The Compiler and Toolchain

CSE 220: Systems Programming

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The C Toolchain

The C compiler as we know it is actually many tools.

This is due to:

- C's particular history
- Common compiler design
- The specific design goal of compilation in parts

What we actually invoke is the compiler driver.

The compiler is only a single step of the multi-step process!

Compiling a C Program

A C program consists of one or more source files.

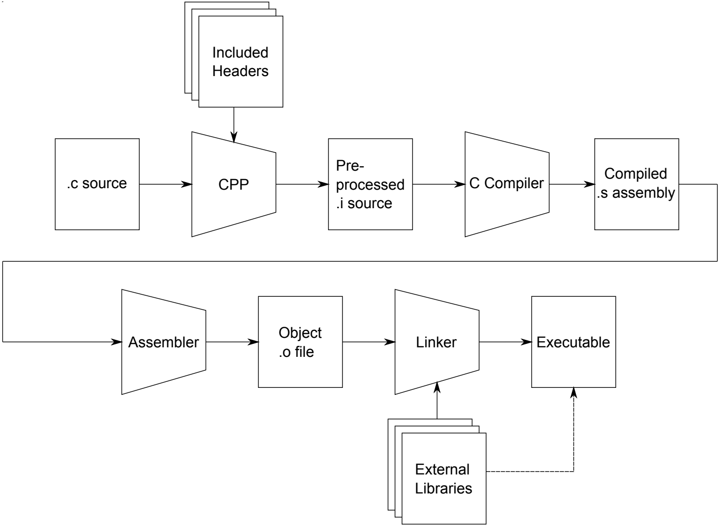
The C compiler driver passes the source code through several stages to translate it into machine code.

A source file[1] is sometimes called a translation unit.

Each stage may be invoked individually …more later.

[1] Plus some other stuff

The Complete Toolchain



The C Compiler Driver

First, we will ignore most stages of compilation.

The C compiler driver can take a `.c` source file and produce an executable directly.

We'll look at that with Hello World:

```
#include <stdio.h>

int main(int argc, char *argv[]) {
    printf("Hello, world!\n");
    return 0;
}
```

Compiling Hello World

We compile Hello World as follows:

```
gcc -Wall -Werror -O2 -g -std=c99 -o helloworld helloworld.c
```

This command says:

- `-Wall`: Turn on all warnings
- `-Werror`: Treat all warnings as errors
- `-O2`: Turn on moderate optimization
- `-g`: Include debugging information
- `-std=c99`: Use the 1999 ISO C Standard
- `-o helloworld`: Call the output `helloworld`
- `helloworld.c`: Compile the file `helloworld.c`

Compiling Hello World II

The C compiler driver ran all of the steps necessary to build an executable for us.

- The C preprocessor handled including a header
- The compiler produced assembly
- The assembler produced object code
- The linker produced `helloworld`

```
[elb@westruun]~/.../posix$ ./helloworld
Hello, world!
```

Compiling in Steps

The compiler driver can be used to invoke each step of the compilation individually.

It can also be used to invoke up to a step.

The starting step is determined by the input filename.

The ending step is determined by compiler options.

We will explore each step in some detail.

The C Preprocessor

The preprocessor does just what it sounds like.

It performs certain source code transformations before the C is processed by the compiler.

It doesn't understand C, and can be used for other things!

Functions of the Preprocessor

The C preprocessor applies preprocessor directives and macros to a source file, and removes comments.

Directives begin with #.

- `#include`: (Preprocess and) insert another file
- `#define`: Define a symbol or macro
- `#ifdef`/`#endif`: Include the enclosed block only if a symbol is defined
- `#if`/`#endif`: Include only if a condition is true
- ...

Preprocessor directives end with the current line (not a semicolon).

Including headers

The `#include` directive is primarily used to incorporate headers.

There are two syntaxes for inclusion:

- `#include <file>`
  Include a file from the system include path (defined by the toolchain)
- `#include "file"`
  Include a file from the current directory

Defining Symbols and Macros

The `#define` directive defines a symbol or macro:

```
#define PI 3.14159

#define PLUSONE(x) (x + 1)

PLUSONE(PI) /* Becomes (3.14159 + 1) */
```

Macros are expanded, not calculated!
The expansion will be given directly to the compiler.

