CMPSC 311 - Introduction to Systems Programming

File Input/Output

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(Slides are mostly by

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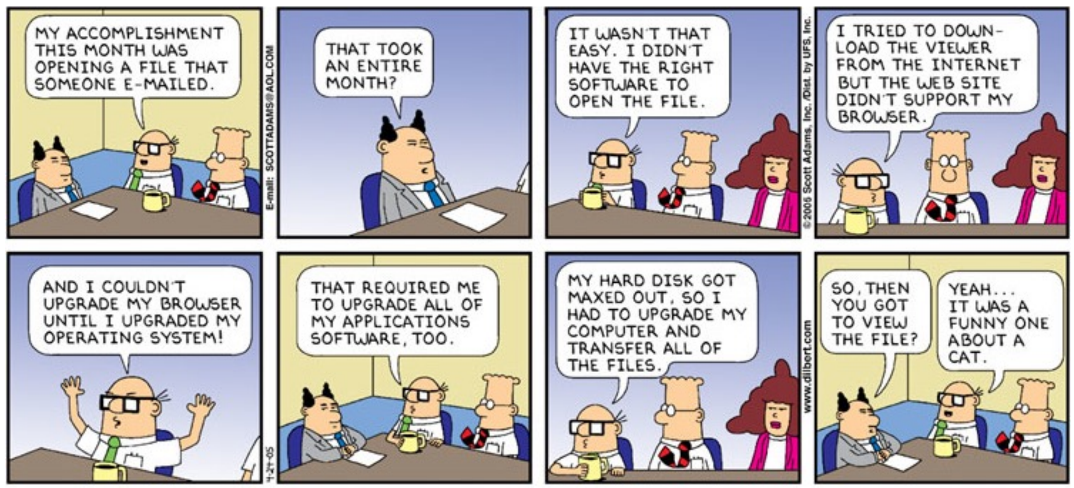
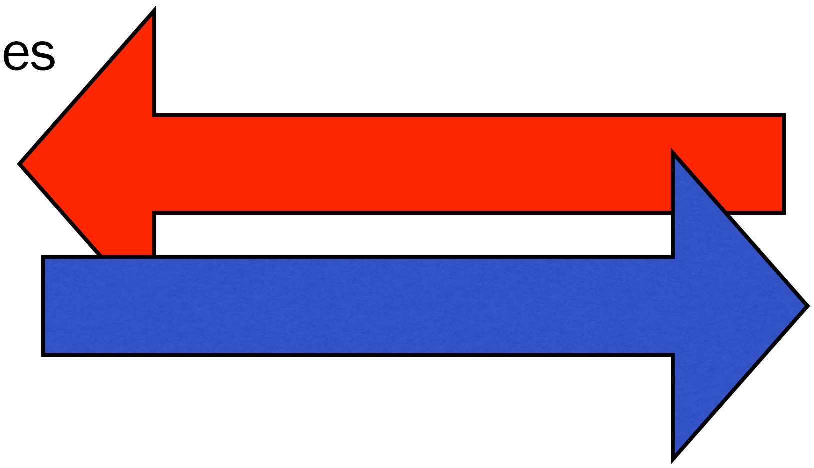


