https://www.cse.unsw.edu.au/~cs1521/22T1/
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 and more convenient than real machine
- The virtual machine interface can be consistent across different hardware.
  - programs can portably access hardware across different hardware configurations
  - e.g. linux available for almost all suitable hardware
- can coordinate/share access to resources between users
- 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 - What is It

- System call allows 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 systems have different system calls.
  - E.g., Linux system calls are very different from 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.
SPIM/MIPSY provides a virtual machine which can execute MIPS programs

SPIM/MIPSY also provides a tiny operating system

small number of SPIM system calls for I/O and memory allocation

access is via the \textit{syscall} instruction
  - MIPS programs running on real hardware also use \textit{syscall}
  - on Linux \textit{syscall}, passes execution to operating system code
  - Linux operating system code carries out request specified in $v0$ and $a0$

SPIM/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. \textit{printf} & \textit{fgets}
  - which make system calls (often via other functions)
Linux provides 400+ system calls
- see `/usr/include/asm/unistd_64.h` on a CSE machine

like SPIM/MIPSy every Linux system call has a number, e.g. write bytes to a file is system call 2

the C function `syscall` allows to make a Linux system call without writing assembler
- `syscall` will be written partly/entirely in assembler
  - e.g. source for x86_64: [https://code.woboq.org/userspace/glibc/sysdeps/unix/sysv/linux/x86_64/syscall.S.html](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
- e.g. the write system call has a wrapper C function called `write`
- these wrapper function are safer & more convenient

we only use `syscall` to experiment & learn
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
// 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
    // 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], 0, 0);
    long write_file_descriptor = syscall(2, argv[2], 0x41, 0644);
}
Using system calls to copy a file #2 - copying the bytes

```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);
}
```

source code for cp_syscalls.c

https://www.cse.unsw.edu.au/~cs1521/22T1/
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 platforms without these functions
- POSIX standardizes some of these functions
  - some non-Unix systems provide implementations of these functions while
- 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`, ...
The function `open` is a part of the C library. It is a wrapper for an 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 return error information
- functions typically return \(-1\) to indicate error
- and set `errno` to integer value indicating reason for error
- values defined in `errno.h`
- see `man errno` for more information
- `strerror()` converts `errno` integer value to reason as a string
- convenient function `perror()` looks at `errno` and prints message with reason
- `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`
  - workaround clever `#define` to function which return 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
  streamline 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[16] = ”Hello, Andrew!\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, 15); // prints Hello, Andrew! 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

https://www.cse.unsw.edu.au/~cs1521/22T1/
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 here as program about to exit
close(read_file_descriptor);
close(write_file_descriptor);
```

source code for cp_libc.c

https://www.cse.unsw.edu.au/~cs1521/22T1/COMP1521.22T1---Files
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
**C library wrapper for lseek system call**

```c
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:

```c
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
```
- 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 the 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,
stdio.h - fclose()

```c
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
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, 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);
```
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
char bytes[] = ”Hello, stdio!
”; // 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
```c
// create file "hello.txt" containing 1 line: Hello, Andrew
#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, Andrew!\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], "rb");
if (input_stream == NULL) {
    perror(argv[1]);  // prints why the open failed
    return 1;
}
FILE *output_stream = fopen(argv[2], "wb");
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

https://www.cse.unsw.edu.au/~cs1521/22T1/COMP1521_22T1~Files
// 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
$ clang -O3 cp_fgetc.c -o cp_fgetc
$r 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
```c
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:

  ```c
  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));
```

**NOTE:** important error checking is missing above
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
Using fseek to create a gigantic sparse file (advanced topic)

// 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;
}

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

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

```c
// 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, ...);
```

```c
// 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 ‘\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:
- \texttt{.} current directory
- \texttt{..} parent directory

Some programs (shell, \texttt{ls}) treat filenames starting with \texttt{.} 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 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 byte
- file ownership
- file access permissions - who can read, write, execute the file
- timestamps - time of creation/access/update

Note: file systems add much complexity to improve performance

- e.g. very small files might be stored in an inode itself
unix-like file systems effectively have an array of inodes

every inode has a **inode-number** (or **i-number**) - its index in this array

directories are effectively a list of (name, inode-number) pairs

inode-number uniquely identify files within a filesystem
  - just a zid uniquely identifies a student within UNSW

**ls** -i prints **inode-number**, e.g.:

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

https://www.cse.unsw.edu.au/~cs1521/22T1/
`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** 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

https://www.cse.unsw.edu.au/~cs1521/22T1/COMP1521 22T1 — Files
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], S_IRWXU | S_IRWXG | S_IROTH | S_IXOTH) != 0) {
            perror(argv[arg]); // prints why the mkdir failed
            return 1;
        }
    }
    return 0;
}
```

source code for mkdir.c

https://www.cse.unsw.edu.au/~cs1521/22T1/COMP1521.22T1---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/~cs1521/22T1/COMP1521.22T1---Files
removing 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

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

https://www.cse.unsw.edu.au/~cs1521/22T1/
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

https://www.cse.unsw.edu.au/~cs1521/22T1/COMP1521_22T1---Files
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);
}
```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;
```

source code for many_links.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);