COMP1521 23T1 — Files

https://www.cse.unsw.edu.au/~cs1521/223T12T3/

Operating system - What Does it Do.

- Operating system sits between the user and the hardware.
- Operating system effectively provides a virtual machine to each user.
- This virtual machine is much simpler than a real machine
  - much easier for user to write code
  - difficult (bug-prone) code implemented by operating system
- The virtual machine interface can stay the same across different hardware.
  - much easier for user to write portable code which works on different hardware
- Operating systems can coordinate/share access to resources between users.
- Operating systems can provide privileges/security.

Operating System - What Does it Need from Hardware.

- needs hardware to provide a **privileged** mode
  - code running in privileged mode can access all hardware and memory
  - code running in privileged mode has unlimited access to memory
- needs hardware to provide a **non-privileged** mode which:
  - code running in non-privileged mode can not access hardware directly
  - code running in non-privileged mode has limited access to memory
  - provides mechanism to make requests to operating system
- operating system (kernel) code runs in **privileged** mode
- operating system runs user code in **non-privileged** mode
  - with memory access restrictions so user code can only memory allocated to it
- user code can make requests to operating system called **system calls**
  - a system call transfers execution to operating system code in privileged mode
  - at completion of request operating system (usually) returns execution back to user code in non-privileged mode

System Call - What is It

- system call allow programs to request hardware operations
- system call transfers execution to OS 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
- different operating system have different system calls
  - e.g Linux system calls very different Windows system calls
- Linux provides 400+ system calls
- examples of operations that might be provided by system call:
  - read or write bytes to a file
  - request more memory
  - create a process (run a program)
  - terminate a process
  - send information via a network

System Calls in mipsy

- `mipsy` provides a virtual machine which can execute MIPS programs
- `mipsy` also provides a tiny operating system
- small number of `mipsy` system calls for I/O and memory allocation
- access is via the **`syscall`** instruction
  - MIPS programs running on real hardware also use **`syscall`**
  - on Linux **`syscall`**, passes execution to operating system code
  - Linux operating system code carries out request specified in `$v0` and `$a0`
- `mipsy` system calls are designed for students writing tiny MIPS programs without library functions
  - e.g system call **`1`** - print an integer, system call **`5`** read an integer
- system calls on real operating systems are more general
  - e.g. system call might be read ***n*** bytes, write ***n*** bytes
  - users don't normally access system calls directly
  - users call library functions e.g. **`printf`** & **`fgets`** which make system calls (often via other functions)

Experimenting with Linux System Calls

- like `mipsy` every Linux system call has a number, e.g write bytes to a file is system call **2**
- 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_stat 4
...
#define __NR_pidfd_getfd 438
#define __NR_faccessat2 439
#define __NR_process_madvise 440
```

System Calls to Manipulate files

Some important Unix system calls:

- **`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`** — stop using a **file descriptor**
- **`4`** — **`stat`** — get file system metadata for a pathname
- **`8`** — **`lseek`** — move **file descriptor** to a specified offset within a file
- above system calls manipulate files as a *stream of bytes* accessed via a ***file descriptor***
  - **file descriptors** are small integers
  - really index to a per-process array maintained by operating system
- On Unix-like systems: a ***file*** is sequence (array) of zero or more bytes.
  - no meaning for bytes associated with file
    - file metadata doesn't record that it is e.g. ASCII, MP4, JPG, ...
    - Unix-like files are just bytes

Using system calls to copy a file #1 - opening files

- the C function **syscall** allows to make a Linux system call without writing assembler
  - **syscall** itself uis written partly/entirely in assembler
    - e.g.: https://code.woboq.org/userspace/glibc/sysdeps/unix/sysv/linux/x86_64/syscall.S.html
- **syscall** is not normally used by programmers in regular C code
  - most system calls have their own C wrapper functiont, these wrapper function are safer & more convenient
  - e.g. the write system call has a wrapper C function called **write**
- we only use **syscall** to experiment & learn

```c
// cp <file1> <file2> with syscalls and no error handling
int main(int argc, char *argv[]) {
    // system call number 2 is open, takes 3 arguments:
    //   1) address of zero-terminated string containing file pathname
    //   2) bitmap indicating whether to write, read, ... file
    //      O_WRONLY | O_CREAT == 0x41 == write to file, creating if necessary
    //   3) permissions if file will be newly created
    //      0644 == readable to everyone, writeable by owner
    long read_file_descriptor  = syscall(2, argv[1], O_RDONLY,           0);
    long write_file_descriptor = syscall(2, argv[2], O_WRONLY | O_CREAT, 0644);
```

source code for cp_syscalls.c

Using system calls to copy a file #2 - copying the bytes

