Linking: from the object file to the executable

An overview of static and dynamic linking

Andrea Gussoni
andrea1.gussoni at polimi.it

Politecnico di Milano

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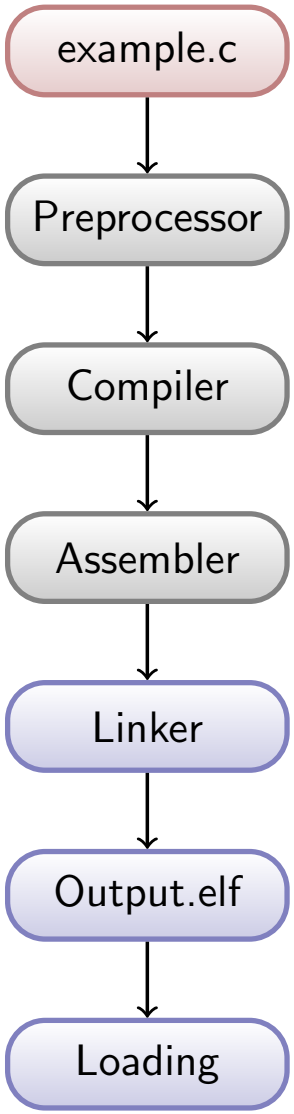
Compiler Pipeline



ELF file structure

- An object file is the final form of a translation unit,
- It's divided in several sections:

`.text`	Machine code
`.data`	Initialized writable data
`.bss`	Non-initilized writable data
`.rodata`	Read-only data
`.eh_frame`	Stack-frame information for C++ exception handling
`.symtab`	Symbol table (variable and function names)
`.strtab`	Strings
`.rela.text`	Relocation section

Running Example

```c
#include <stdint.h>

uint32_t uninitialized;
uint32_t zero_initialized = 0;
const uint32_t constant = 0x41424344 ;
const uint32_t *initialized = &constant ;

uint32_t my_function(void) {
  return 42 + uninitialized;
}
```

Running Example

```
$ gcc -c example.c -o example.o -fno-PIC -fno-stack-protector
```

Running Example

```
$ readelf -h example.o
ELF Header:
  Magic:   7f 45 4c 46 02 01 01 00 00 00 00 00 00 00 00 00
  Class:                             ELF64
  Data:                              2's complement, little endian
  Version:                           1 (current)
  OS/ABI:                            UNIX - System V
  ABI Version:                       0
  Type:                              REL (Relocatable file)
  Machine:                           Advanced Micro Devices X86-64
  Version:                           0x1
  Entry point address:               0x0
  Start of program headers:          0 (bytes into file)
  Start of section headers:          768 (bytes into file)
  Flags:                             0x0
  Size of this header:               64 (bytes)
  Size of program headers:           0 (bytes)
  Number of program headers:         0
  Size of section headers:           64 (bytes)
  Number of section headers:         14
  Section header string table index: 13
```

Running Example

```
$ objdump -d -j .text example.o

Disassembly of section .text:

0000000000000000 <my_function>:
   0:   55                          push   rbp
   1:   48 89 e5                    mov    rbp,rsp
   4:   8b 05 00 00 00 00           mov    eax,[rip+0x0]
   a:   83 c0 2a                    add    eax,0x2a
   d:   5d                          pop    rbp
   e:   c3                          ret
```

Sections

```
$ readelf -S --wide example.o

There are 14 section headers, starting at offset 0x300:

Section Headers:
  [Nr] Name              Type            Off    Size   ES Flg Lk Inf
  [ 0]                   NULL            000    000    00      0   0
  [ 1] .text             PROGBITS        040    00f    00  AX  0   0
  [ 2] .rela.text        RELA            250    018    18   I 11   1
  [ 3] .data             PROGBITS        050    008    00  WA  0   0
  [ 4] .rela.data        RELA            268    018    18   I 11   3
  [ 5] .bss              NOBITS          058    004    00  WA  0   0
  [ 6] .rodata           PROGBITS        058    004    00   A  0   0
  ...
  [11] .symtab           SYMTAB          0c0    150    18     12   9
  [12] .strtab           STRTAB          210    03f    00      0   0
  [13] .shstrtab         STRTAB          298    066    00      0   0
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```

Sections

We'll see where uninitialized variables are stored later.

.text

