COMP1521 23T2 — Files

https://www.cse.unsw.edu.au/~cs1521/223T22T3/
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.
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 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
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
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 the 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
the C function **syscall** allows to make a Linux system call without writing assembler

**syscall** itself is 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 function, 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
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);
}
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
Unix-like (POSIX) systems add some extra file-system-related C types in these include files:

```c
#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`, ...
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 \texttt{-1} to indicate error
- and set \texttt{errno} to integer value indicating reason for error
- these integer values are \texttt{\#define}-d in \texttt{errno.h}
- see \texttt{man errno} for more information
- convenient function \texttt{perror()} looks at \texttt{errno} and prints message with reason
- or \texttt{strerror()} converts \texttt{errno} integer value to string describing reason for error
- \texttt{errno} looks like \texttt{int} global variable
  - C library designed before multi-threaded systems in common use
  - \texttt{errno} can not really be a global variable on multi-threaded platform
  - each thread needs a separate \texttt{errno}
  - clever workaround: \texttt{errno \#defined} to function which returns address of variable for this thread
C library wrapper for read system call

```c
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

```c
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 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
// 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

```c
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

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C library wrapper for close system call

```c
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

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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 \texttt{fd}
- \texttt{offset} is in units of bytes, and can be negative
- \texttt{whence} can be one of ...
  - SEEK_SET — set file position to \texttt{offset} from start of file
  - SEEK_CUR — set file position to \texttt{offset} from current position
  - SEEK_END — set file position to \texttt{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:

  \begin{verbatim}
  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
  \end{verbatim}
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
**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,
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

```c
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

https://www.cse.unsw.edu.au/~cs1521/23T2T3/
stdio.h - convenience functions for stdin/stdout

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

```c
int getchar();  // 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, ...)

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

// 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

https://www.cse.unsw.edu.au/~cs1521/223T22T3/
stdio.h - creating a file

// 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

https://www.cse.unsw.edu.au/~cs1521/223T22T3/COMP1521.23T2 — Files
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
// 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);
}
$ 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
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 \texttt{fgetc()} calls requests 4096 bytes via \texttt{read()}
    - returns 1 byte stores remaining 4095 bytes in an array, the \textit{input buffer}

  - next 4095 \texttt{fgetc()} calls return a byte from \textit{(input buffer)} and do not to call \texttt{read()}

  - 4097th \texttt{fgetc()} call requests 4096 bytes via \texttt{read()}

  - returns 1 byte, stores remaining 4095 bytes in the \textit{(input buffer)}

  - and so on

- first 4095 \texttt{fputc()} calls put bytes in an array, the \textit{(output buffer)}

  - 4096th \texttt{fputc()} calls \texttt{write()} for all 4096 bytes in the \textit{output buffer}

  - and so on

  - \textit{output buffer}* emptied by \texttt{exit} or main returning

  - program can explicitly force empty of output buffer with \texttt{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));
```

**NOTE:** important error checking is missing above
Using fseek to read bytes in the middle of a file

```c
// 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

```c
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);
```

- random changes to search for errors/vulnerabilities called fuzzing
// Create a 16 terabyte 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;
}

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

```c
// 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 filenames are sequences of 1 or more bytes.
- filenames can contain any byte except \texttt{0x00} and \texttt{0x2F}
- \texttt{0x00} bytes (ASCII ‘\textbackslash 0’) used to terminate filenames
- \texttt{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
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* pathnames 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
  - ...

[Link to course material](https://www.cse.unsw.edu.au/~cs1521/223T22T3/COMP1521-23T2---Files)
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
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
unix-like file systems effectively have a large array of inodes containing 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**

```bash
$ 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**
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 \(\text{inodes}[\text{inumber}]\)
- 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
  - accessing 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)
$ 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

```c
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

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

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

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

- same as `stat()` but doesn’t follow symbolic links
```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 */
    timespec st_atim; /* Time of last access */
    timespec st_mtim; /* Time of last modification */
    timespec st_ctim; /* Time of last status change */
};
```
**st_mode field of struct stat**

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

<table>
<thead>
<tr>
<th>Code</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S_IFLNK</td>
<td>0120000</td>
<td>symbolic link</td>
</tr>
<tr>
<td>S_IFREG</td>
<td>0100000</td>
<td>regular file</td>
</tr>
<tr>
<td>S_IFBLK</td>
<td>0060000</td>
<td>block device</td>
</tr>
<tr>
<td>S_IFDIR</td>
<td>0040000</td>
<td>directory</td>
</tr>
<tr>
<td>S_IFCHR</td>
<td>0020000</td>
<td>character device</td>
</tr>
<tr>
<td>S_IFIFO</td>
<td>0010000</td>
<td>FIFO</td>
</tr>
<tr>
<td>S_IRUSR</td>
<td>0000400</td>
<td>owner has read permission</td>
</tr>
<tr>
<td>S_IWUSR</td>
<td>0000200</td>
<td>owner has write permission</td>
</tr>
<tr>
<td>S_IXUSR</td>
<td>0000100</td>
<td>owner has execute permission</td>
</tr>
<tr>
<td>S_IRGRP</td>
<td>0000040</td>
<td>group has read permission</td>
</tr>
<tr>
<td>S_IWGRP</td>
<td>0000020</td>
<td>group has write permission</td>
</tr>
<tr>
<td>S_IXGRP</td>
<td>0000010</td>
<td>group has execute permission</td>
</tr>
<tr>
<td>S_IROTH</td>
<td>0000004</td>
<td>others have read permission</td>
</tr>
<tr>
<td>S_IWOTH</td>
<td>0000002</td>
<td>others have write permission</td>
</tr>
<tr>
<td>S_IXOTH</td>
<td>0000001</td>
<td>others have execute permission</td>
</tr>
</tbody>
</table>
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);
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:

```c
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

https://www.cse.unsw.edu.au/~cs1521/223T22T3/COMP1521.23T2 — Files
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

https://www.cse.unsw.edu.au/~cs1521/223T22T3/COMP1521.23T2 — Files
// 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

$ gcc rm.c
$ ./a.out rm.c
$ ls -l rm.c
ls: cannot access 'rm.c': No such file or directory
// rename the specified file

```c
int main(int argc, char *argv[]) {
  if (argc != 3) {
    fprintf(stderr, "Usage: %s <old-filename> <new-filename>
", 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

// 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
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);
}
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
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);
}
Creating 1000 hard links to a file (creating a link)

```c
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;
```
#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);