```
while (1) {
    // system call number 0 is read -  takes 3 arguments:
    //   1) file descriptor
    //   2) memory address to put bytes read
    //   3) maximum number of bytes read
    // returns number of bytes actually read
    char bytes[4096];
    long bytes_read = syscall(0, read_file_descriptor, bytes, 4096);
    if (bytes_read <= 0) {
        break;
    }
    // system call number 1 is write - takes 3 arguments:
    //   1) file descriptor
    //   2) memory address to take bytes from
    //   3) number of bytes to written
    // returns number of bytes actually written
    syscall(1, write_file_descriptor, bytes, bytes_read);
}
```

source code for cp_syscalls.c

C Library Wrappers for System Calls

- On Unix-like systems there are C library functions corresponding to each system call,
  - e.g. `open`, `read`, `write`, `close`
  - the **`syscall`** function is not used in normal coding
- These functions are not portable
  - C used on many non-Unix operating systems with different system calls
- POSIX standardizes a few of these functions
  - some non-Unix systems provide implementations of these functions
- but better to use functions from standard C library, available everywhere
  - e.g fopen, fgets, fputc from **`stdio.h`**
  - on Unix-like systems these will call `open`, `read`, `write`
  - on other platforms, will call other low-level functions
- but sometimes we need to use lower level non-portable functions
  - e.g. a database implementation need more control over I/O operations

Extra Types for File System Operations

Unix-like (POSIX) systems add some extra file-system-related C types in these include files:

```
#include <sys/types.h>
#include <sys/stat.h>
```

- **`off_t`** — offsets within files
  - typically **`int64_t`** - signed to allow backward references
- **`size_t`** — number of bytes in some object
  - typically **`uint64_t`** - unsigned since objects can't have negative size
- **`ssize_t`** — sizes of read/written bytes
  - typically **`uint64_t`** - similar to **`size_t`**, but signed to allow for error values
- **`struct stat`** — file system object metadata
  - stores information *about* file, not its contents
  - requires other types: **`ino_t`**, **`dev_t`**, **`time_t`**, **`uid_t`**, ...

C library wrapper for open system call

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

- open file at **`pathname`**, according to **`flags`**
- **`flags`** is a bit-mask defined in `<fcntl.h>`
  - `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)`
- if successful, return file descriptor (small non-negative `int`)
- if unsuccessful, return **`-1`** and set **`errno`** to value indicating reason

errno - why did that system call fail?

- 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
- these integer values are `#define`-d in **`errno.h`**
- see **`man errno`** for more infomation
- convenient function **`perror()`** looks at `errno` and prints message with reason
- or **`strerror()`** converts `errno` integer value to string describing reason for error
- **`errno`** looks like **`int`** global variable
  - C library designed before multi-threaded systems in common use
  - `errno` can not really be a global variable on multi-threaded platform
  - each thread needs a separate **`errno`**
  - clever workaround: **`errno #define`**d to function which returns address of variable for this thread

C 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 does (can) not check **buf** points to enough space
- if successful, number of bytes actually read is returned
- **`0`** returned, if no more bytes to read
- **`-1`** returned if error and **`errno`** set to reason
- associated with a file descriptor is a ***current position*** in file
- next call to **read()** will return next bytes from file
- repeated calls to reads will yield entire contents of file
- can also modify this current position with **`lseek()`**

C library wrapper for write system call

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

- attempt to write **count** bytes from *buf* into

  stream identified by file descriptor **`fd`**
- if successful, number of bytes actually written is returned
- if unsuccessful, returns `-1` and set **`errno`**
- does (can) not check **buf** points to **count** bytes of data
- associated with a file descriptor is a ***current position*** in file
- next call to **write** will follow bytes already written
- file often created by repeated calls to write
- can also modify this current position with `lseek`

Hello write!

```
// hello world implemented with libc
#include <unistd.h>
int main(void) {
    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
    return 0;
}
```

source code for hello_libc.c

Using libc system call wrappers to copy a file

```
// cp <file1> <file2> implemented with libc and no error handling
int main(int argc, char *argv[]) {
    // open takes 3 arguments:
    //   1) address of zero-terminated string containing pathname of file to open
    //   2) bitmap indicating whether to write, read, ... file
    //   3) permissions if file will be newly created
    //      0644 == readable to everyone, writeable by owner
    int read_file_descriptor = open(argv[1], O_RDONLY);
    int write_file_descriptor = open(argv[2], O_WRONLY | O_CREAT, 0644);
```

source code for cp_libc.c

Using libc system call wrappers to copy a file