```
$ objdump -d -j .text example.o

Disassembly of section .text:

0000000000000000 <my_function>:
   0:   55                          push   rbp
   1:   48 89 e5                    mov    rbp,rsp
   4:   8b 05 00 00 00 00           mov    eax,[rip+0x0]
   a:   83 c0 2a                    add    eax,0x2a
   d:   5d                          pop    rbp
   e:   c3                          ret
```

.data, .rodata and .bss

```
$ objdump -s -j .data -j .rodata -j .bss example.o

Contents of section .data:
 0000 00000000 00000000                    ........
Contents of section .rodata:
 0000 44434241                             DCBA
```

.bss

.bss is not stored on file, since its content it's all zeroes

Create custom sections

To create a custom section with GCC, you can use the following attribute:

```
__attribute__ ((section ("mysection")))
```

Symbols

- A symbol is a label for a piece of code or data
- A symbol is composed by:

`st_name`	Index of the name in the symbol string table
`st_value`	Symbol offset in the table
`st_size`	Symbol size
`st_info`	Symbol type and binding
`st_other`	Symbol visibility
`st_shndx`	Index of the containing section

Undefined symbols

- If the value of `st_shndx` is equal to `0`, it means that the symbol is not defined in the current translation unit.
- Later on, the linker will be tasked with the resolution of all these symbols.

Common symbols

If st_shndx is `COM (0xfff2)`, it's a common symbol

- Used for uninitialized global variables
- You can have multiple definition in different TUs
- They can have different size, the largest will be chosen.
- It has no storage associated in any object file
- It ends up in .bss

Symbol Types

A symbol have an associated type:

`STT_OBJECT`	Data object (variable, array)
`STT_FUNC`	Function
`STT_SECTION`	Section
`STT_FILE`	Source file associated

Symbol binding

The binding property of a symbol specifies how it can be used in other translation units:

STB_LOCAL	Symbol is not visible outside the current translation unit
STB_GLOBAL	Symbol visible to all the translation units
STB_WEAK	Like GLOBAL, but the definition has lower precedence

Symbol visibility

- A *module* is an executable or a dynamic library
- The symbol visibility specifies the symbol exported from the current executable or library
- Standard executables usually do not export symbols

Symbol visibility

The visibility type can be:

`STV_DEFAULT`	Global and weak symbols available
`STV_PROTECTED`	Available, but uses own version
`STV_HIDDEN`	Unavailable, always use own version

Symbol table example

```
$ readelf -r example.o

 Num:  Value   Size  Type     Bind   Vis       Ndx  Name
   0:  00000      0  NOTYPE   LOCAL  DEFAULT   UND
   1:  00000      0  FILE     LOCAL  DEFAULT   ABS  example.c
   2:  00000      0  SECTION  LOCAL  DEFAULT     1
  ...
   9:  00004      4  OBJECT   GLOBAL DEFAULT   COM  uninitialized
  10:  00000      4  OBJECT   GLOBAL DEFAULT     5  zero_initialized
  11:  00000      4  OBJECT   GLOBAL DEFAULT     6  constant
  12:  00000      8  OBJECT   GLOBAL DEFAULT     3  initialized
  13:  00000     15  FUNC     GLOBAL DEFAULT     1  my_function
```

Relocations

Relocations are directives for the loader, that instruct it to write the value of a certain symbol in a certain location

Structure of a relocation

- Relocations are organized in *relocation tables*
- There can be a relocation table for each section
- The field composing a relocation are:

  `r_offset` Offset in the section where to write
  `r_info` Type of the relocation and symbol identifier
  `r_addend` Constant value to add to the value

Relocation types

- In `r_info` it is specified how the relocation should write the symbol's value
- Relocation types are architecture-specific, e.g.:

`R_X86_64_64`	Full symbol value (64 bit)
`R_X86_64_PC32`	Offset from the relocation target (32 bit)

Relocation Example