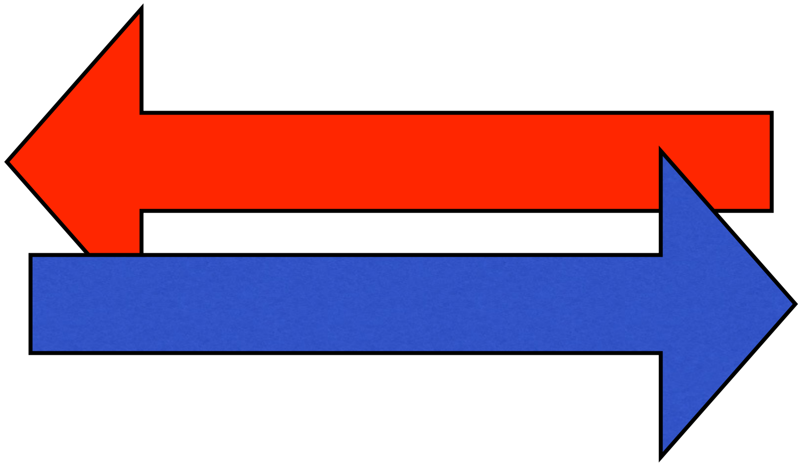
Input/Output

- Input/output is the process of moving bytes into and out of devices, files, networks, etc.
  - terminal/keyboard (terminal I/O)
  - secondary storage (file I/O)
  - network (network I/O)
- Different I/O types require different interfaces
  - terminal I/O is messy
    - full of legacy details (not covered)
  - we will cover file I/O and network I/O



Buffered vs. Unbuffered

- When the system is buffering
  - It may read more that requested in the expectation you will read more later (read buffering)
  - it may not commit all bytes to the target (write buffering)



Blocking vs. Nonblocking vs. Asynchronous

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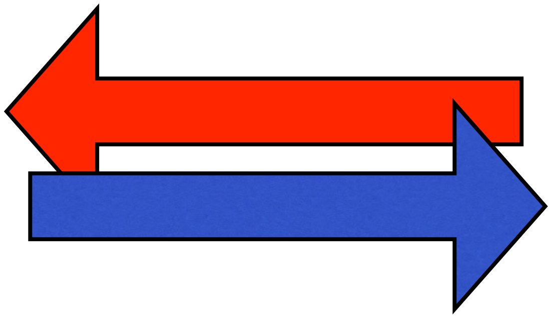


- Non-blocking I/O
  - The call does not wait for the read or write to complete before returning
  - Thus a write/read may commit/return some, all, or none of the data requested
  - When fewer than request bytes are read/written this is called a short read or short write
- Asynchronous I/O
  - Uses a different API than blocking/non-blocking I/O
  - I/O request returns immediately
  - A callback is generated when I/O completes
- How you program I/O operations is dependent on the blocking behavior of I/O you are using.

Terminal IO

- There are three default terminal channels.
  - `STDIN`
  - `STDOUT`
  - `STDERR`

- UNIX commands/programs for terminal output
  - `echo` - prints out formatted output to terminal STDOUT
    - e.g., `echo "hello world"`
  - `cat` - prints out file (or STDIN) contents to STDOUT
    - e.g., `cat mdadm.c`
  - `less` - provides a read-only viewer for input (or file)
    - e.g., `less mdadm.c`

IO Redirection

- Redirection uses file for inputs, outputs, or both
  - Output redirection sends the output of a program to a file (re-directs to a file), e.g.,
    - `echo "cmpsc311 output redirection" > this.dat`

```
$ echo "cmpsc311 output redirection" > this.dat
$ cat this.dat
cmpsc311 output redirection
```

  - Input redirection uses the contents of a file as the program input (re-directs from a file), e.g.,
    - `cat < this.dat`

```
$ cat < this.dat
cmpsc311 output redirection
```

  - You can also do both at the same time, e.g.,
    - `cat < this.dat > other.dat`

Reading from STDIN vs from a file

```
#include <stdio.h>

int main(void) {
  char buf[80];
  printf("What is your name? ");
  scanf("%s", buf);
  printf("Hello, %s\n", buf);

  return 0;
}
```

```
$ ./hello
What is your name? Neo
Hello, Neo
$ cat name
Trinity
$ ./hello <name
What is your name? Hello, Trinity
$ ./hello <name >out
$ cat out
What is your name? Hello, Trinity
$
```

