Use gcc to learn C compilation process

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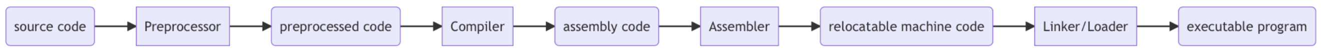
Recently, I suddenly discovered something when I was learning about clang/llvm: `gcc` is a collection of tools that includes or calls all tools that convert source code into executable program, not just a simple compiler. This helped me gain a deeper understanding of "compilers", so I wrote this article as a record.

More details about the principles and mechanisms of "compiler" are in another article: "What is the differences between gcc and Clang/LLVM?"

Complete process of converting source code into executable program

The complete process of converting source code into an executable program, which is what we usually call the "compilation process", is actually as follows (rounded brackets represent code, square brackets represent various processors):



From source code to executable program, it has to go through preprocessor, compiler, assembler, linker or loader. The compiler is only responsible for converting the source code into corresponding assembly code.

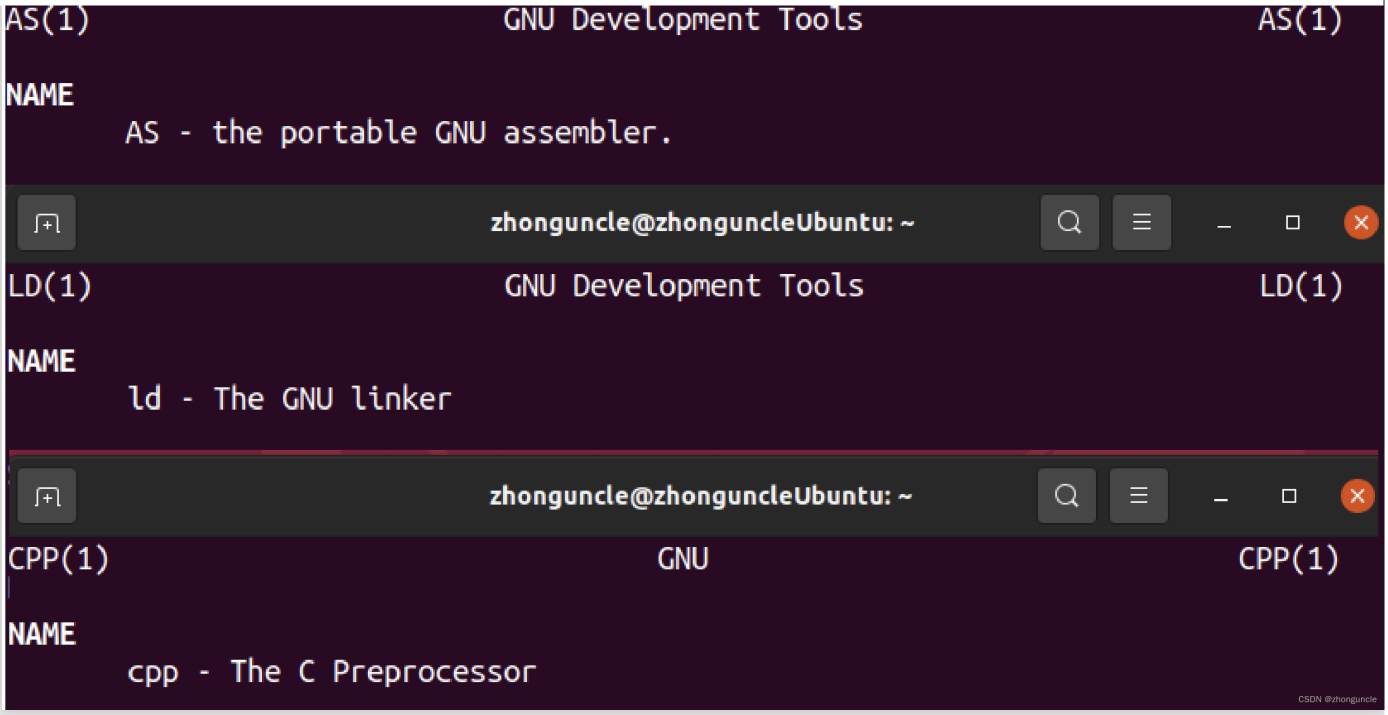
Next, use `gcc` to show the process above.

gcc and cpp, as, ld

Except the compiler and assembler, the other three programs above are rarely used or even heard. Let's use the most classic C language and `gcc` to introduce this process. `gcc` contains the preprocessor `cpp` , and also calls the assembler `as` and the connector `ld` .