```
$ readelf -r example.o

Relocation section '.rela.text' contains 1 entry:
  Offset   Type            Sym. Name + Addend
  000006   R_X86_64_PC32   uninitialized + 0

Relocation section '.rela.data' contains 1 entry:
  Offset   Type            Sym. Name + Addend
  000000   R_X86_64_64     constant + 0
```

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The Linker

- The linker is usually invoked directly by the compiler (with gcc you can see the invocation with the -v flag).
- The main linkers are:
  - `ld.bfd` High retrocompatibility, not optimized
  - `ld.gold` Elf-only, optimized
  - `lld` LLVM-based, "limited" application, hugely optimized

The Linker

- Take all the input object files
- Lay out the output binary
- Build the final symbol table
- Apply all the relocations
- Output the final executable or dynamic library

Binary layout

- Fix a starting address for each section name
- Concatenate all the sections with the same name
- Keep sections with same features close to each other

Building the symbol table

- Scan all the input symbol tables and merge them
- Set symbol values to their final virtual address
- Check all the undefined symbols have been resolved
- Check no symbol is defined twice

Relocations

Simply apply all the relocations directives using the symbols' final address

Before linking

```
$ objdump -d -j .text example.o

Disassembly of section .text:

0000000000000000 <my_function>:
   0:   55                      push   rbp
   1:   48 89 e5                mov    rbp,rsp
   4:   8b 05 00 00 00 00       mov    eax,[rip+0x0]
   a:   83 c0 2a                add    eax,0x2a
   d:   5d                      pop    rbp
   e:   c3                      ret
```

After linking

```
$ gcc main.c example.c -o main -fno-PIC -fno-stack-protector
$ objdump -d -j .text main

Disassembly of section .text:

0000000000000631 <my_function>:
 631:   55                      push   rbp
 632:   48 89 e5                mov    rbp,rsp
 635:   8b 05 e5 09 20 00       mov    eax,[rip+0x2009e5] # 201020
 63b:   83 c0 2a                add    eax,0x2a
 63e:   5d                      pop    rbp
 63f:   c3                      ret
```

Static libraries

- Static libraries (`.a` files) are copied in the final executable
- They are an archive composed by object files

```
ar rcs mylib.a example.o foo.o
ranlib mylib.a
```

- Typically a library is linked with the `-l` parameter

```
gcc -lmylib main.c -o main.o
```

- Only the object files providing otherwise undefined symbols will be linked in

Memory mapping

Similar sections of different objects will be mapped together in the final linking:

- Code will go in an executable page
- Read-only data will go in a read-only page
- Writeable data will go in a writeable page

Memory Layout

- In memory the sections will be grouped together if they require identical permissions
- Segments are defined in the program headers
- A segment is described by:

`p_offset`	Offset from the beginning of the file
`p_vaddr`	Virtual address in memory where it should be loaded
`p_filesz`	Size of the segment in the file
`p_memsz`	Size of the segment in memory
`p_flags`	Permissions

Standard segments

Programs are usually composed by two segments:

+rx `.text`, `.rodata`, `.plt`

+rw `.got`, `.data`, `.bss`

Loader

- At program startup, the kernel reads the program headers and maps the required pages in memory setting the appropriate permissions
- Why `p_filesz` and `p_memsize` are both specified?
- They may differ (e.g., `.bbs` which is all zeroes)
- The exceeding portion is zero-initialized

Loader

- At program startup, the kernel reads the program headers and maps the required pages in memory setting the appropriate permissions
- Why `p_filesz` and `p_memsize` are both specified?
- They may differ (e.g., `.bbs` which is all zeroes)
- The exceeding portion is zero-initialized

```
$ readelf -l main

Program Headers:
  Type   Offset VirtAddr FileSiz  MemSiz   Flg Align
  ...
  LOAD   0x0000 0x000000 0x000838 0x000838 R E 0x200000
  LOAD   0x0df0 0x200df0 0x000228 0x000238 RW  0x200000
  ...