```
while (1) {
    // read takes 3 arguments:
    //   1) file descriptor
    //   2) memory address to put bytes read
    //   3) maximum number of bytes read
    // returns number of bytes actually read
    char bytes[4096];
    ssize_t bytes_read = read(read_file_descriptor, bytes, 4096);
    if (bytes_read <= 0) {
        break;
    }
    // write takes 3 arguments:
    //   1) file descriptor
    //   2) memory address to take bytes from
    //   3) number of bytes to written
    // returns number of bytes actually written
    write(write_file_descriptor, bytes, bytes_read);
}
// good practice to close file descriptions as soon as finished using them
// not necessary needed here as program about to exit
close(read_file_descriptor);
close(write_file_descriptor);
```

source code for cp_libc.c

C library wrapper for close system call

```
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()`**

An aside: removing a file e.g. via `rm`

- removes the file's entry from a directory
- but the file (inode and data) persist until
    - all references to the file (inode) from other directories are removed
    - all processes accessing the file `close()` their file descriptor
- after this, the operating system reclaims the space used by the files

C library wrapper for lseek system call

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

- change the *current position* in stream indicated by **fd**
- **offset** is in units of bytes, and can be negative
- **whence** can be one of …
  - SEEK_SET — set file position to **offset** from start of file
  - SEEK_CUR — set file position to **offset** from current position
  - SEEK_END — set file position to **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
- for example:

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

stdio.h - C Standard Library I/O Functions

- system calls provide operations to manipulate files.
- libc provides a non-portable low-level API to manipulate files
- `stdio.h` provides a portable higher-level API to manipulate files.
- `stdio.h` is part of standard C library
- available in every C implementation that can do I/O
- `stdio.h` functions are portable, convenient & efficient
- use `stdio.h` functions for file operations unless you have a good reason not to
  - e.g .program with special I/O requirements like a database implementation
- on Unix-like systems they will call open()/read()/write()/...
  - but with buffering for efficiency

stdio.h - fopen()

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

- **fopen()** is `stdio.h` equivalent to **open()**
- **mode** is string of 1 or more characters including:
  - **r** open text file for reading.
  - **w** open text file for writing truncated to 0 zero length if it exists created if does not exist
  - **a** open text file for writing writes append to it if it exists created if does not exist
- fopen returns a **FILE *** pointer
  - **FILE** is `stdio.h` equivalent to file descriptors
  - **FILE** is an opaque struct - we can not access fields
  - **FILE** stores file descriptor
  - **FILE** may also for efficiency store buffered data,

stdio.h - fclose()

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

- **`fclose()`** is `stdio.h` equivalent to **`close()`**
- call **`fclose()`** as soon as finished with stream
- number of streams open at any time is limited (to maybe 1024)
- stdio functions for efficiency may delay calling **`write()`**
  - only calls **`write()`** when it has enough data (perhaps 4096 bytes)
  - also calls **`write()`** if needed when program exits or **`fclose()`**
- so last data may not be written until **`fclose`** or program exit
  - good practice to call **`fclose`** as soon as finished using stream
- **`fflush(stream)`** forces any buffered data to be written

stdio.h - read and writing

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

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

int fscanf(FILE *stream, const char *format, ...)  // formatted input
int fprintf(FILE *stream, const char *format, ...) // formatted output

// 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);
```

- fputs/fgets, fscanf/fprintf can not be used for binary data because may contain zero bytes
  - can use text (ASCII/Unicode) but can not use to e.g. read a *jpg*
- scanf/fscanf/sscanf often avoided in serious code
  - but fine while learning to code

stdio.h - convenience functions for stdin/stdout

- as we often read/write to stdin/stdout `stdio.h` provides convenience functions, we can use:

```
int getchar()                // fgetc(stdin)
int putchar(int c)           // fputc(c, stdin)

int puts(char *s)            // fputs(s,stdout)

int scanf(char *format, ...)   // fscanf(stdin, format, ...)
int printf(char *format, ...)  // fprintf(stdout, format, ...)

char *gets(char *s);         // NEVER USE - major security vulnerability
                             // string may overflow array

// also NEVER USE %s with scanf - similarly major security vulnerability
scanf("%s", array);
```

stdio.h - using fputc to output bytes