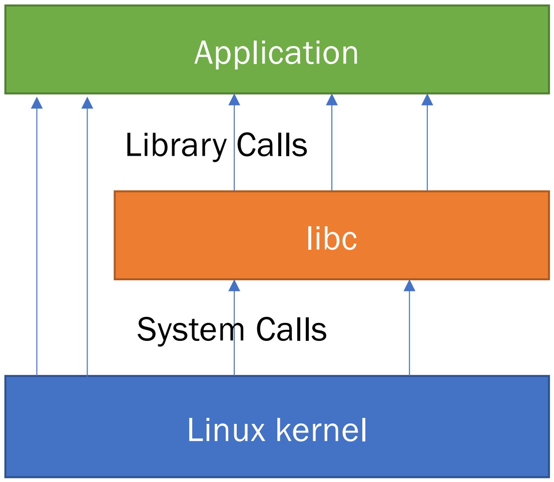
Pipes

- Pipes take the output from one program and uses it as input for another, e.g.,
  - `cat this.dat | less`
- You can also chain pipes together, e.g.,
  - `cat numbers.txt | sort -n | cat`

```
3$ cat numbers.txt
14
21
7
4
$ cat numbers.txt | sort -n | cat
4
7
14
21
$
```

libc

- libc is the standard library for the C programming language. In contains the code and interfaces we use to for basic program operation and interact with the parent operating system. Basics iterfaces:
  - `stdio.h` – declarations for input/outout
  - `stdlib.h` – declarations for misc system interfaces
  - `stdint.h` – declarations for basic integer data types
  - `signal.h` – declarations for OS signals and functions
  - `math.h` – declarations of many useful math functions
  - `time.h` – declarations for basic time handling functions
  - … many, many more



Library call vs system call

- Difference between `open` and `fopen`
  - open is a system call

```
DESCRIPTION
       The  open()  system  call opens the file specified by pathname.  If the
       specified file does not exist, it may optionally (if O_CREAT is  speci-
       fied in flags) be created by open().
```

  - fopen is a library call

```
DESCRIPTION
       The fopen() function opens the file whose name is the string pointed to
       by pathname and associates a stream with it.
```

man man

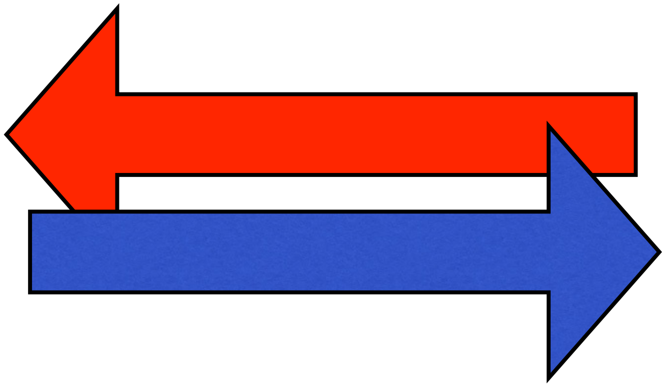
- Systems calls, library calls, etc., have their own sections

```
1   Executable programs or shell commands
2   System calls (functions provided by the kernel)
3   Library calls (functions within program libraries)
4   Special files (usually found in /dev)
5   File formats and conventions, e.g. /etc/passwd
6   Games
7   Miscellaneous (including  macro  packages  and  conventions),  e.g.
    man(7), groff(7)
8   System administration commands (usually only for root)
9   Kernel routines [Non standard]
```

- Use “man 3 fopen” to read the manual page of fopen library call
- You will see references such as “foo(2)” or “bar(3)”
  - the number in parenthesis refers to the manual page section, implies the call type

File IO

- File IO provides random access to a file within the filesystem:
  - With a specific "path" (location of the file)
  - At any point in time it has location pointer in the file
    - Next reads and writes will begin at that position
  - All file I/O works in the following way
    - open the file
    - read/write the contents
    - close the file



Locating files for IO

- An absolute path fully specifies the directories and filename itself from the filesystem root "/", e.g.,

  `/home/mcdaniel/courses/cmpsc311-sum19/this.dat`

- A relative path is the directories and filename from (or relative to) the current directory, e.g.,

  `./courses/cmpsc311-sum19/this.dat`

  `courses/cmpsc311-sum19/this.dat`

- All of these references refer to the same file!