> I thought `as` and `ld` were also included in `gcc` . But the GNU development team told me that `gcc` only contains the preprocessor and compiler. The assembler and linker are not part of the GCC project and must be provided separately (in many systems, it is provided by the binutils project) (verified, Ubuntu is in this way)

The manuals of gcc, as, ld are as follows:



```
AS(1)                     GNU Development Tools                     AS(1)

NAME
       AS - the portable GNU assembler.
```

zhonguncle@zhonguncleUbuntu: ~

```
LD(1)                     GNU Development Tools                     LD(1)

NAME
       ld - The GNU linker
```

zhonguncle@zhonguncleUbuntu: ~

```
CPP(1)                            GNU                              CPP(1)

NAME
       cpp - The C Preprocessor
```

As an annoyance, although the `gcc` command is called “compiler”, it includes a preprocessor and automatically calls other processing programs. So on the surface, `gcc` converts the source code to executable program by itself completely.

Since it is composed of multiple tools, you can also decide which step to proceed to, you can see it below.

Preparation of demonstration

In order to facilitate readers to understand the process of compilation, I will use an sample program to demonstrate. The sample program will calculate `12*13*14` and when the value is less than `1000` , outputing the value. Otherwise output the value exceeded the limit (In here, it will definitely exceed the limit).

We need three files and a blank directory `build` .

The empty directory `build` is for processing generated files conveniently. Just clear this folder after testing. Otherwise the two tests might make a mess. Use command below to generate `build` :

```
mkdir build
```

Three files are `main.c` 、 `calc.c` 和 `calc.h` . The code are：

```
//main.c
#include <stdio.h>
#include "calc.h"

#define MAXNUM 1000

int main()
{
    if (a >= MAXNUM)
        printf("Over Limit!\n");
    else
        printf("Result: %d", a);

    return 0;
}
```

```
//calc.c
#include <stdio.h>
#include "calc.h"

int calc(int a, int b, int c)
{
        return a*b*c;
}
```

```
//calc.h
int calc(int, int, int);
```

Use `gcc` to demonstrate the compilation process step by step

`gcc` supports stopping at a specified step, it is also can be thought as set the end point. When you operate it manually in sequence, it means only performing a certain step. We will use this mechanism to show the entire compilation process.

The usages of most programs is almost equivalent to `gcc` options, except for some small details. **The only large difference is the linker.**

So this section is just to let you understand the process. Next section will explain the details of each processor.

Preprocess

The first is to preprocess the source code. If you need to stop after preprocessing, you need to use the option `-E` (it is also mean just use preprocessor):

```
$ gcc -E ../calc.c -o calc.i
$ gcc -E ../main.c -o main.i
```

Use `-o` to specify the output file name here. Because preprocessor `cpp` called by `gcc` will output processed code to standard output, instead of generating a file. The suffix of processed code files is `.i` , so here the suffix is changed to `.i` .

Use `ls` to view the following:

Compile

Next is the compilation. If you want to compile but not assemble, use the `-S` option:

```
$ gcc -S main.i calc.i
```

Here, the two files will be compiled and generate the assembly language file and suffix of filename is replaced with `.s`. Use `ls` to view the following:

```
$ ls
calc.i  calc.s  main.i  main.s
```

Assemble

Next is the assembly stage. The option `-c` compiles and assembles but does not link. The suffix is used to determine which step of the entire compilation process to start from and stop. We compiled just now, but not assembled.

Use `-c` here is equivalent to using only the assembler:

```
$ gcc -c calc.s main.s
```

Like the `-S` option, it will generate an object file. The file name uses `.o` to replace the `.c`, `.i`, `.s` and other suffixes in the source file name. At this time, use `ls` to view the following:

```
$ ls
calc.i  calc.o  calc.s  main.i  main.o  main.s
```

Link

The final step is linking object files. You can use `-o` to output directly, because the result from object files is executable program, it is the same as result from source code to executable program. These options only set terminal step. Here we set the output file name to `calc`:

```
$ gcc -o calc main.o calc.o
```

Use `ls` to view the following:

```
$ ls
calc  calc.i  calc.o  calc.s  main.i  main.o  main.s
```

Run `calc`:

Work nice!

Call cpp, gcc, as, ld individually

Except for the linker, others are almost same as using `gcc` plus options, so I will talk about a lot of details and extensions.

This is for demonstration and learning purposes, so I will use cpp, gcc, as, ld step by step. In actual, you don't compile program like below usually. It just for education.