 Section to Segment mapping:
  Segment Sections...
  ...
   02     .text .rodata
   03     .data .bss
  ...
```

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Dynamic linking

- Dynamic linking is needed to support dynamic libraries
- Why dynamic linking?:
  - Fix a bug in a library $\Rightarrow$ fix all the binaries that uses it
  - Library loaded in memory only once $\Rightarrow$ save memory
  - Do not replicate code $\Rightarrow$ save disk space

Dynamic linking

- It is performed at run-time
- Loads the dynamic libraries in memory
- Resolves the address of symbols in dynamic libraries

Dynamic linker

```
$ readelf -l main
Elf file type is DYN (Shared object file)
Entry point 0x540
There are 9 program headers, starting at offset 64

Program Headers:
  Type      Offset   VirtAddr FileSiz MemSiz Flg Align
  ...
  INTERP    0x000238 0x000238 0x0001c 0x001c R   0x1
  [Requesting program interpreter: /lib64/ld-linux-x86-64.so.2]
```

Differences w.r.t. static linking

- Used sections:

  `.dynsym` Dynamic symbol table
  `.dynstr` String table for `.dynsym`
  `.rela.dyn` Dynamic relocation table

- Uses a different set of relocation types
- `r_offset` is not an offset in a section, but a virtual address

Dynamic libraries

- Dynamic libraries can be placed anywhere in the memory at runtime
- They can't have absolute addresses at linking time
- We can't patch them at run-time
- No dynamic relocations in `.text` or `.rodata`

Position Independent Code

- Dynamic libraries are usually compiled as `PIC`
- We can't use absolute addresses, since we do not know where they will be loaded
- The solution is to use the value of the program counter as a base index, and express all the addresses as offsets with respect to this value.
- Also the distance between `.text` and `.data` should be constant

Example

libone.c:

```
extern int libtwo_variable;

int libone_function(void) {
  return 42 + libtwo_variable;
}
```

libtwo.c:

```
int libtwo_variable = 0x42;

int libtwo_function(void) {
  return 0;
}
```

Building a dynamic library

- To create a dynamic library:

```
gcc -fPIC -c libone.c -o libone.o
gcc -shared -fPIC -o libone.so libone.o
```

- Linking against a dynamic library:

```
gcc main -c -lone -o main
```

- Dynamic libraries are not copied into the final executable
- They must be available in the predefined system paths (e.g. `/usr/lib`, `/lib`, ...)

Linking order

- Input object files are always linked in
- Their order doesn't matter
- Static and dynamic libraries order instead is important
- Suppose `libone.so` requires `libtwo.so`
- The `-ltwo` parameter must be passed before `-lone`
- You can use fixed-point linking with `--start-group`/`--end-group`:

```
gcc -Wl,--start-group -lone -ltwo -Wl,--end-group
```

Symbols in another library

How can we access symbols in another library?

- We can't patch `.text`
- Two main problems:
  - How can we access global variables defined in other modules?
  - How can we call functions defined in other modules?

The GOT

- The GOT (*Global Offset Table*), is the mechanism that enables dynamic resolution of external symbols at runtime.
- For global variables:
  - Contains a pointer-sized entry for each imported variables
  - It is populated at startup by the dynamic loader
  - Holds the runtime address of the variables

Example relocations

```
$ gcc -shared -fPIC -L. -ltwo libone.c -o libone.so
$ readelf -S libone.so

Section Headers:
  [Nr] Name  Type          Address Off  Size ES Flg Lk Inf
  ...
  [16] .got     PROGBITS  0200fd8 0fd8 0028 08  WA  0   0
  ...

$ readelf -r libone.so

Relocation section '.rela.dyn':
  Offset  Info      Type              Sym. Name + Addend
  ...
  200fe0  200000006 R_X86_64_GLOB_DAT libtwo_variable + 0
  ...
```

Example relocations