FILE* based IO

- One of the basic ways to manage input and output is to use the FILE set of functions provided by libc.
  - The FILE structure is a data structure created to manage input and output for a file
  - An abstraction of "high level" file I/O that avoids some of the details of programming
  - Almost always used for reading and writing ASCII data

```
(gdb) p *file
$3 = {_flags = -72539008, _IO_read_ptr = 0x0, _IO_read_end = 0x0,
_IO_read_base = 0x0, _IO_write_base = 0x0, _IO_write_ptr = 0x0,
  _IO_write_end = 0x0, _IO_buf_base = 0x0, _IO_buf_end = 0x0,
_IO_save_base = 0x0, _IO_backup_base = 0x0, _IO_save_end = 0x0,
  _markers = 0x0, _chain = 0x7ffff7dd41a0 <_IO_2_1_stderr_>, _fileno =
7, _flags2 = 0, _old_offset = 0, _cur_column = 0,
  _vtable_offset = 0 '\000', _shortbuf = "", _lock = 0x6020f0, _offset
= -1, __pad1 = 0x0, __pad2 = 0x602100, __pad3 = 0x0, __pad4 = 0x0,
  __pad5 = 0, _mode = 0, _unused2 = '\000' <repeats 19 times>}
```

`fopen()`

- The fopen function opens a file for IO and returns a pointer to a FILE* structure:

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

- Where,
  - path is a string containing the absolute or relative path to the file to be opened.
  - mode is a string describing the ways the file will be used
  - For example, `FILE *file = fopen( filename, "r+" );`
  - Returns a pointer to FILE* if successful, NULL otherwise
    - You don't have to allocate or deallocate the FILE* structure

`fopen()`

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

- Where,
  - path is a string containi[…] the file to be opened.
  - mode is a string describ[…]
  - For example, `FILE *file = fopen( filename, "r+" );`
  - Returns a pointer to FILE* if successful, NULL otherwise
    - You don't have to allocate or deallocate the FILE* structure

A FILE* structure is also referred to as a *stream*.

fopen modes

- "r" - Open text file for reading. The stream is positioned at the beginning of the file.
- "r+" - Open for reading and writing. The stream is positioned at the beginning of the file.
- "w" - Truncate file to zero length or create text file for writing. The stream is positioned at the beginning of the file.
- "w+" - Open for reading and writing. The file is created if it does not exist, otherwise it is truncated.
- "a" Open for appending (writing at end of file). The file is created if it does not exist.
- "a+" Open for reading and appending (writing at end of file). The file is created if it does not exist.

FILE *

Reading the file

- There are two dominant ways to read the file, `fscanf` and `fgets`
  - `fscanf` reads the data from the file just like `scanf`, just reading and writing, e.g.,

```
if ( fscanf( file, "%d %d %d\n", &x, &y, &z ) == 3 ) {
  printf( "Read coordinates [%d,%d,%d]\n", x, y, z );
}
```

  - `fgets` reads a line of text from the file, e.g.,

```
if ( fgets(str,128,file) != NULL  ) {
  printf( "Read line [%s]\n", str );
}
```

Writing the file

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- There are two dominant ways to write the file, `fprintf` and `fputs`
  - `fprintf` writes the data to the file just like `printf`, just reading and writing, e.g.,

```
fprintf( file, "%d %d %d\n", x, y, z );
```