Use preprocessor cpp

The first step is to use the preprocessor `cpp` :

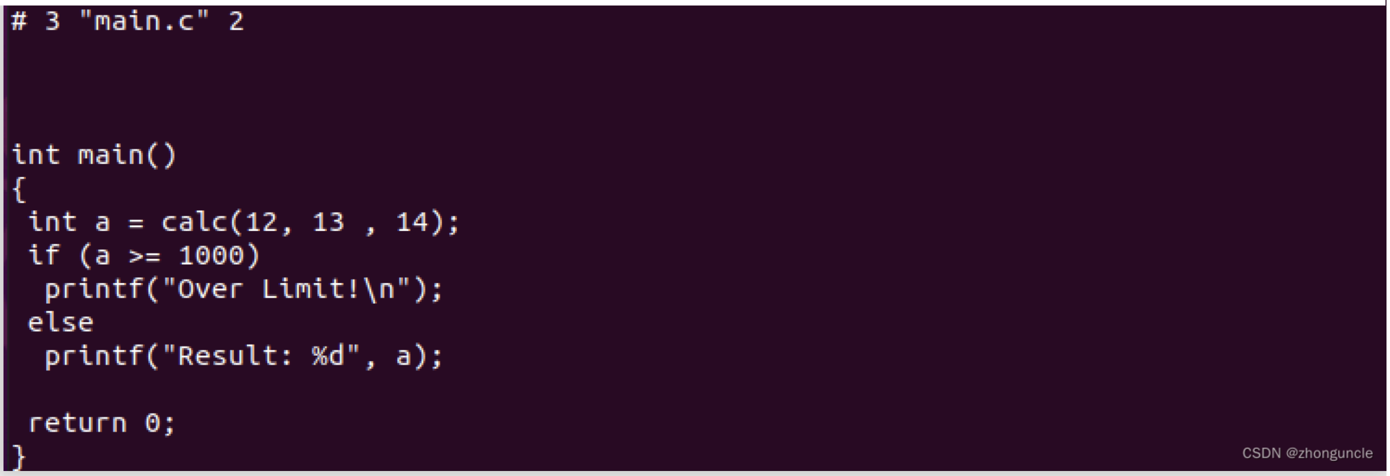
```
$ cpp ../calc.c -o calc.i
$ cpp ../main.c -o main.i
$ ls
calc.i main.i
```

Directly use `cpp` does not generate a file, because it directly output to standard output. If you want to save it as a file, you need to use the option `-o` . Due to we need use it, so must use `-o` . But since `cpp` is one-to-one, so we need use two commands.

The preprocessor will replace the referenced header files (#include), macros (#define), state controls (ifdef, etc.) in the source code. Since this step is **mainly** to replace macros and preprocessor, so it is also called a macro processor.

The preprocessed code will use for other tool, not just for compiler, because the preprocessor may be run more than once, or for other purposes. You can even add C macros to the assembly code, then use the preprocessor to process it, and then use the assembler to convert it into an executable program (C headers in Asm).

Let's look at the preprocessed code (`main.i`). We can see that a lot of code has been generated (`wc` statistics are 743 lines, and the source code is only 16 lines), but much of them is replacement of `#include <stdio.h>` , so we only look the end part:



```
# 3 "main.c" 2


int main()
{
 int a = calc(12, 13 , 14);
 if (a >= 1000)
  printf("Over Limit!\n");
 else
  printf("Result: %d", a);

 return 0;
}
```

`#include "calc.h"` has been replaced by `int calc(int, int, int);` , which is in the header file, and the macro `MAXNUM` has also been replaced by corresponding `1000` .

Use compiler `gcc`

Next, the preprocessed code is used by compiler. For some internal details of compiler, please see my another blog “What is the differences between gcc and Clang/LLVM?”

Since the compiler is `gcc` , we still need to use `gcc -S` to convert the preprocessed file into an assembly code file:

```
$ gcc -S main.i calc.i
$ ls
calc.i  calc.s  main.i  main.s
```

The file generated is in assembly language:

```
        .file   "calc.c"
        .text
        .globl  calc
        .type   calc, @function
calc:
.LFB0:
        .cfi_startproc
        endbr64
        pushq   %rbp
        .cfi_def_cfa_offset 16
        .cfi_offset 6, -16
        movq    %rsp, %rbp
        .cfi_def_cfa_register 6
        movl    %edi, -4(%rbp)
        movl    %esi, -8(%rbp)
        movl    %edx, -12(%rbp)
        movl    -4(%rbp), %eax
        imull   -8(%rbp), %eax
        .cfi_def_cfa 7, 8
        ret
        .cfi_endproc
.LFE0:
        .size   calc, .-calc
        .ident  "GCC: (Ubuntu 11.3.0-1ubuntu1~22.04.1) 11.3.0"
        .section        .note.GNU-stack,"",@progbits
        .section        .note.gnu.property,"a"
        .align 8
        .long   1f - 0f
        .long   4f - 1f
        .long   5
0:
        .string "GNU"
1:
        .align 8
        .long   0xc0000002
        .long   3f - 2f
2:
        .long   0x3
3:
        .align 8
4:
```

Notice, if you want to use assembly code generated like above, you maybe need to read my articles: 「Updating」The syntax style of Apple's as assembler, because I know that many people learn assembly through university or textbooks, and many textbooks are base on Microsoft's `masm` assembler-style assembly language (Intel syntax), which is different from the syntax of as (AT&T syntax), is in some places opposite. Although Apple wrote its own `as`, it is only slightly different from GNU's as. Many syntaxes are almost the same, so you can refer to them.