```c
char bytes[] = "Hello, stdio!\n"; // 15 bytes
// write 14 bytes so we don't write (terminating) 0 byte
for (int i = 0; i < (sizeof bytes) - 1; i++) {
    fputc(bytes[i], stdout);
}
// or as we know bytes is 0-terminated
for (int i = 0; bytes[i] != '\0'; i++) {
    fputc(bytes[i], stdout);
}
// or if you prefer pointers
for (char *p = &bytes[0]; *p != '\0'; p++) {
    fputc(*p, stdout);
}
```

source code for hello_stdio.c

stdio.h - using fputs, fwrite & fprintf to output bytes

```c
char bytes[] = "Hello, stdio!\n"; // 15 bytes
```

```c
// fputs relies on bytes being 0-terminated
fputs(bytes, stdout);
// write 14 1 byte items
fwrite(bytes, 1, (sizeof bytes) - 1, stdout);
// %s relies on bytes being 0-terminated
fprintf(stdout, "%s", bytes);
```

source code for hello_stdio.c

stdio.h - creating a file

```c
// create file "hello.txt" containing 1 line: Hello, Zac!
#include <stdio.h>
#include <stdlib.h>
int main(int argc, char *argv[]) {
    FILE *output_stream = fopen("hello.txt", "w");
    if (output_stream == NULL) {
        perror("hello.txt");
        return 1;
    }
    fprintf(output_stream, "Hello, Zac!\n");
    // fclose will flush data to file, best to close file ASAP
    // optional here as fclose occurs automatically on exit
    fclose(output_stream);
    return 0;
}
```

source code for create_file_fopen.c

stdio.h - using fgetc to copy a file

```c
FILE *input_stream = fopen(argv[1], "r");
if (input_stream == NULL) {
    perror(argv[1]);  // prints why the open failed
    return 1;
}
FILE *output_stream = fopen(argv[2], "w");
if (output_stream == NULL) {
    perror(argv[2]);
    return 1;
}
int c; // not char!
while ((c = fgetc(input_stream)) != EOF) {
    fputc(c, output_stream);
}
fclose(input_stream);  // optional here as fclose occurs
fclose(output_stream); // automatically on exit
```

source code for cp_fgetc.c

Copying One Byte Per Time with System Calls

```c
// copy bytes one at a time from  pathname passed as
// command-line argument 1 to pathname given as argument 2
int read_file_descriptor = open(argv[1], O_RDONLY);
int write_file_descriptor = open(argv[2], O_WRONLY | O_CREAT, 0644);
while (1) {
    char bytes[1];
    ssize_t bytes_read = read(read_file_descriptor, bytes, 1);
    if (bytes_read <= 0) {
        break;
    }
    write(write_file_descriptor, bytes, 1);
}
```

source code for cp_libc_one_byte.c

I/O Performance & Buffering - Copying One Byte Per Time

```
$ clang -O3 cp_libc_one_byte.c -o cp_libc_one_byte
$ 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_libc_one_byte random_file random_file_copy
real  0m5.262s
user  0m0.432s
sys   0m4.826s
```

- much slower than previous version which copies 4096 bytes at a time

```
$ clang -O3 cp_libc.c -o cp_libc
$  time ./cp_libc random_file random_file_copy
real  0m0.008s
user  0m0.001s
sys   0m0.007s
```

- main reason - system calls are expensive

I/O Performance & Buffering - stdio Copying 1 Byte Per Time

```
$ clang -O3 cp_fgetc.c -o cp_fgetc
$ time ./cp_fgetc random_file random_file_copy
real   0m0.059s
user   0m0.042s
sys    0m0.009s
```

- at the user level copies 1 byte at time using `fgetc`/`fputc`
- much faster that coping 1 byte at time using `read`/`write`
- little slower than coping 4096 bytes at time using `read`/`write`
- how?

I/O Performance & Buffering - stdio buffering

- assume stdio buffering size (`BUFSIZ`) is `4096` (typical)
- first **`fgetc()`** calls requests 4096 bytes via **`read()`**
  - returns 1 byte stores remaining 4095 bytes in an array, the ***input buffer***
- next 4095 **`fgetc()`** calls return a byte from (***input buffer***) and do not to call **`read()`**
- 4097th **`fgetc()`** call requests 4096 bytes via **`read()`**
- returns 1 byte, stores remaining 4095 bytes in the (***input buffer***)
- and so on

- first 4095 **`fputc()`** calls put bytes in an array, the (***output buffer***)
- 4096th **`fputc()`** calls **`write()`** for all 4096 bytes in the ***output buffer***
- and so on
- ***output buffer**** emptied by **`exit`** or `main` returning
- program can explicitly force empty of output buffer with **`fflush()`** call

stdio.h - other operations

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

- **fseek()** is stdio equivalent to **`lseek()`**, just like lseek():
- **`offset`** is in units of bytes, and can be negative
- **`whence`** can be one of ...
  - SEEK_SET — set file position to **`offset`** from start of file
  - SEEK_CUR — set file position to **`offset`** from current position
  - SEEK_END — set file position to **`offset`** from end of file
- for example:

```
fseek(stream, 42, SEEK_SET); // move to after 42nd byte in file
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
```

Using fseek to read the last byte then the first byte of a file

```c
FILE *input_stream = fopen(argv[1], "rb");
// move to a position 1 byte from end of file
// then read 1 byte
fseek(input_stream, -1, SEEK_END);
printf("last byte of the file is 0x%02x\n", fgetc(input_stream));
// move to a position 0 bytes from start of file
// then read 1 byte
fseek(input_stream, 0, SEEK_SET);
printf("first byte of the file is 0x%02x\n", fgetc(input_stream));
```

source code for fseek.c

- NOTE: important error checking is missing above

Using fseek to read bytes in the middle of a file

```
// move to a position 41 bytes from start of file
// then read 1 byte
fseek(input_stream, 41, SEEK_SET);
printf("42nd byte of the file is 0x%02x\n", fgetc(input_stream));
// move to a position 58 bytes from current position
// then read 1 byte
fseek(input_stream, 58, SEEK_CUR);
printf("100th byte of the file is 0x%02x\n", fgetc(input_stream));
```

source code for fseek.c

- NOTE: important error checking is missing above

Using fseek to change a random file bit

```
FILE *f = fopen(argv[1], "r+");     // open for reading and writing
fseek(f, 0, SEEK_END);              // move to end of file
long n_bytes = ftell(f);            // get number of bytes in file
srandom(time(NULL));                // initialize random number
                                    // generator with current time
long target_byte = random() % n_bytes; // pick a random byte
fseek(f, target_byte, SEEK_SET);  // move to byte
int byte = fgetc(f);              // read byte
int bit = random() % 8;           // pick a random bit
int new_byte = byte ^ (1 << bit); // flip the bit
fseek(f, -1, SEEK_CUR);           // move back to same position
fputc(new_byte, f);               // write the byte
fclose(f);
```

source code for fuzz.c

- random changes to search for errors/vulnerabilities called fuzzing

Using fseek to create a gigantic sparse file (advanced topic)

```c
// Create a 16 terabyte sparse file
// https://en.wikipedia.org/wiki/Sparse_file
// error checking omitted for clarity
#include <stdio.h>
int main(void) {
    FILE *f = fopen("sparse_file.txt", "w");
    fprintf(f, "Hello, Andrew!\n");
    fseek(f, 16L * 1000 * 1000 * 1000 * 1000, SEEK_CUR);
    fprintf(f, "Goodbye, Andrew!\n");
    fclose(f);
    return 0;
}
```

source code for create_gigantic_file.c

- almost all the 16Tb are zeros which the file system doesn't actually store

stdio.h - I/O to strings

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

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

// snprintf is like printf, but output goes to char array str
// handy for creating strings passed to other functions
// size contains size of str
int snprintf(char *str, size_t size, const char *format, ...);

// also sprintf - more convenient -  but can overflow str
// major security vulnerability -  DO NOT USE
int sprintf(char *str, const char *format, ...); // DO NOT USE
```

What Really are Files and Directories?

- ***file systems*** manage persistent stored data e.g. on magnetic disk or SSD
- On Unix-like systems:
  - a ***file*** is sequence (array) of zero or more bytes.
  - no meaning for bytes associated with file
    - file metadata doesn't record that it is e.g. ASCII, MP4, JPG, ...
    - Unix-like files are just bytes
  - a ***directory*** is an object containing zero or more files or directories.
- file systems maintain metadata for files & directories, e.g. permissions

Unix-like Files & Directories

- Unix-like filenames are sequences of 1 or more bytes.
  - filenames can contain any byte except **`0x00`** and **`0x2F`**
  - **`0x00`** bytes (ASCII '\0') used to terminate filenames
  - **`0x2F`** bytes (ASCII '/') used to separate components of pathnames.
  - maximum filename length, depends on file system, typically 255
- Two filenames can not be used - they have a special meaning:
  - **`.`** current directory
  - **`..`** parent directory
- Some programs (shell, ls) treat filenames starting with **`.`** specially.
- Unix-like directories are sets of files or directories