  - `fputs` writes a line of text to the file, e.g.,

```
if ( fputs(str,file) != NULL  ) {
  printf( "wrote line [%s]\n", str );
}
```

fflush

- `FILE*`-based IO is buffered
- `fflush` attempts to reset/the flush state

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

  - `FILE*`-based writes are buffered, so there may be data written, but not yet pushed to the OS.
    - `fflush()` forces a write of all buffered data
  - `FILE*`-based reads are buffered, so the current data (in the process space) may not be current
    - `fflush()` discards buffered data from the underlying file
- If the stream argument is `NULL`, `fflush()` flushes all open output streams
- fflush() does not guarantee that data is safely on disk; for that use fsync(2)

fclose()

- `fclose()` closes the file and releases the memory associated with the FILE* structure.

```
fclose( file );
file = NULL;
```

Note: `fclose()` implicitly flushes the data to OS.

Putting it all together …

```
int show_fopen( void ) {

    int x, y, z;
    FILE *file;
    char *filename = "/tmp/fopen.dat", str[128];
    file = fopen( filename, "r+" );

    // open for reading and writing
    if ( file == NULL ) {
        fprintf( stderr, "fopen() failed, error=%s\n", strerror(errno) );
        return( -1 );
    }

    // Read until you reach the end
    while ( !feof(file) ) {
        if ( fscanf( file, "%d %d %d\n", &x, &y, &z ) == 3 ) {
                printf( "Read coordinates [%d,%d,%d]\n", x, y, z );
        }
        if ( !feof(file) ) {
            fgets(str,128,file); // Need to get end of previous line
            if ( fgets(str,128,file) != NULL  ) {
                printf( "Read line [%s]\n", str );
            }
        }
    }
```

Putting it all together …

```
    // Now add some new coordinates
    x = 21;
    y = 34;
    z = 98;
    fprintf( file, "%d %d %d\n", x, y, z );
    printf( "Wrote %d %d %d\n", x, y, z );
    if ( fputs(str,file) >= 0 ) {
        printf( "wrote line [%s]\n", str );
    }
    fflush( file );

    // Close the file and return
    fclose( file );
    return( 0 );
}
```

```
$ cat /tmp/fopen.dat
1 2 3
4 5 6
11 12 14
16 17 23
$ ./io
This is cmpsc311, IO example
Read coordinates [1,2,3]
Read line [11 12 14
]
Read coordinates [16,17,23]
Wrote 21 34 98
wrote line [11 12 14
]
$ cat /tmp/fopen.dat
1 2 3
4 5 6
11 12 14
16 17 23
21 34 98
11 12 14
$
```

open()

- The open system call opens a file for IO and returns an integer file handle:

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

- Where,
  - path is a string containing the absolute or relative path to the file to be opened.
  - flags indicates the kind of open you are requesting
  - mode sets a security policy for the file

- `open()` returns a "file handle"

open() flags

- The "flags" to open with
  - `O_RDONLY` - read only
  - `O_WRONLY` - write only
  - `O_RDWR` - read and write
- Options
  - `O_CREAT` - If the file does not exist it will be created.
  - `O_EXCL` Ensure that this call creates the file, fail otherwise (fail if already exists)
  - `O_TRUNC` - If the file already exists it will be truncated to length 0.

Note: You bitwise or (|) the mode/options you want

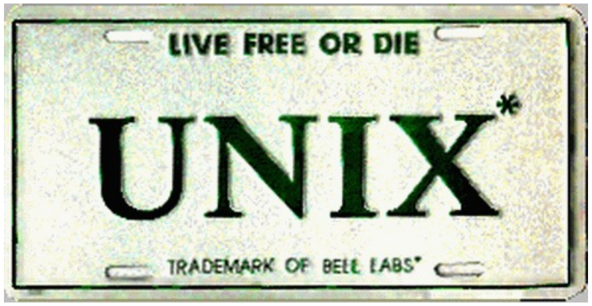
Access Control in UNIX

- The UNIX filesystem implements discretionary access control through file permissions set by user
  - The permissions are set at the discretion of the user
- Every file in the file system has a set of bits which determine who has access to the files
  - User - the owner is typically the creator of the file, and the entity in control of the access control policy
  - Group - a set of users on the system setup by the admin
  - World - the set of everyone on the system

- Note: this can be overridden by the “root” user

UNIX filesystem rights …

- There are three rights in the UNIX filesystem
  - READ - allows the subject (process) to read the contents of the file.
  - WRITE - allows the subject (process) to alter the contents of the file.
  - EXECUTE - allows the subject (process) to execute the contents of the file (e.g., shell program, executable, …)



- Q: why is execute a right?
- Q: does read implicitly give you the right to execute?

