** is returned and **errno** set
- file descriptor **current position** in file is updated

Libc library wrapper for read system call

```
ssize_t write(int fd, const void *buf, size_t count);
```

- attempt to write **`count`** bytes from **`buf`** into stream identified by **`fd`**
- if successful, number of bytes actually written is returned
- if unsuccessful**, -1** returned and **errno is set**
- file descriptor **current position** in file is updated

Code Demo

open_read.c
open_write.c
open_issue.c

stdio.h - fopen()

```
FILE *fopen(const char *pathname, const char *mode);
```

- **mode** is string of 1 or more characters including:
  - r open file for reading.
  - w open file for writing
    truncated to 0 zero length if it exists
    created if does not exist
  - a open file for writing
    writes append to it if it exists
    created if does not exist

FILE *

fopen returns a **FILE** pointer

- FILE is an opaque struct - we can not access fields
- FILE stores file descriptor
- FILE may also for efficiency store buffered data

Demo: Modify open_read.c and open_write.c to use stdio.h

stdio.h fclose()

```
int fclose(FILE *stream);
```

- calls close
- number of streams open at any time is limited (to maybe 1024)
- writes unwritten buffered data to the stream

stdio.h reading and writing

```
int fgetc(FILE *stream) ;                   // read a byte
int fputc(int c, FILE *stream);             // write a byte

// read/write array of bytes (fgetc/fputc + loop often better)
size_t fread(void *ptr, size_t size, size_t nmemb,
             FILE *stream);

size_t fwrite(const void *ptr, size_t size, size_t nmemb,
              FILE *stream);
```

stdio.h reading and writing text only

```
char *fputs(char *s, FILE *stream);              // write a string
char *fgets(char *s, int size, FILE *stream);    // read a line
```

//formatted input/output

```
int fscanf(FILE *stream, const char *format, ...);
int fprintf(FILE *stream, const char *format, ...);
```

These functions can not be used for binary data as they may contain zero bytes

- can use to read text (ASCII/Unicode)
- can **not** use to read a *jpg* for example

stdio.h convenience functions

To read/write to stdin/stdout

```
int getchar(void);                  // fgetc(stdin)
int putchar(int c);                 // fputc(c, stdout)
int puts(char *s);                  // fputs(s, stdout)
int scanf(char *format, ...);       // fscanf(stdin, format, ...)
int printf(char *format, ...);      // fprintf(stdout, format, ...)
```

These should never be used: security vulnerability, buffer overflow

```
char *gets(char *s);
scanf("%s", array);                 // Ok in general.
                                    // Don't use with %s
```

stdio.h - IO to strings

`stdio.h` provides useful functions which operate on strings

```
// like scanf, but input comes from char array str
int sscanf(const char *str, const char *format, ...);

// like printf, but output goes to char array str
// handy for creating strings passed to other functions
// size contains size of str
// Do not use similar function sprintf as it is a security vulnerability
int snprintf(char *str, size_t size, const char *format, ...);
```

Exercise

Implement linux **cp** command

1. byte at a time stdio.h
2. using fgets and fprintf/fputs - what is the problem with this approach?

We also have implementations using syscall and libc

Which is the best approach?

Demo: fgetc return type bug

- To make a buggy version:
  - Use char instead of int for fgetc (this creates bugs with getchar too)

- Reminder: getchar and fgetc return int
  - Legal values they can return -1..255. (257 possible values)
  - This can’t fit in signed char or unsigned char!

- signed char (or char on our system) can store -1 and detect EOF,
  - but valid byte value 0xFF gets mistaken for EOF

- unsigned char can’t store -1 and can’t detect EOF

Demo: cp using fgets and fprintf

- Using fgets and fprintf to copy a file
- Seems to work fine when copying text files BUT
  - Breaks for binary files with 0x00 bytes
  - They are interpreted as end of string ‘\0’ character

Reminder: only use fgets, fprintf, fscanf, or fputs for text

IO Performance & Buffering libc vs stdio

Let's compare our implementations of cp!

```
$ clang -O3 cp_x.c -o cp_x
$ dd bs=1M count=10 </dev/urandom >random_file
10485760 bytes (10 MB, 10 MiB) copied, 0.183075 s, 57.3 MB/s
$ time ./cp_x random_file random_file_copy
```

Can we get any insights from strace?

```
$strace ./cp_x random_file random_file_copy
```

Compare:

Linux cp command, cp_fgetc_one_byte.c, cp_libc_one_byte.c, cp_libc.c

stdio.h buffering for efficiency

- **Goal:** reduce number of system calls (expensive)
- **Reading:**
  - Uses a **read** system call to fill whole buffer
  - subsequent reads get bytes from the buffer
  - does not do another **read** system call till it runs out of data in the buffer
- **Writing**:
  - Delays calls to **write** system call by storing data in buffer (array) instead
  - calls **write** system call only when
    - buffer is full,
    - file is closed,
    - fflush is called
    - a newline is encountered for output to terminal

fflush stdio buffers

You can manually flush stdio buffers by using:

```
int fflush(FILE *stream);
```

For example

- this would force a write system call to stdout and empty the output buffer
  `fflush(stdout);`
- Can also be used for files that have been opened for writing.
- Should not be used for stdin or files opened for read only.

Seeking with libc system call wrapper

```
off_t lseek(int fd, off_t offset, int whence);
```

- change the **current position** in given stream
- **offset** is in bytes, and can be negative
- **whence** can be one of
    - SEEK_SET : set **offset** from start of file
    - SEEK_CUR: set file **offset** from current position
    - SEEK_END: set file **offset** from end of file

- seeking beyond end of file leaves a gap which reads as 0's
- seeking back beyond start of file sets position to start of file

Seeking with stdio.h

`int fseek(FILE *stream, long offset, int whence);`

- is stdio equivalent to **`lseek()`** except:
  - requires a FILE * input instead of int file descriptor
  - influences stdio buffers
  - returns 0 or -1 for error

```
fseek(stream, 42, SEEK_SET); // move to after 42nd byte
fseek(stream, 58, SEEK_CUR); // 58 bytes forward from current position
fseek(stream, -7, SEEK_CUR);  // 7 bytes backward from current position
fseek(stream, -1, SEEK_END);  // move to before last byte in file
```

`long ftell(FILE *stream);` //return current file position

Demo code fseek.c and fuzz.c and advanced example: create_gigantic_file.c

What we learnt today

- System calls relate to files:
  - open, close, read, write, lseek
- Equivalent stdio portable functions:
  - fopen, fclose, fgetc, fputc etc. fseek

Next Lecture

- File Systems:
  - File metadata
    - Permissions
    - system call stat
  - Hard Links and Symbolic Links
  - Working with directories

Feedback Please!

Your feedback is valuable!

If you have any feedback from today's lecture, please follow the link below or use the QR Code.

Please remember to keep your feedback constructive, so I can action it and improve your learning experience.

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