Linking: Basic Concepts & Static Linking

Introduction to Computer Systems
15th Lecture, Nov. 11, 2021

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Outline of Linking

- **Linking: combining object files into programs**
  - Object files
  - Linking mechanism
    - Symbols and symbol resolution
    - Relocation
- **Libraries**
- **Dynamic linking, loading & execution**
- **Library inter-positioning**

Why Linkers?

- **Reason 1: Modularity**
  - Program can be written as a collection of smaller source files, rather than one monolithic mass.
  - Can build libraries of common functions (more on this later)
    - e.g., Math library, standard C library

Why Linkers? (cont)

- **Reason 2: Efficiency**
  - Time: Separate compilation
    - Change one source file, compile, and then relink.
    - No need to recompile other source files.
    - Can compile multiple files concurrently.
  - Space: Libraries
    - Common functions can be aggregated into a single file...
    - **Option 1: *Static Linking***
      - Executable files and running memory images contain only the library code they actually use
    - **Option 2: *Dynamic linking***
      - Executable files contain no library code
      - During execution, single copy of library code can be shared across all executing processes

Why bother learning about linker?

- **Help you build large programs.**
  - Linking errors link missing modules, libraries or incompatible library may be baffling and frustrating.
- **Help you avoid dangerous errors.**
  - Linkers decisions on symbol reference solving may silently affect the correctness of your program.
- **Help you understand how language scoping rules implemented.**
  - Global vs. local names, What does ***static*** really means.
- **Help you understand other important systems concepts.**
  - Virtual memory, paging an memory mapping.
- **Enable you to exploit shared libraries.**

Example C Program

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

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

int main(int argc, char** argv)
{
    int val = sum(array, 2);
    return val;
}
```

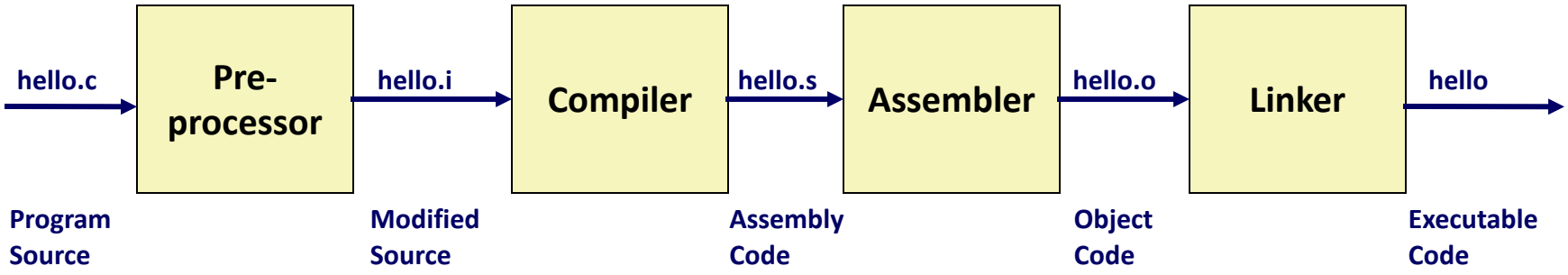
main.c

```c
int sum(int *a, int n)
{
    int i, s = 0;

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

sum.c

Compiler Driver，GCC as an Example

- **Gcc is the compiler driver in compilation toolchain.**
- **Gcc invokes several other compilation phases**
  - cpp, the preprocessor
  - cc1, the Compiler
  - as/gas, the assembler
  - ld, the linker
- **What does each one do? What are their outputs?**



Preprocessor

- **First, *gcc* compiler driver invokes *cpp* to generate expanded source**
  - Preprocessor just does text substitution/ gcc with option "-E"
  - Converts the C source file to another C source file
  - Expands "#" directives

```
#include <stdio.h>
#define FOO 4
int main(){
     printf("hello, world %d\n", FOO);
}
```

```
…
extern int printf (const char *__restrict __format,
    ...);
…
int main() {
 printf("hello, world %d\n", 4);
}
```

Directives of Preprocessor

- **Included files:**

```
#include <foo.h>          /* /usr/include/…  */
#include "bar.h"          /* within cwd */
```

- **Defined constants:**

```
#define MAXVAL   40000000
```

  - By convention, all capitals tells us it's a constant, not a variable.