UNIX Access Policy

- Really, this is a bit string encoding an access policy:

```
rwx rwx rwx
```

World
Group
Owner

- And a policy is encoded as "`r`", "`w`", "`x`" if enabled, and "`-`" if not, e.g,

```
rwxrw---x
```

- Says user can read, write and execute, group can read and write, and world can execute only.

UNIX Access Policy

- Really, this is a bit string encoding an access policy:

```
rwx rwx rwx
```

```
$ ls -l .
total 20
-rw-rw-r-- 1 mcdaniel professor    12  Oct 10 14:18 fopen.dat
-rwxrwxr-x 1 mcdaniel professor 12058 Oct 10 15:42 io
-rw-rw-r-- 1 mcdaniel professor 1176  Oct 10 15:42 io.c
$
```

- And a polic nd “-” if not, e.g,

```
rwxrw---x
```

- Says user can read, write and execute, group can read and write, and world can execute only.

Setting an access policy

- Specify a file access policy by bit-wise ORing (|):
  - `S_IRWXU` 00700 user (file owner) has read, write and execute
  - `S_IRUSR` 00400 user has read permission
  - `S_IWUSR` 00200 user has write permission
  - `S_IXUSR` 00100 user has execute permission
  - `S_IRWXG` 00070 group has read, write and execute permission
  - `S_IRGRP` 00040 group has read permission
  - `S_IWGRP` 00020 group has write permission
  - `S_IXGRP` 00010 group has execute permission
  - `S_IRWXO` 00007 world has read, write and execute permission
  - `S_IROTH` 00004 world has read permission
  - `S_IWOTH` 00002 world has write permission
  - `S_IXOTH` 00001 world has execute permission

Putting it together …

- So an open looks something like …

```
// Setup the file for creating and open
flags = O_WRONLY|O_CREAT|O_EXCL; // Create a NEW file (no overwrite)
mode = S_IRUSR|S_IWUSR|S_IRGRP;   // User can read/write, group read
fhandle = open( filename, flags, mode );
if ( fhandle == -1 ) {
    fprintf( stderr, "open() failed, error=%s\n", strerror(errno) );
    return( -1 );
}
```

Q: But why is an `int` returned by `open()` a file?

File descriptor

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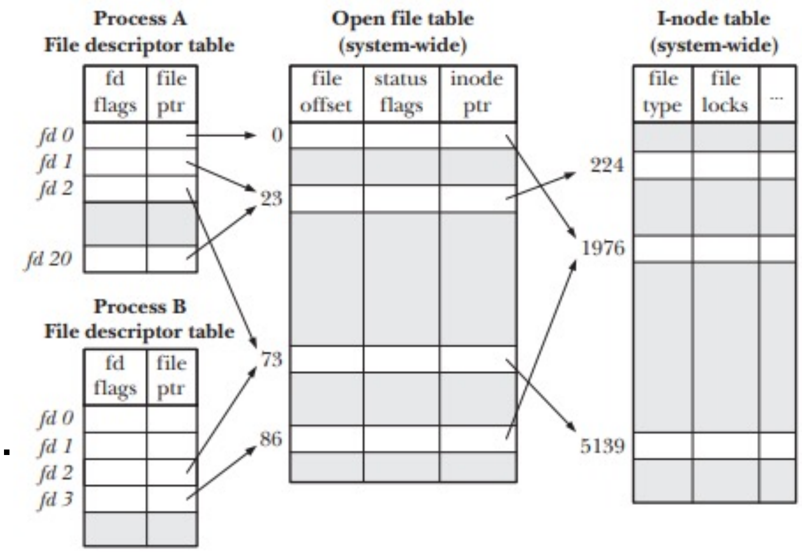
- A file descriptor is an index assigned by the kernel into a table of file information maintained in the OS
  - The file descriptor table is unique to each process and contains the details of open files.
  - File descriptors are used to reference when calling the I/O system calls.
  - The kernel accesses the file for the process and returns the results in system call response.



