

Systems Programming

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Preface

These notes attempt to give a concise overview of **Systems Programming** course at the University of Tennessee. The contents of these notes come from Dr. James Plank's online COSC 360 notes¹ as well as select comments from his in-person lectures.

¹https://web.eecs.utk.edu/~jplank/plank/classes/cs360/lecture_notes.html

Moving from C++ to C

In moving from C++ to C, we lose a lot of nice features: standard template library (STL), `iostream`, objects, methods, and operator overloading to name a few. We can think of C as a subset of C++ in terms of features. Only in rare circumstances will C code not compile in C++.

1.1 Basic Terminal I/O

In C, `stdio.h` provides `printf()` for terminal output, and `fgets()` and `scanf()` for terminal input.

Code Snippet 1.1.1 ► Hello World in C

```
1  #include <stdio.h>
2
3  int main() {
4      printf("Hello world!\n");
5
6      return 0;
7  }
```

1.2 Scalar Types

Definition 1.2.1 ► Scalar Type

A **scalar type** is a type that stores a single value.

In C, there are seven default scalar types:

- `char` — 1 byte
- `short` — 2 bytes
- `int` — 4 bytes

- `long` — 4 or 8 bytes (depending on machine)
- `float` — 4 bytes
- `double` — 8 bytes
- `pointer` — 4 or 8 bytes (depending on machine)

Unlike C++, `bool` is not a default scalar type. As of C99, `bool` is defined in `stdbool.h`. Despite only storing 1 bit of info, `bool` occupies 1 byte of memory.

Scalar variables can be declared in one of three scopes:

- outside of all functions as **global** variables
- inside a function implementation as a **local** variable
- inside a function prototype as a **procedure** parameter

Global variables are allocated to memory once the program starts and only deallocates once the program terminates. **Local** variables are only allocated once the program reaches its function and are deallocated when the function ends.

There are no reference variables (&) in C. Function parameters are **always** copied.

1.3 Aggregate Types

Definition 1.3.1 ► Aggregate Type

An **aggregate type** stores one or more values.

In C, there are only two aggregate types: Array and Structure.

Definition 1.3.2 ► Array

An **array** is a contiguous piece of memory that stores multiple variables of the same scalar type.

In most programming languages (including C), arrays are represented by the memory address of its first element. Since the array is contiguous, C can easily calculate the memory address of all other elements.

In C, arrays can only be declared either globally or locally. When we pass an array to a function, we are only passing a pointer to its first element.

Definition 1.3.3 ► Structure

A **structure** or **struct** is a contiguous piece of memory that stores multiple variables which can be different scalar types.

In C++, we can use structs and classes interchangeably—the only difference being that, by default, structs make members public while classes makes members private. In contrast, C does not have classes, and structs in C don't have the following capabilities:

- No **access modifiers** like public, private, or protected
- No **constructors** nor **destructors**
- No **method functions**

In addition, C structs do not create a type by default. We have to explicitly create one using the typedef keyword.

Member variables of a struct get padded to be aligned to ensure each variable is aligned to 4-bytes **and** consecutive memory is aligned to 4-bytes.

The assignment operator (=) works as intended with structs but not so with arrays. If we have `int arr1[20]` and `int arr2[20]`, we cannot simply write `arr1 = arr2;`. Instead, we have to iterate through the array and copy each `int` one at a time.

Generally, we always copy a specific number of bytes using the assignment operator. The only exception is when we copy a struct that has an array as a member. Assignment operators for structs copies **all data**.

Code Snippet 1.3.1 ► Assignment Operator for Aggregate Types

```
1  typedef struct {
2      int arr[10];
3  } MyStruct;
4
5  int main() {
6      MyStruct ms1, ms2;
7  }
```

```
8    /* will compile; copies 40 bytes from ms1 to ms2 */
9    ms2 = ms1;
10
11    /* won't compile (can't use assignment operator on arrays)
12    ms2.arr = ms1.arr; */
13
14    /* right way */
15    for (int i = 0; i < 10; ++i) {
16        ms1.arr[i] = ms2.arr[i];
17    }
18
19    return 0;
20 }
```

Similarly, if a function an argument that is a struct with a member array, it will **copy** the struct as a procedure parameter.

Code Snippet 1.3.2 ► Confusing Struct Argument

```
1  typedef struct {
2      int arr[10];
3  } MyStruct;
4
5  void my_func(MyStruct ms) { ms.arr[9] = -1; }
6
7  int main() {
8      MyStruct ms;
9      ms.arr[9] = 10;
10     my_func(ms);
11
12     return 0;
13 }
```

s.arr[9] will still be 10! That's because my_func() takes a MyStruct parameter, creating a copy of MyStruct for use in the function. Hence, we are only changing the copied MyStruct which gets deleted at the end of the function. In this case, my_func() effectively does nothing.

1.4 Memory and `malloc()`

`malloc()` returns a pointer to a piece of continuous memory allocated only to our program. When we call `malloc()`, we specify a certain number of bytes which is then allocated to the program by the operating system. If the operating system can't allocate that much memory, `malloc` returns `NULL`. To prevent potential bus errors, `malloc()` only returns pointers aligned to 8 bytes.

All `malloc`'ed memory is deallocated either by calling `free()` on the pointer or when the program terminates. `free()` is mostly useful to deallocate data once it's no longer being used. Generally, there is no reason to call `free()` right before the program terminates.

1.5 Strings

Definition 1.5.1 ► String, Null Character

In C and C++, a string is a contiguous sequence of characters whose last character is the null character (ASCII value 0).

While C++ has `std::string` which handles the memory of the characters for us, we don't have such luxury in C. Instead, we have to explicitly use an array of `char`, handling it just as we would any other array.

When using a function like `printf("%s", str)`, we are only passing a pointer to the first character of `str`. Then, `printf` iteratively prints each byte in its ASCII representation, stopping once it reaches the null character.

1.6 Libfdr

To ease the transition between C++ and C, Dr. Plank has created a library for formatting input doubly-linked lists, and red-black trees (hence, `fdr`).¹

- The *fields* library helps parse input from `stdin` and files
- The *dlist* library provides doubly-linked lists
- The *JRB* library provides red-black trees, similar to `std::multimap`

¹Documentation is available on https://web.eecs.utk.edu/~jplank/plank/classes/cs360/lecture_notes.html.

File System

Definition 2.0.1 ► File System

A **file system** is a hierarchy of files and directories.

In the UNIX file system, every user has a home directory, aliased by “~”.

Definition 2.0.2 ► Signal

A **signal** is an interruption in a running program.

Definition 2.0.3 ► System Call

System calls allow programs to directly interface with the operating system. In C, system calls appear just as regular procedure calls.

Unlike creating a frame for regular procedures, system calls interrupt the program and are expensive.

In C, there are five system calls defined in `fcntl.h` for file I/O:

- `open()` – opens a handle to a file for I/O; specifies read and/or write permission
- `close()` – close a handle to a file
- `read()` –
- `write()`
- `lseek()`

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