- **Defined macros:**

```
#define MIN(x,y)    ((x)<(y) ? (x):(y))
```

- **Conditional compilation:**
  - Code you think you may need again.
- **Control your optimization flags**

```
#pragma optimize("-fno-common", on)
```

- **Extensions for your language or libraries**

```
#pragma omp parallel for
```

Example: Conditional Compilation for Debugging

- **Debug print statements**
  - Include or exclude code using DEBUG condition and #ifdef, #if preprocessor directive in source code.

```
#ifdef DEBUG          or  #if defined( DEBUG )
#endif
```

  - Set DEBUG condition via gcc –D DEBUG in compilation or within source code via #define DEBUG, More readable than commenting out.

```
#include <stdio.h>
int main() {
#ifdef DEBUG
  printf("Debug flag on\n");
#endif
  printf("Hello world\n"); return 0;
}
```

```
% gcc -o def def.c
% ./def
Hello world
```

```
% gcc -D DEBUG -o def def.c
% ./def
Debug flag on
Hello world
```

Example: Conditional Compilation for Portability

- **Compilers with "built in" constants defined**
- **Use to conditionally include code**
  - Operating system specific code

```
#if defined(__i386__) || defined(WIN32) || …
```

  - Compiler-specific code

```
#if defined(__ICC) || defined(__INTEL_COMPILER)
```

  - Processor-specific code

```
#if defined(__SSE__)
```

Compiler

- **Next, *gcc* invokes *cc1* to generate assembly code**
  - Translates high-level C code into assembly

```
…
extern int printf (const char *__restrict __format,
    ...);
…
int main() {
 printf("hello, world %d\n", 4);
}
```

```
        .section        .rodata
.LC0:
        .string "hello, world %d\n"

        .text
main:
        pushq   %rbp
        movq    %rsp, %rbp
        movl    $4, %esi
        movl    $.LC0, %edi
        movl    $0, %eax
        call    printf
        popq    %rbp
        ret
```

