

# CSE 220: Systems Programming

## The Compiler and Toolchain

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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.

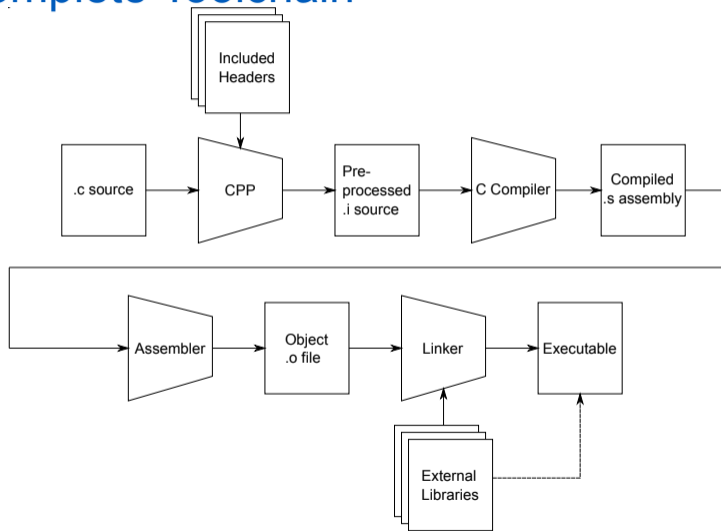
A source file<sup>1</sup> is sometimes called a translation unit.

Each stage may be invoked individually ...more later.

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<sup>1</sup>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 02 -std=c99 -S helloworld.c
```

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

# helloworld.s |

```
.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 the (complicated) printf() with the (simpler) 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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