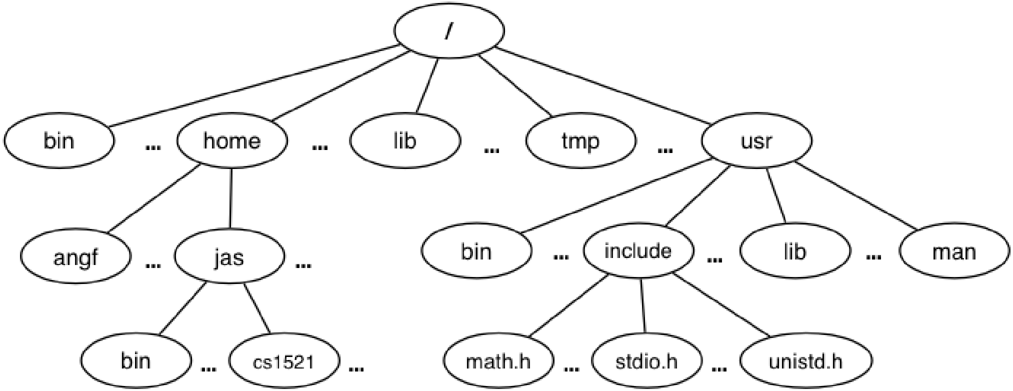
Unix/Linux Pathnames

- Files & directories accessed via pathnames, e.g: `/home/z5555555/lab07/main.c`
- *absolute* pathnames start with a leading **/** and give full path from root
  - e.g. `/usr/include/stdio.h`, `/cs1521/public_html/`
- every process (running program) has a *current working directory* (CWD)
  - this is an absolute pathname
- shell command pwd prints *current working directory*
- *relative* pathname do not start with a leading **/**
  - e.g. `../../another/path/prog.c`, `./a.out`, `main.c`
- *relative* pathnames appended to *current working directory* of process using them
- Assume process *current working directory* is `/home/z5555555/lab07/`
  - `main.c` translated to absolute path `/home/z5555555/lab07/main.c`
  - `../a.out` translated to absolute path `/home/z5555555/lab07/../a.out`
  - which is equivalent to absolute path `/home/z5555555/a.out`

Everything is a File

- Originally files only managed data stored on a magnetic disk.
- Unix philosophy is: ***Everything is a File***.
- File system used to access:
  - files
  - directories (folders)
  - storage devices (disks, SSD, ...)
  - peripherals (keyboard, mouse, USB, ...)
  - system information
  - inter-process communication
  - network
  - ...

Unix/Linux File System



- Unix/Linux file system is tree-like
- Exception: if you follow symbolic links it is a *graph*.
  - and you may infinitely loop attempting to traverse a file system
  - but only if you follow symbolic links

File Metadata

Metadata for file system objects is stored in ***inodes***, which hold

- location of file contents in file systems
- file type (regular file, directory, ...)
- file size in bytes
- file ownership
- file access permissions - who can read, write, execute the file
- timestamps - times of file was created, last accessed, last updated

File system implementations often add complexity to improve performance

- e.g. very small files might be stored in an inode itself

File Inodes

- unix-like file systems effectively have a large array of inodes containg metadata
- an inode's index in this array is its ***inode-number*** (or ***i-number***)
- inode-number uniquely identify files within a filesystem
  - just a zid uniquely identifies a student within UNSW
- directories are effectively a list of (name, inode-number) pairs
- **`ls -i`** prints **inode-numbers**

```
$ ls -i file.c
109988273 file.c
$
```

- note there is usually more than one file systems mounted on a Unix-like system
  - each file-systems has a separate set of **inode-numbers**
  - files on different file-systems could have the same **inode-number**

File Access: Behind the Scenes

Access to files by name proceeds (roughly) as...

- open directory and scan for *name*
- if not found, “No such file or directory”
- if found as (*name*,`inumber`), access inode table `inodes[inumber]`
- collect file metadata and...
  - check file access permissions given current user/group
    - if don’t have required access, “Permission denied”
  - collect information about file’s location and size
  - update access timestamp
- use data in inode to access file contents

Hard Links & Symbolic Links

File system *links* allow multiple paths to access the same file

- Hard links
  - multiple names referencing the same file (inode)
  - the two entries must be on the same filesystem
  - all hard links to a file have equal status
  - file destroyed when last hard link removed
  - can not create a (extra) hard link to directories
- Symbolic links (symlinks)
  - point to another path name
  - acessing the symlink (by default) accesses the file being pointed to
  - symbolic link can point to a directory
  - symbolic link can point to a pathname on another filesystems
  - symbolic links don’t have permissions (just a pointer)