```
$ objdump -j .text -d libone.so

00000000000005ca <libone_function>:
 5ca:   push   rbp
 5cb:   mov    rbp,rsp
 5ce:   mov    rax,[rip+0x200a0b] # 200fe0 <libtwo_variable>
 5d5:   mov    eax,[rax]
 5d7:   add    eax,0x2a
 5da:   pop    rbp
 5db:   ret
```

External functions

- In principle we could apply the same procedure also for the functions.
- This means that at startup the dynamic loader should apply all the relocations
- Often programs import a lot of functions, but they are not actually used very often
- *Lazy loading* is a mechanism to resolve the address only when a function is actually used

New sections

- Dynamic loading requires three new sections:

`.plt`	Small code stubs to call library functions
`.got.plt`	Lazy GOT for library functions addresses
`.rela.plt`	Relocation table relative to `.got.plt`

Example

```
#include <stdio.h>

int main (void) {
  int a = 1;
  int b = 2;
  int c = a + b;

  printf("%d\n", c);
  return 0;
}

$ gcc example.c
```

Sections

```
$ readelf -S a.out
Section Headers:
  [Nr] Name              Type            Address          Size   ES Flg Lk Inf
  ...
  [10] .rela.plt         RELA            00004a0 000018 18   AI  5  23
  [12] .plt              PROGBITS        00004d0 000020 10   AX  0   0
  ...
  [14] .text             PROGBITS        0000500 0001c2 00   AX  0   0
  ...
  [22] .got              PROGBITS        0200a20 000028 08   WA  0   0
  [23] .got.plt          PROGBITS        0200a48 000020 08   WA  0   0
  ...
```

.text

```
$ objdump -d -j .text a.out
Disassembly of section .text:

000000000000060a <main>:
...
 63c: e8 9f fe ff ff   callq  4e0 <printf@plt>
...
```

`.plt` section

- For each function, in the `.plt` section we have a little stub of code which is used for the lazy loading
- The first entry in the `.plt` is the code used to invoke the dynamic loader during lazy loading

.plt section

```
$ objdump -d -j .plt a.out

Disassembly of section .plt:

00000000000004d0 <.plt>:
 4d0:   ff 35 7a 05 20 00      pushq  0x20057a(%rip)
 4d6:   ff 25 7c 05 20 00      jmpq   *0x20057c(%rip)
 4dc:   0f 1f 40 00            nopl   0x0(%rax)

00000000000004e0 <printf@plt>:
 4e0:   ff 25 7a 05 20 00      jmpq   *0x20057a(%rip) # 200a60
 4e6:   68 00 00 00 00         pushq  $0x0
 4eb:   e9 e0 ff ff ff         jmpq   4d0 <.plt>
```

`.plt` section

- The first instruction is a jump to an address contained in the `GOT`.

Relocations

```
$ readelf -r a.out

Relocation section '.rela.plt':
Offset          Info           Type                     Sym. Name + Addend
200a60          200000007 R_X86_64_JUMP_SLO printf@GLIBC_2.2.5 + 0
```

.got section

```
Contents of section .got.plt:
  200a48 30082000 00000000 00000000 00000000  0. ............
  200a58 00000000 00000000 e6040000 00000000  ................
```

Relocations

- If we interpret that address in little endian, we obtain the address of the second instruction of the stub.
- The stub pushes `0` on the stack and call the dynamic loader
- The value which is pushed on the stack is simply an identifier for the function for which we need to resolve the address.

Relocations

- Isn't this mechanism expensive?
- Actually, only the first time the external function is called this mechanism is invoked
- The slot that we saw earlier in the GOT is overwritten with the actual value in memory of the external function
- In this way, from the second time on, no extra cost is paid

Section vs segments

- The loader knows only about program headers
- It can ignore at all the information about sections
- It uses `PT_DYNAMIC` which points directly to `.dynamic` which contains:
  - Needed libraries
  - Address and size of `.dynsym`, `.dynstr`, `.got.plt`, `.rela.plt`

.dynamic

```
$ readelf -l a.out

Elf file type is DYN (Shared object file)
Entry point 0x540
There are 9 program headers, starting at offset 64

Program Headers:
  Type      Offset   VirtAddr FileSiz  MemSiz   Flg
  ...
  DYNAMIC   0x000830 0x200830 0x0001f0 0x0001f0 RW
  ...

