

Lecture 18: Linking

Philipp Koehn

October 13, 2025

601.229 Computer Systems Fundamentals



Hello World

```
#include <stdlib.h>
#include <stdio.h>

int main(void) {
    printf("Hello world!\n");
    return EXIT_SUCCESS;
}
```

Compilation

- ▶ Compile

```
$ gcc -Og hello-world.c
```

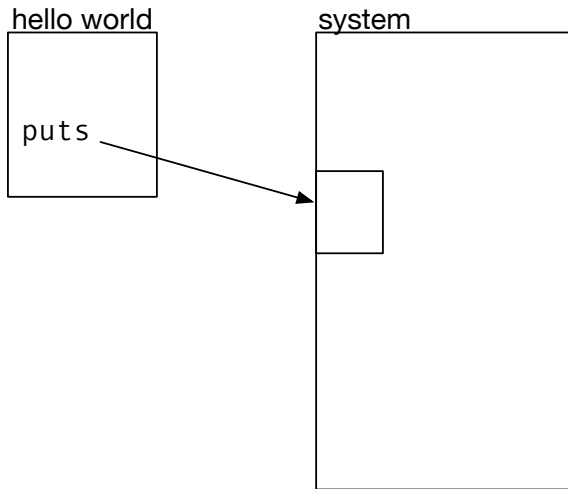
- ▶ Resulting program

```
$ ls -l a.out
```

```
-rwxr-xr-x. 1 phi users 8512 Nov 16 03:57 a.out
```

- ▶ That's pretty small!

Dynamic Linking



Static Linking

- ▶ Compile with `--static`
- ▶ Results in very large file
- ▶ Includes the entire library!

Benefits of Dynamic Linking

- ▶ Makes code smaller
 - ▶ needs less disk space
 - ▶ needs less RAM
- ▶ Library is not part of the compiled program
 - ⇒ when it gets updated, no need to recompile

Example: Code in 2 Files

main.c

```
int sum(int *a, int n);

int array[2] = {1, 2};

int main() {
    int val = sum(array, 2);
    return val;
}
```

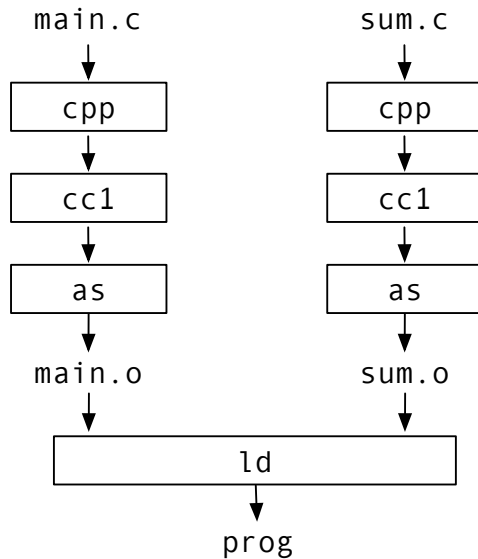
sum.c

```
int sum(int *a, int n) {
    int i, s = 0;
    for(i = 0; i<n; i++) {
        s += a[i];
    }
    return s;
}
```

Compile and Run

```
$ gcc -Og -o prog main.c sum.c  
$ ./prog  
$ echo $?  
3
```

Static Linking



Static Linking

- ▶ Symbol resolution
 - ▶ object files define and reference symbols (functions, global variables, static variables)
 - ▶ need to connect symbol to exactly one definition

Static Linking

- ▶ Symbol resolution
 - ▶ object files define and reference symbols (functions, global variables, static variables)
 - ▶ need to connect symbol to exactly one definition
- ▶ Relocation
 - ▶ assemblers generate object files that starts at address 0
 - ▶ when combining multiple object files, code must be shifted
 - ▶ all reference to memory addresses must be adjusted
 - ▶ assembler stores meta information in object file
 - ▶ linker is guided by relocation entries

Object Files

- ▶ Relocatable object file
 - ▶ binary code
 - ▶ meta information that allows symbol resolution and relocation
- ▶ Executable object file
 - ▶ binary code
 - ▶ can be copied into memory and executed
- ▶ Shared object file
 - ▶ binary code
 - ▶ can be loaded into memory
 - ▶ can be linked dynamically

Relocatable Object Files

- ▶ Executable and Linkable Format (ELF)
 - ▶ header
 - ▶ sections with different type of data
 - ▶ section header table

ELF header
.text
.rodata
.data
.bss
.symtab
.rel.text
.rel.data
.debug
.line
.strtab
Section header table

Sections

- .text** machine code of compiled program
- .rodata** read-only data (e.g., strings in printf statements)
- .data** initialized global and static C variables
- .bss** uninitialized global and static C variables
- .symtab** symbol table
- .rel.text** list of locations in .text section (machine code)
to be modified when object is relocated
- .rel.data** same for .data
- .debug** debugging symbol table
(only compiled with -g)
- .line** mapping between line number and machine code
(only compiled with -g)
- .strtab** string table for .symtab and .debug

Symbols

- ▶ Global symbols that can be used by other objects
- ▶ Global symbols of other objects (not defined here)
- ▶ Local symbols only used in object defined with "static" attribute
- ▶ Note: non-static local variable are not exposed

ELF Symbol Table Entry

Name	Pointer to string of symbol name
Type	Function or data type
Binding	Indicates local or global
Section	Index of which section it belongs to
Value	Section offset
Size	Size in bytes

Example

```
$ readelf -a main.o
```

```
Section Headers:
```

```
 [ 1] .text
```

```
 [ 3] .data
```

