CSE 410: Systems Programming

Input and Output

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I/O Kernel Services

We have seen some text I/O using the C Standard Library.

- `fread()`
- `fgets()`
- `printf()`
- ...

However, all I/O is built on kernel system calls.

In this lecture, we'll look at those services *vs.* standard I/O.

Everything is a File

These services are particularly important on UNIX systems.

On UNIX, “everything is a file”.

Many devices and services are accessed by opening device nodes that behave like files.

Examples:

- `/dev/null`: Always readable, contains no data. Always writable, discards anything written to it.
- `/dev/urandom`: Always readable, reads a cryptographically secure stream of random data.

File Descriptors

All access to files is through file descriptors.

A file descriptor is a small integer representing an open file in a particular process.

There are three "standard" file descriptors:

- 0: standard input
- 1: standard output
- 2: standard error

…sound familiar? (`stdin`, `stdout`, `stderr`)

File Modes

Every file on a POSIX system has an owner and group.

File permissions are handled by mode bits.[1]

Mode bits are of the form: `rwxrwxrwx`

The `rwx` triplets are user, group, and other permissions.

- The user bits apply to the file's owner.
- The group bits apply to members of the file's group.
- The other bits apply to all other users.

`r` means read, `w` means write, `x` execute.

[1] Modern POSIX systems also have access control lists.

Mode Examples

File modes are normally represented as octal numbers.

Octal numbers range from 0-7 and are three bits long.

`rwxrwxrwx`

Examples:

- `750` (`111101000`b): `rwxr-x---`
  User can read, write, execute; group can read and execute; others have no access.
- `664` (`110110100`b): `rw-rw-r--`
  User and group can read and write, others can read.

System Call Failures

Kernel I/O system calls (indeed, most system calls) return a negative integer on failure.

When this happens, the global variable `errno` is set to a reason.

Include `errno.h` to define `errno` in your code.

The functions `perror()` and `strerror()` produce a human-readable error from `errno`.

Opening Files

There are two[2] calls to open a file on a POSIX system:

```
#include <fcntl.h>

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

The `creat()` system call is exactly like calling:
`open(path, O_CREAT|O_WRONLY|O_TRUNC, mode);`

Both functions return a filedescriptor on success.

[2]…OK, three.

Open Flags

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

The `flags` parameter controls how `open()` behaves:

- `O_RDONLY`: Open read-only
- `O_WRONLY`: Open write-only
- `O_RDWR`: Open for reading and writing
- `O_CREAT`: When writing, create the file if it doesn't exist
- `O_EXCL`: When creating a file, fail if it already exists
- `O_APPEND`: When writing, start at the end of the file
- `O_TRUC`: When writing, truncate the file to 0 bytes
- `O_CLOEXEC`: Close this file on `exec()`

O_CREAT|O_EXCL

The combination of flags O_CREAT|O_EXCL allows for exclusive access among cooperating processes.

The kernel will create the file if and only if it doesn't already exist.

This is an atomic action:
An atomic action appears to be indivisible from the outside.

If every process uses O_CREAT|O_EXCL for a file, the file can be used as a lock.
(More about locking later …)

Reading

```
#include <unistd.h>

int read(int fd, void *buffer, size_t bytes);
```

The `read()` system call reads data from an open file.

It reads raw bytes with no translation!

In particular, it will (maybe) not read a NUL-terminated string.

Its return value is:

- 0: end of file
- $>$ 0: bytes read; EOF if $<$ `bytes`
- $<$ 0: error

Writing

```
#include <unistd.h>

int write(int fd, const void *buffer, size_t bytes);
```

The `write()` sytem call writes data to an open file.

Like `read()`, it deals in raw binary data.

Its return value is:

- ≥ 0: bytes written; full disk / *etc.* if $<$ `bytes`
- < 0: error

Closing File Descriptors

```c
#include <unistd.h>

int close(int fd);
```

An open file can be closed with the `close()` system call.

Using a descriptor after close is an error.

A closed descriptor may be reused by subsequent opens.

UNIX I/O Example

```c
#include <unistd.h>
#include <fcntl.h>

int main(int argc, char *argv[]) {
    char buf[1024];
    int fd, bytes;

    if ((fd = open(argv[1], O_RDONLY)) < 0)
        { return -1; }
    while ((bytes = read(fd, buf, sizeof(buf))) > 0) {
        if (write(1, buf, bytes) < 0) {
            return -1;
        }
    }
    return bytes >= 0;
}
```

What Standard?

If UNIX I/O is part of the POSIX Standard …

Standard I/O is part of the C Standard.

Non-POSIX systems will still have standard I/O!

On UNIX systems, the standard I/O functions wrap UNIX I/O.

Opening Streams

A standard I/O stream wraps a file descriptor.

```
#include <stdio.h>

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

`fopen()` opens a file, `fdopen()` wraps an open file descriptor.

The `mode` parameter here confusingly corresponds to open `flags`.

Stream Modes

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

A stream can be opened for various purposes, according to `mode`:

- `"r"`: reading
- `"w"`: writing, with truncation
- `"a"`: writing, without truncation (append)
- `"r+"`: reading and writing, without truncation
- `"w+"`: reading and writing, with truncation

Write modes always create the file if necessary.