Hard Links & Symbolic Links

```
$ echo 'Hello Andrew' >hello
$ ln hello hola       # create hard link
$ ln -s hello selamat # create symbolic link
$ ls -l hello hola selamat
-rw-r--r-- 2 andrewt 13 Oct 23 16:18 hello
-rw-r--r-- 2 andrewt 13 Oct 23 16:18 hola
lrwxrwxrwx 1 andrewt  5 Oct 23 16:20 selamat -> hello
$ cat hello
Hello Andrew
$ cat hola
Hello Andrew
$ cat selamat
Hello Andrew
```

C library wrapper for stat system call

```
int stat(const char *pathname, struct stat *statbuf)
```

- returns metadata associated with **pathname** in **statbuf**
- metadata returned includes:
    - inode number
    - type (file, directory, symbolic link, device)
    - size of file in bytes (if it is a file)
    - permissions (read, write, execute)
    - times of last access/modification/status-change
- returns `-1` and sets **`errno`** if metadata not accessible

```
int fstat(int fd, struct stat *statbuf)
```

- same as `stat()` but gets data via an open file descriptor

```
int lstat(const char *pathname, struct stat *statbuf)`
```

- same as `stat()` but doesn't follow symbolic links

definition of struct stat

```c
struct stat {
  dev_t     st_dev;         /* ID of device containing file */
  ino_t     st_ino;         /* Inode number */
  mode_t    st_mode;        /* File type and mode */
  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 ID (if special file) */
  off_t     st_size;        /* Total size, in bytes */
  blksize_t st_blksize;     /* Block size for filesystem I/O */
  blkcnt_t  st_blocks;      /* Number of 512B blocks allocated */
  struct timespec st_atim;  /* Time of last access */
  struct timespec st_mtim;  /* Time of last modification */
  struct timespec st_ctim;  /* Time of last status change */
};
```

st_mode field of struct stat

`st_mode` is a bitwise-or of these values (& others):

```
S_IFLNK    0120000   symbolic link
S_IFREG    0100000   regular file
S_IFBLK    0060000   block device
S_IFDIR    0040000   directory
S_IFCHR    0020000   character device
S_IFIFO    0010000   FIFO
S_IRUSR    0000400   owner has read permission
S_IWUSR    0000200   owner has write permission
S_IXUSR    0000100   owner has execute permission
S_IRGRP    0000040   group has read permission
S_IWGRP    0000020   group has write permission
S_IXGRP    0000010   group has execute permission
S_IROTH    0000004   others have read permission
S_IWOTH    0000002   others have write permission
S_IXOTH    0000001   others have execute permission
```

Using stat

```c
struct stat s;
if (stat(pathname, &s) != 0) {
    perror(pathname);
    exit(1);
}
printf("ino =  %10ld # Inode number\n", s.st_ino);
printf("mode = %10o # File mode \n", s.st_mode);
printf("nlink =%10ld # Link count \n", (long)s.st_nlink);
printf("uid =  %10u # Owner uid\n", s.st_uid);
printf("gid =  %10u # Group gid\n", s.st_gid);
printf("size = %10ld # File size (bytes)\n", (long)s.st_size);
printf("mtime =%10ld # Modification time (seconds since 1/1/70)\n",
       (long)s.st_mtime);
```

source code for stat.c

mkdir

```
int mkdir(const char *pathname, mode_t mode)
```

- create a new directory called **pathname** with permissions **mode**
- if **pathname** is e.g. `a/b/c/d`
  - all of the directories `a`, `b` and `c` must exist
  - directory `c` must be writeable to the caller
  - directory `d` must not already exist
- the new directory contains two initial entries
  - `.` is a reference to itself
  - `..` is a reference to its parent directory
- returns 0 if successful, returns -1 and sets `errno` otherwise

for example:

```
    mkdir("newDir", 0755);
```

Example of using mkdir to create directories

```c
#include <stdio.h>
#include <sys/stat.h>
// create the directories specified as command-line arguments
int main(int argc, char *argv[]) {
    for (int arg = 1; arg < argc; arg++) {
        if (mkdir(argv[arg], 0755) != 0) {
            perror(argv[arg]);  // prints why the mkdir failed
            return 1;
        }
    }
    return 0;
}
```

source code for mkdir.c

Other useful Linux (POSIX) functions

```
chmod(char *pathname, mode_t mode) // change permission of file/...

unlink(char *pathname) // remove a file/directory/...

rename(char *oldpath, char *newpath) // rename a file/directory

chdir(char *path)  // change current working directory

getcwd(char *buf, size_t size) // get current working directory

link(char *oldpath, char *newpath) // create hard link to a file

symlink(char *target, char *linkpath) // create a symbolic link
```