$ readelf -S a.out

Section Headers:
  [Nr] Name       Type      Address Off  Size ES Flg
  ...
  [21] .dynamic   DYNAMIC   0200830 830  01f0 10  WA
  ...
```

```
$ readelf -d a.out

Dynamic section at offset 0xdc8 contains 27 entries:
 Type              Name/Value
 (NEEDED)          Shared library: [libc.so.6]
 ..
 (STRTAB)          0x328
 (SYMTAB)          0x280
 (STRSZ)           132 (bytes)
 (SYMENT)          24 (bytes)
 (DEBUG)           0x0
 (PLTGOT)          0x200a48
 (PLTRELSZ)        24 (bytes)
 (PLTREL)          RELA
 (JMPREL)          0x4a0
 (RELA)            0x3e0
 (RELASZ)          192 (bytes)
 (RELAENT)         24 (bytes)
 ...
```

Section vs segments

- The section table is optional
- Also `.symtab` and `.strtab` are optional
- They are debugging information
- The `strip` tool can remove them to save space

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Relaxation

- Certain architectures offer different instructions for performing jumps depending on how "distant" the target is.
- In principle, the compiler cannot know how long the jump will be, and will therefore need to apply the most conservative assumptions
- This could lead to some inefficiency

Relaxation

- The compiler can introduce *relaxation hints*
- A smart linker can use this hints to reassign addresses and substitute inefficient instructions with more efficient ones

Reducing the code size

- It may happen that some functions, even if unused, are included in the final binary
- The compiler in fact cannot know if a non *static* function will be used
- Only the linker has the necessary visibility to know that

Reducing the code size

- Unfortunately the ELF linker works with a *per-section* granularity, and therefore will link sections as a whole.
- This is not true for example for the Mach-O format, which instead has a finer granularity

A workaround

- We can tell the compiler to emit a section for each function or data object:

```
gcc -ffunction-sections -fdata-sections
```

- Then we instruct the linker to drop all the sections which are not used:

```
gcc -Wl,--gc-sections
```

LTO

- Traditionally compilers optimize with a TU granularity
- LTO (`-flto`) optimizes the program as a whole
- The compiler emit an high-level, internal representation:

  `GCC` an ELF with sections containing GIMPLE

  `clang` a bitcode file containing the LLVM IR
- The linker will merge these IRs and optimize them

LTO

```
cat *.c > all.c

gcc all.c -o all
```

Pros and Cons

Pros:

- Larger visibility across multiple
- Larger optimization opportunities, as aggressive dead code optimization

Cons:

- Resource intensive
- Only a subset of the possible optimizations can be run

Security considerations

`-z relro` Some sections, including `.dynamic`, are marked read-only after they have been initialized by the dynamic loader (now default in Ubuntu 18.04)

`-z now` Disable lazy loading. All import symbols are resolved at startup, and `.got.plt` is marked read-only

`-pie` Compile also standard executables (not only libraries) as PIC, and produce a program which is completely relocatable in memory (default in current versions of GCC)

References I


Kishu Agarwal. *Life of a Binary*. URL: https://kishuagarwal.github.io/life-of-a-binary.html.


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Santa Cruz Operation. *System V Application Binary Interface*. URL: http://www.sco.com/developers/gabi/latest/contents.html.

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- Some credits also goes to this[2] nice write-up by Kishu Agarwal.

[1] https://home.deib.polimi.it/agosta/lib/exe/fetch.php?id=teaching%3Acompilers&cache=cache&media=teaching:cot_slides_linker.pdf

[2] https://kishuagarwal.github.io/life-of-a-binary.html

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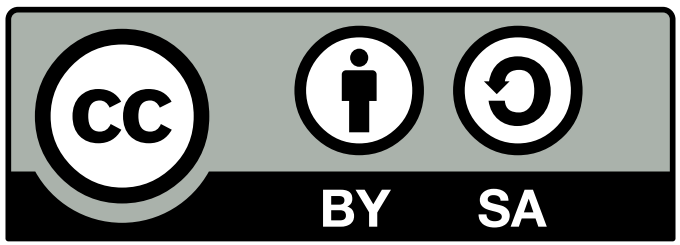

[3] https://creativecommons.org/licenses/by-sa/4.0/