Reading and Writing

- Primitive reading and writing mechanisms that only process only blocks of opaque data:

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

- Where `fd` is the file descriptor, `buf` is an array of bytes to write from or read into, and `count` is the number of bytes to read or write
- Both read() and write() returned the number of bytes read and written.
  - Be sure to always check the result (!!!)
- On reads, you are responsible for supplying a buffer that is large enough to put the output into.

`close()`

- `close()` closes the file and deletes the file's entry in the file descriptor table

```
close(fhandle);
fhandle = -1;
```

Note: Always reset your file handles to `-1` to avoid use after close.

Putting it all together …

```
int show_open( void ) {

    // Setup variables
    char *filename = "/tmp/open.dat";
    int vals[1000] = { [0 ... 999] = 0xff }, vals2[1000];;
    int fhandle, flags;
    mode_t mode;

    // Setup the file for creating and open
    flags = O_WRONLY|O_CREAT|O_EXCL; // Create a NEW file (no overwrite)
    mode = S_IRUSR|S_IWUSR|S_IRGRP;   // User can read/write, group read
    fhandle = open( filename, flags, mode );
    if ( fhandle == -1 ) {
        fprintf( stderr, "open() failed, error=%s\n", strerror(errno) );
        return( -1 );
    }

    // Now write the array to the file
    if ( write(fhandle, (char *)vals, sizeof(vals)) != sizeof(vals) ) {
        fprintf( stderr, "write() failed, error=%s\n", strerror(errno) );
        return( -1 );
    }
    close( fhandle );
    fhandle = -1;
```

Putting it all together …

```
    // Setup the file for reading
    flags = O_RDONLY; // Read an existing file
    fhandle = open( filename, flags, 0 );
    if ( fhandle == -1 ) {
        fprintf( stderr, "open() failed, error=%s\n", strerror(errno) );
        return( -1 );
    }

    // Now read the array from the file
    if ( read(fhandle, (char *)vals2, sizeof(vals2)) != sizeof(vals2) ) {
        fprintf( stderr, "read() failed, error=%s\n", strerror(errno) );
        return( -1 );
    }
    close( fhandle );
    return( 0 );
}
```

```
$ ./io
$ $ od -x -N 256 /tmp/open.dat
0000000 00ff 0000 00ff 0000 00ff 0000 00ff 0000
*
0000400
```

fopen() vs. open()

- Key differences between fopen and open
  - `fopen` provides you with buffering IO that may or may not turn out to be a faster than what you're doing with open.
  - `fopen` does line ending translation if the file is not opened in binary mode, which can be very helpful if your program is ever ported to a non-Unix environment.
  - A `FILE *` gives you the ability to use `fscanf` and other `stdio` functions that parse out data and support formatted output.

- IMO: use `FILE*` style I/O for ASCII processing, and file handle I/O for binary data processing.

A parting note …

- Each of the styles of I/O requires a different set of include files
  - libc file I/O (i.e. using FILE*, fopen, fclose, …) requires:

```
#include <stdio.h>
```

  - system call file I/O requires:

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

- Read the manual page to find out what to include for what call

```
NAME
       open, openat, creat - open and possibly create a file

SYNOPSIS
       #include <sys/types.h>
       #include <sys/stat.h>
       #include <fcntl.h>

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