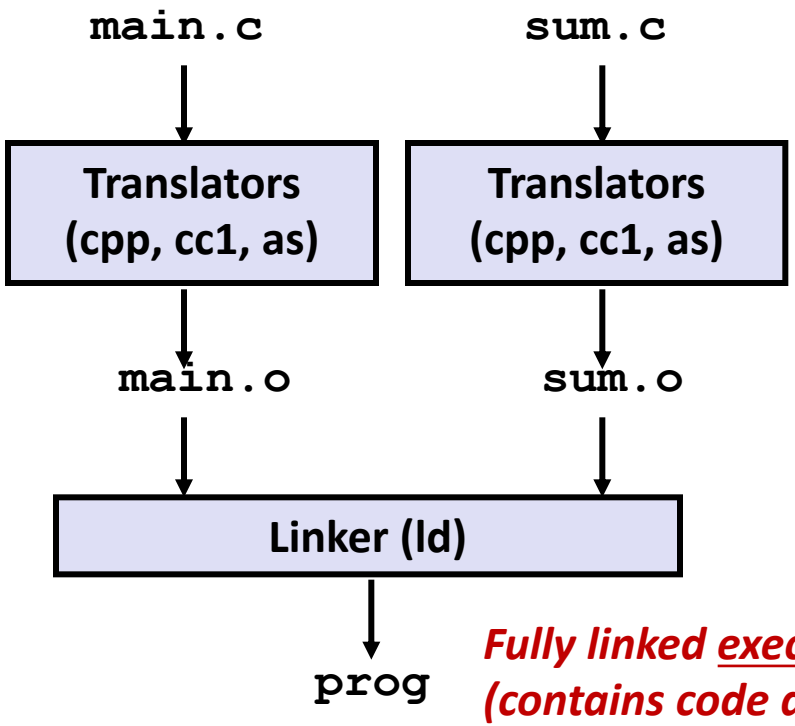
Assembler

- **Furthermore, *gcc* invokes *gas* to generate object code**
  - Translates assembly code into binary object code

```
#  readelf -a hello | grep rodata
   [10] .rodata           PROGBITS         0000000000495d40  00095d40

#  readelf -a hello | grep -E "GLOBAL.* main"
   1591: 0000000000401190    31 FUNC    GLOBAL DEFAULT    6 main

#  readelf -x .rodata hello
   Hex dump of section '.rodata':
   0x00495d40 01000200 68656c6c 6f2c2077 6f726c64 ....hello, world
   0x00495d50 2025640a 00464154 414c3a20 6b65726e  %d..FATAL: kern

#  objdump -d hello
   0000000000401190 <main>:
   401190:       55                      push   %rbp
   401191:       48 89 e5                mov    %rsp,%rbp
   401194:       be 04 00 00 00          mov    $0x4,%esi
   401199:       bf 44 5d 49 00          mov    $0x495d44,%edi
   40119e:       b8 00 00 00 00          mov    $0x0,%eax
   4011a3:       e8 d8 0e 00 00          callq  402080 <_IO_printf>
   4011a8:       b8 00 00 00 00          mov    $0x0,%eax
   4011ad:       5d                      pop    %rbp
   4011ae:       c3                      retq
   4011af:       90                      nop
```

Linking

- **Programs are translated and linked using a *compiler driver*:**
  - `linux> gcc -Og -o prog main.c sum.c`
  - `linux> ./prog`



Source files

Separately compiled relocatable object files

Fully linked executable object file (contains code and data for all functions defined in `main.c` and `sum.c`)

What Do Linkers Do?

- **Step 1: Symbol resolution**
  - Programs define and reference *symbols* (global variables and functions):
    - `void swap() {…}  /* define symbol swap */`
    - `swap();  /* reference symbol swap */`
    - `int *xp = &x;  /* define symbol xp, reference x */`
  - Symbol definitions are stored in object file (by assembler) in *symbol table*.
    - Symbol table is an array of entries
    - Each entry includes name, size, and location of symbol.
  - **During symbol resolution step, the linker associates each symbol reference with exactly one symbol definition.**

Symbols in Example C Program

Definitions

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

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

int main(int argc, char** argv)
{
    int val = sum(array, 2);
    return val;
}
```
main.c

```
int sum(int *a, int n)
{
    int i, s = 0;

    for (i = 0; i < n; i++) {
        s += a[i];
    }
    return s;
}
```
sum.c

Reference

```
# gcc -c -o main.o main.c
# gcc -c -o sum.o sum.c
# nm main.o
0000000000000000 D array
0000000000000000 T main
                 U sum
# nm sum.o
0000000000000000 T sum
```

You may also try:
objdump -t main.o
objdump -t sum.o

What Do Linkers Do? (cont)

- **Step 2: Relocation**
  - Merges separate code and data sections into single sections
  - Relocates symbols from their relative locations in the `.o` files to their final absolute memory locations in the executable.
  - Updates all references to these symbols to reflect their new positions.

Let's look at these two steps in more detail….

Three Kinds of Object Files (Modules)

- **Relocatable object file (`.o` file)**
  - Contains code and data in a form that can be combined with other relocatable object files to form executable object file.
    - Each `.o` file is produced from exactly one source (`.c`) file
- **Executable object file (`a.out` file)**
  - Contains code and data in a form that can be copied directly into memory and then executed.
- **Shared object file (`.so` file)**
  - Special type of relocatable object file that can be loaded into memory and linked dynamically, at either load time or run-time.
  - Called *Dynamic Link Libraries* (DLLs) by Windows

Three Kinds of Object Files under Linux

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

# file main
main: ELF 64-bit LSB executable, x86-64, version 1 (SYSV), dynamically
linked (uses shared libs), for GNU/Linux 2.6.24,
BuildID[sha1]=0x34c39011eac6fd0ebae938e4087e788b28a4f6dd, not stripped

# ldd main
        linux-vdso.so.1 =>  (0x00007fff9dbfe000)
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007f4bef587000)
        /lib64/ld-linux-x86-64.so.2 (0x00007f4bef956000)

# file /lib/x86_64-linux-gnu/libc.so.6
/lib/x86_64-linux-gnu/libc.so.6: symbolic link to `libc-2.15.so'

# file /lib/x86_64-linux-gnu/libc-2.15.so
/lib/x86_64-linux-gnu/libc-2.15.so: ELF 64-bit LSB shared object, x86-64,
version 1 (SYSV), dynamically linked (uses shared libs),
BuildID[sha1]=0x760efc6878e468a84b60e307a5bad802cbe2a480, for GNU/Linux
2.6.24, stripped
```

Relocatable object file (.o file)

Executable object file (a.out file)

Shared object file (.so file)