However, not recommended to use the assembly code generated by `gcc` to learn assembly, because there are too many things hidden. You can see how many libraries are referenced in the `ld` part later.

Use assembler as

We will use assembler `as` to convert the assembly file into an object file (containing machine language), which requires `as` , which will automatically replace the suffix like `gcc -c` :

```
$ as calc.s -o calc.o
$ as main.s -o main.o
$ ls
a.out  calc.o calc.i  calc.s  main.i  main.o main.s
```

You don't process two files at one time, otherwise happen error like:

```
main.s:12: Error: symbol `.LFB0' is already defined
main.s:45: Error: symbol `.LFE0' is already defined
```

Because both files have `.LFB0` and `.LFE0` section, they are repeated. So you can compile them separately and the link will automatically process them later. Or you also can drop these parts manually to generate it into one object file.

Using linker `ld`

To be honest, `ld` is only used for display. Even if you are handwriting assembly code, it is recommended to use `gcc` for link, rather than use `ld`. Because the reference library of Ubuntu is very complicated now, the path accessible by `ld` is empty by default and so you need to set manually. The use of `crt0.o` mentioned in the documentation and on the Internet also not work.

How linker work

In order to introduce the linker, first need to explain how the program runs. You can read some professional books yourself for details. I just give a simple explanation: the essence of the program is a file that stores machine code. After executing, it will be put into the memory. Whether it is swap or any memory storage mechanism, logically it is continuous. There is a program counter that will record the current absolute memory address. When the memory address reaches the space of this program, it will start calling the instructions of this program to perform operations. So no matter how you jump or loop, it is actually continuous and sequential.

The file that stores instructions is object file, but the order may be wrong, or instructions of the referenced external library may not be included. So we need linker to put these instructions together in right order.

If you use `file` command to view the `main.o`, you can see it is a “relocatable” file:

```
$ file main.o
main.o: ELF 64-bit LSB relocatable, x86-64, version 1 (SYSV), not stripped
```

If you run it, it will show:

```
$ ./main.o
-bash: ./main.o: cannot execute binary file: Exec format error
```

Linker will “link” it and other object file together, allocate relative address of each section, final get an execution file. After that, if program is running, process will gengerate absolute address.

Use `ld` to finish

If you use `ld` to simply link the two object files, the following error will occur:

```
ld: main.o: in function `main':
main.c:(.text+0x37): undefined reference to `puts'
ld: main.c:(.text+0x52): undefined reference to `printf'
```

There are two types of errors, let's explain below:

- The first error `ld: warning: cannot find entry symbol _start; defaulting to 0000000000401000` is because the default entry of the Ubuntu program is `_start` instead of the classic `main`, so it needs to be modified.
- The second error is because `puts` and `printf` are part of the C standard library, but `ld` does not automatically call and connect the C standard library and needs to be called manually.

In order to fixing these errors, the simple command is as follows (actually the program generated by this command has error):

```
ld main.o calc.o -o calc -I/lib64/ld-linux-x86-64.so.2 -lc -e main
```

`ld` will no longer report error, but when you run the generated executable program, you will find that although `Over Limit!` is output, the error `Segmentation fault (core dumped)` will be reported. as follows:

```
$ ./calc
Over Limit!
Segmentation fault (core dumped)
```

The `Segmentation fault (core dumped)` error is because the settings of link are incorrect (the library is incorrect or not enough), so generated executable program will access memory space that out of process space.

To solve this problem, the complete command will be very long.

If it's Ubuntu 20.04:

```
ld -o calc -I /usr/lib/gcc/x86_64-linux-gnu/9/collect2 -plugin /usr/lib/gcc/x86_64-linux
```

If Ubuntu (WSL):

```
$ ld -o calc -I /usr/lib/gcc/x86_64-linux-gnu/11/collect2 -plugin /usr/lib/gcc/x86_64-li
```

You can copy it to see how long this command is. When you use `gcc` to generate a program, `gcc` will call `ld` and above flags and options to generate. So when you need to link in actual work, you just use `gcc` directly.

```
$ ./calc
Over Limit!
```

I learned a lot when writing this article, I hope these will help someone in need~