Num:	Value	Size	Type	Bind	Vis	Ndx	Name
8:	000000000000000000	24	FUNC	GLOBAL	DEFAULT	1	main
9:	000000000000000000	8	OBJECT	GLOBAL	DEFAULT	3	array
10:	000000000000000000	0	NOTYPE	GLOBAL	DEFAULT	UND	sum

- ▶ main is a function (FUNC) in section .text (1)
- ▶ array is an object (OBJECT) in section .data (3)
- ▶ sum is undefined (UND)

Symbol Resolution

- ▶ Linker must resolve all symbols to connect references to addresses
- ▶ Local symbols are contained to their object, each has a unique name
- ▶ Symbols in an object file may be undefined (listed as UND in symbol table)
⇒ these must be defined in other objects
- ▶ If not found, linker complains:

```
$ gcc -Og main.c  
/tmp/ccZzl3Pp.o: In function `main':  
main.c:(.text+0xf): undefined reference to `sum'  
collect2: error: ld returned 1 exit status
```

Static Libraries

- ▶ Goal: link various standard functions statically
→ binary without dependency
- ▶ Plan A
 - ▶ put everything into big libc.o
 - ▶ link it to the application object file
 - ▶ ... but that adds too big of a file
- ▶ Plan B
 - ▶ have separate object files printf.o, scanf.o, ...
 - ▶ link only the ones that are needed
 - ▶ ... but that requires a lot of tedious bookkeeping by programmer

Static Libraries

- ▶ Solution: archives
 - ▶ Combine object files `printf.o`, `scanf.o`, ... into archive `libc.a`
 - ▶ Let linker pick out the ones that are needed
- ```
$ gcc main.c /usr/lib/libc.a
```

# Static Libraries

- ▶ Solution: archives
- ▶ Combine object files `printf.o`, `scanf.o`, ... into archive `libc.a`
- ▶ Let linker pick out the ones that are needed  
`$ gcc main.c /usr/lib/libc.a`
- ▶ You can build your own libraries  
`$ ar rcs libmy.a my1.o my2.o my3.o`

# Relocation

- ▶ Multiple object files
- ▶ Merge all sections, e.g., all .data sections together
- ▶ Assign run time memory addresses for each symbol
- ▶ Modify each symbol reference
- ▶ This is aided by relocation entries

# Relocation Entry

|               |                                        |
|---------------|----------------------------------------|
| <b>Offset</b> | Offset of reference within object      |
| <b>Type</b>   | Relocation type                        |
| <b>Symbol</b> | Symbol table index                     |
| <b>Added</b>  | Constant part of relocation expression |

Type may be

- ▶ absolute 32 bit address, or
- ▶ address relative to program counter

# Zoom poll!

Consider the following code:

```
1: extern int a; // defined elsewhere
2:
3: void f(int b) {
4: a++;
5: b++;
6: printf("%d %d", a, b);
7: }
```

For which source lines are  
relocation entries needed to resolve  
the addresses of code or data?

- A. 4 only
- B. 5 only
- C. 6 only
- D. 4 and 6
- E. 4, 5, and 6

# Relocating Symbol Addresses

## ► main.o

|     |                |       |                |
|-----|----------------|-------|----------------|
| 0:  | 48 83 ec 08    | sub   | \$0x8,%rsp     |
| 4:  | be 02 00 00 00 | mov   | \$0x2,%esi     |
| 9:  | bf 00 00 00 00 | mov   | \$0x0,%edi     |
| e:  | e8 00 00 00 00 | callq | 13 <main+0x13> |
| 13: | 48 83 c4 08    | add   | \$0x8,%rsp     |
| 17: | c3             | retq  |                |

## ► Relocation entries

- a: R\_X86\_64\_32 array
- f: R\_X86\_64\_PC32 sum-0x4
- At line 9: reference to array
- At line e: reference to sum function (undefined in object)

0000000000000000 <sum>:

|     |                |           |                    |
|-----|----------------|-----------|--------------------|
| 0:  | b8 00 00 00 00 | mov       | \$0x0,%eax         |
| 5:  | ba 00 00 00 00 | mov       | \$0x0,%edx         |
| a:  | eb 09          | jmp       | 15 <sum+0x15>      |
| c:  | 48 63 ca       | movslq    | %edx,%rcx          |
| f:  | 03 04 8f       | add       | (%rdi,%rcx,4),%eax |
| 12: | 83 c2 01       | add       | \$0x1,%edx         |
| 15: | 39 f2          | cmp       | %esi,%edx          |
| 17: | 7c f3          | j1        | c <sum+0xc>        |
| 19: | f3 c3          | repz retq |                    |

# main.o + sum.o → prog

00000000004004f6 <main>:

```
4004f6: 48 83 ec 08
4004fa: be 02 00 00 00
4004ff: bf 30 10 60 00
400504: e8 05 00 00 00
400509: 48 83 c4 08
40050d: c3
```

000000000040050e <sum>:

```
40050e: b8 00 00 00 00
400513: ba 00 00 00 00
400518: eb 09
40051a: 48 63 ca
40051d: 03 04 8f
400520: 83 c2 01
400523: 39 f2
400525: 7c f3
400527: f3 c3
400529: 0f 1f 80 00 00 00 00
```

```
sub $0x8,%rsp
mov $0x2,%esi
mov $0x601030,%edi
callq 40050e <sum>
add $0x8,%rsp
retq

mov $0x0,%eax
mov $0x0,%edx
jmp 400523 <sum+0x15>
movslq %edx,%rcx
add (%rdi,%rcx,4),%eax
add $0x1,%edx
cmp %esi,%edx
jl 40051a <sum+0xc>
repz retq
nopl 0x0(%rax)
```

# Loading Executable Object Files