Binary I/O

The standard I/O functions may perform transformations.

They may assume that they operate on text files.

You can open for binary I/O using `"b"` after the mode character:

```
fopen("somefile", "rb");
```

On POSIX systems, the `"b"` is ignored.

This is a feature of the C Standard that is unused on POSIX systems.

Reading and Writing

```
#include <stdio.h>

size_t fread(void *dest, size_t size, size_t nmemb,
    FILE *fp);
size_t fwrite(const void *buf, size_t size, size_t
    nmemb, FILE *fp);
```

These functions read and write binary data.
(This is in contrast to the string I/O functions.)

Both write in terms of items of size bytes.

The return value is:

- the number of items read/written (up to nmemb)
- 0 on error or EOF

Errors and EOF

Unlike UNIX I/O, errors and EOF return the same value.

There are two functions provided to detect errors and EOF:

- `int feof(FILE *fp);`
- `int ferror(FILE *fp);`

These functions return non-zero if EOF or an error has occurred.

`clearerr()` will reset the error/EOF status of a stream:

- `void clearerr(FILE *fp);`

Standard I/O Example

```c
#include <stdio.h>

int main(int argc, char *argv[]) {
    char buf[1024];
    FILE *fp;
    int bytes;

    if ((fp = fopen(argv[1], "r")) == NULL)
        { return -1; }
    while (!feof(fp) &&
           (bytes = fread(buf, 1, sizeof(buf), fp)) > 0) {
        if (fwrite(buf, 1, bytes, stdout) == 0) {
            return -1;
        }
    }
    return ferror(fp) || ferror(stdout);
}
```

System Call Overhead

The overhead of calling a system call is often not small.

This overhead is due to the cost of:

- Changing protection domains
- Validating pointers
- Adjusting memory maps
- …

It is better to make fewer system calls that do more work.

Standard I/O Buffering

The standard I/O functions use buffering to reduce overhead.

For example, `fread()` for 1 byte might read a full disk block.

This has important implications for correctness!

For example, device I/O may require very precise read/write sizes.

Write buffering can cause short writes.

Buffer flushing fixes this short write problem:

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

Buffering and Performance: UNIX I/O

```c
int fd = open("megabyte.dat", O_RDONLY);
int total;
unsigned char c;

while (read(fd, &c, 1) == 1) {
    total += c;
}
```

Time:

```
Real time elapsed: 0:00.58
System time used : 0.41
User time used   : 0.16
```

Buffering and Performance: Standard I/O

```
FILE *fp = fopen("megabyte.dat", "rb");
int total;
unsigned char c;

while (!ferror(fp) && fread(&c, 1, 1, fp) == 1) {
    total += c;
}
```

Time:

```
Real time elapsed: 0:00.02
System time used : 0.00
User time used   : 0.02
```

What's the Difference?

read():

```
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
100.00    0.009763           0   1048578           read
  0.00    0.000000           0         3           open
  0.00    0.000000           0         2           close
------ ----------- ----------- --------- --------- ----------------
100.00    0.009763               1048583           total
```

fread():

```
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
  0.00    0.000000           0       258           read
  0.00    0.000000           0         3           open
  0.00    0.000000           0         2           close
------ ----------- ----------- --------- --------- ----------------
100.00    0.000000                   263           total
```

Buffering Mechanism

When the user requests a small read, the standard library makes a larger read.

For example, our reads of one byte turn into 4 kB reads.

The standard library buffers the remaining data in memory.

Future reads for buffered data read from memory.

Reads for data not in the buffer cause a new buffer to be fetched.

Buffer Example

```c
fread(&len, sizeof(len), 1, fp);
data = malloc(len);
fread(&data, 1, len, fp);
```

Standard I/O buffer for `fp`:

Buffer Example

```
fread(&len, sizeof(len), 1, fp);
data = malloc(len);
fread(&data, 1, len, fp);
```

Standard I/O buffer for `fp`:

First, `fread` reads a buffer of data from `fp`.

Buffer Example

```
fread(&len, sizeof(len), 1, fp);
data = malloc(len);
fread(&data, 1, len, fp);
```

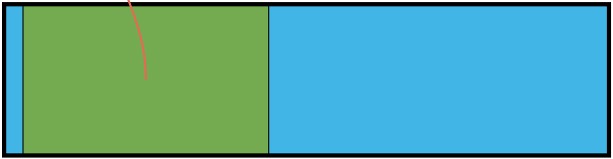
Standard I/O buffer for `fp`:

Then it returns `sizeof(size_t)` bytes from that buffer.

Buffer Example

```
fread(&len, sizeof(len), 1, fp);
data = malloc(len);
fread(&data, 1, len, fp);
```

Standard I/O buffer for `fp`:



The next read reads only from the buffer.

Summary

- UNIX I/O is defined by the POSIX Standard
- Standard I/O is defined by the C Standard
- The kernel tracks open files with file descriptors
- All file I/O goes through the kernel
- The standard I/O library is buffered

Next Time …

- …

References I

Required Readings

[1] Randal E. Bryant and David R. O'Hallaron. *Computer Science: A Programmer's Perspective*. Third Edition. Chapter 10: 10.1-10.4, 10.10-10.12. Pearson, 2016.

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