Conditional Compilation

The various `#if` directives control conditional compilation.

```
#ifdef ARGUMENT
/* This code will be included only if ARGUMENT is
   a symbol defined by the preprocessor --
   regardless of its expansion */
#endif
```

The `#ifndef` directive requires `ARGUMENT` to be undefined.

The `#if` directive requires `ARGUMENT` to evaluate to true.

Using the Preprocessor

The preprocessor can be invoked as gcc -E.

Using the preprocessor correctly and safely is tricky.

For now, it is best to limit your use of the preprocessor.

Do use it for debugging, though!

The C Compiler

The compiler transforms C into machine-dependent assembly code.

It produces an object file via the assembler.

The compiler is the only part of the toolchain that understands C.

It understands:

- The semantics of C
- The capabilities of the machine

It uses these things to transform C into assembly.

Assembly Language

Assembly language is machine-specific, but human-readable.

Assembly language contains:

- Descriptions of machine instructions
- Descriptions of data
- Address labels marking variables and functions (symbols)
- Metadata about the code and compiler transformations

All of the semantics of the C program are in the assembly.

The structure of the assembly may be very different!

Compiling to Assembly

Let's compile to assembly using `-S`:

```
$ gcc -Wall -Werror O2 -std=c99 -S helloworld.c
```

On the next slides, we'll examine the output from `helloworld.s`.

helloworld.s I

```
	.file	"helloworld.c"
	.section	.rodata.str1.1,"aMS",@progbits,1
.LC0:
	.string "Hello, world!"
	.section	.text.startup,"ax",@progbits
	.p2align 4,,15
	.globl	main
	.type	main, @function
```

We'll get to the details later, but for now notice:

- `.LC0:` is a local label
- `.string` declares a string constant (no newline!)
- The `.globl` and `.type` directives declare that we're defining a global function named `main`

helloworld.s II

```
main:
.LFB11:
        .cfi_startproc
        leaq    .LC0(%rip), %rdi
        subq    $8, %rsp
        .cfi_def_cfa_offset 16
        call    puts@PLT
        xorl    %eax, %eax
        addq    $8, %rsp
        .cfi_def_cfa_offset 8
        ret
        .cfi_endproc
```

We'll skip the postamble, for now.

The Generated Code

First of all, you aren't expected to understand the assembly.

```
leaq    .LC0(%rip), %rdi
```

This code loads the string constant's address (from .LC0).

Then, later:

```
call    puts@PLT
```

…it calls `puts()` to output the string.

Note that the C compiler:

- Noticed we were outputting a static string
- Noticed it ended in a newline
- Replaced `printf()` with `puts()` *and a modified string*

The Assembler

The assembler transforms assembly language into machine code.

Machine code is binary instructions understood by the processor.

The output of the assembler is object files.

An object file contains:

- Machine code
- Data
- Metadata about the structure of the code and data

Compiling to an Object File

You may wish to compile to an object file.

This is used when multiple source files will be linked.

In this case, use `-c`:

```
$ gcc -Wall -Werror -O2 -std=c99 -c helloworld.c
```

This will produce `helloworld.o`.

The Linker

The linker turns one or more object files into an executable.

An executable is:

- The machine code and data from object files
- Metadata used by the OS to run a complete program

An executable's metadata includes:

- The platform on which it runs
- The entry point (where it should start execution)
- Anything it requires from libraries, *etc.*

Linking

Compiling any input files without an explicit output stage will invoke the linker.

```
gcc -Wall -Werror -O2 -std=c99 -o helloworld helloworld.o
```

This command will link `helloworld.o` with the system libraries to produce `helloworld`.

You can view the linkage with `ldd`:

```
[elb@westruun]~/.../posix$ ldd helloworld
  linux-vdso.so.1 (0x00007ffe34d1a000)
  libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007f24dacbb000)
  /lib64/ld-linux-x86-64.so.2 (0x00007f24db25c000)
```

Summary

- The “C compiler” is actually a chain of tools
  - We invoke the compiler driver
  - The preprocessor transforms the source code
  - The compiler turns C into assembly language
  - The assembler turns assembly language into machine code in object files
  - The linker links object files into an executable

References I

Required Readings

[1] Randal E. Bryant and David R. O'Hallaron. *Computer Science: A Programmer's Perspective*. Third Edition. Chapter 1: Intro, 1.1-1.4. Pearson, 2016.

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