file permissions

- file permissions are separated into three types:
  - **read * - permission to get bytes of file
  - **write* - permission to change bytes of file
  - **execute* - permission to execute file
- read/write/execute often represented as bits of an octal digit
- file permissions are specified for 3 groups of users:
  - **owner** - permissions for the file owner
  - **group** - permissions for users in the group of the file
  - **other** - permissions for any other user

changing file permissions

```c
// first argument is mode in octal
mode_t mode = strtol(argv[1], &end, 8);
// check first argument was a valid octal number
if (argv[1][0] == '\0' || end[0] != '\0') {
    fprintf(stderr, "%s: invalid mode: %s\n", argv[0], argv[1]);
    return 1;
}
for (int arg = 2; arg < argc; arg++) {
    if (chmod(argv[arg], mode) != 0) {
        perror(argv[arg]);  // prints why the chmod failed
        return 1;
    }
}
```

source code for chmod.c

removing files

```c
// remove the specified files
int main(int argc, char *argv[]) {
    for (int arg = 1; arg < argc; arg++) {
        if (unlink(argv[arg]) != 0) {
            perror(argv[arg]);  // prints why the unlink failed
            return 1;
        }
    }
    return 0;
}
```

source code for rm.c

```
$ dcc rm.c
$ ./a.out rm.c
$ ls -l rm.c
ls: cannot access 'rm.c': No such file or directory
```

renaming a file

```
// rename the specified file
int main(int argc, char *argv[]) {
    if (argc != 3) {
        fprintf(stderr, "Usage: %s <old-filename> <new-filename>\n",
                argv[0]);
        return 1;
    }
    char *old_filename = argv[1];
    char *new_filename = argv[2];
    if (rename(old_filename, new_filename) != 0) {
        fprintf(stderr, "%s rename %s %s:", argv[0], old_filename,
                new_filename);
        perror("");
        return 1;
    }
    return 0;
}
```

source code for rename.c

cd-ing up one directory at a time

```c
// use repeated chdir("..") to climb to root of the file system
char pathname[PATH_MAX];
while (1) {
    if (getcwd(pathname, sizeof pathname) == NULL) {
        perror("getcwd");
        return 1;
    }
    printf("getcwd() returned %s\n", pathname);
    if (strcmp(pathname, "/") == 0) {
        return 0;
    }
    if (chdir("..") != 0) {
        perror("chdir");
        return 1;
    }
}
```

source code for getcwd.c

making a 1000-deep directory (advanced)

```c
for (int i = 0; i < 1000;i++) {
    char dirname[256];
    snprintf(dirname, sizeof dirname, "d%d", i);
    if (mkdir(dirname, 0755) != 0) {
        perror(dirname);
        return 1;
    }
    if (chdir(dirname) != 0) {
        perror(dirname);
        return 1;
    }
    char pathname[1000000];
    if (getcwd(pathname, sizeof pathname) == NULL) {
        perror("getcwd");
        return 1;
    }
    printf("\nCurrent directory now: %s\n", pathname);
}
```

source code for nest_directories.c

creating 1000 hard links to a file - creating the file (advanced)

```c
int main(int argc, char *argv[]) {
    char pathname[256] = "hello.txt";
    // create a target file
    FILE *f1;
    if ((f1 = fopen(pathname, "w")) == NULL) {
        perror(pathname);
        return 1;
    }
    fprintf(f1, "Hello Andrew!\n");
    fclose(f1);
```

source code for many_links.c

creating 1000 hard links to a file -checking the file (advanced)

```
for (int i = 0; i < 1000; i++) {
    printf("Verifying '%s' contains: ", pathname);
    FILE *f2;
    if ((f2 = fopen(pathname, "r")) == NULL) {
        perror(pathname);
        return 1;
    }
    int c;
    while ((c = fgetc(f2)) != EOF) {
        fputc(c, stdout);
    }
    fclose(f2);
```

source code for many_links.c

creating 1000 hard links to a file (creating a link)

```
        char new_pathname[256];
        snprintf(new_pathname, sizeof new_pathname,
                 "hello_%d.txt", i);
        printf("Creating a link %s -> %s\n",
               new_pathname, pathname);
        if (link(pathname, new_pathname) != 0) {
            perror(pathname);
            return 1;
        }
    }
    return 0;
}
```

source code for many_links.c

POSIX functions to access directory contents (advanced)

```c
#include <sys/types.h>
#include <dirent.h>

// open a directory stream for directory name
DIR *opendir(const char *name);

// return a pointer to next directory entry
struct dirent *readdir(DIR *dirp);

// close a directory stream
int closedir(DIR *dirp);
```