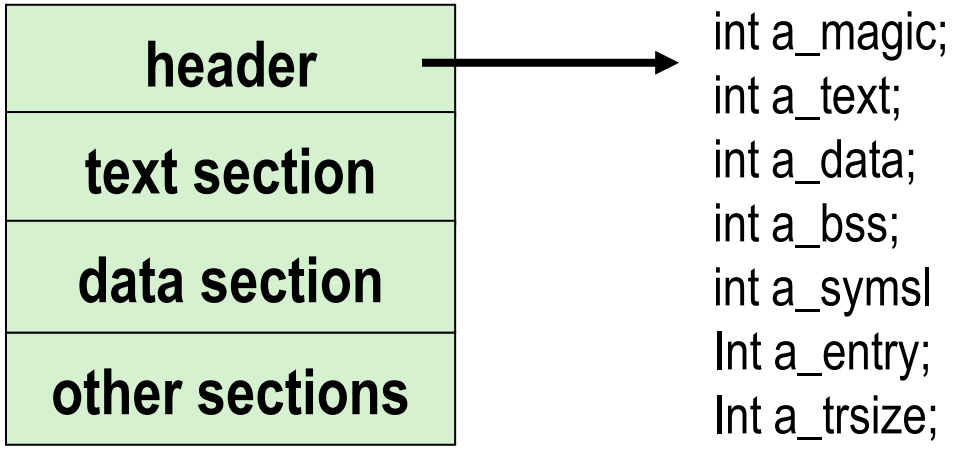
Object File Format

- **Unix like System**
  - Early Unix had a simple a.out format until early days of free Linux/BSD
  - AT&T's 2nd try was COFF, still limited, but widely adopted with changes
  - AT&T's third try was ELF, now used in almost all Unix systems
- **Early DOS and Windows had several limited formats**
- **Since the 32-bit era, Windows uses the PE (Portable Executable) format, partially derived from COFF**
- **OS X era Apple (including iOS, etc) uses a format named Mach-O**

Although our discussion will focus on ELF, basic concepts are similiar

Simplest Object File Format (Cont.)

- **The NULL object format: DOS COM Files**
  - Only have binary code. Fits in a single segment. No relocation.
  - DOS EXE file header has *relocation table*.
    program_base_address + segment_number + offset
- **Unix simple a.out format**
  - Can be linked to start at a fixed address. No relocation needed at load-time.
  - Hard to support dynamic linking

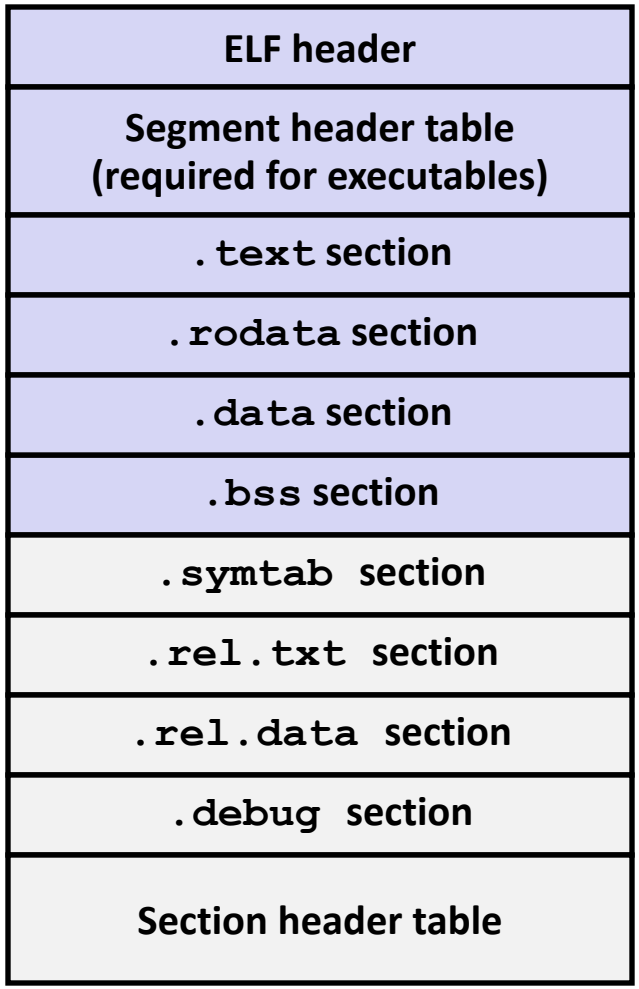


Executable and Linkable Format (ELF)

- **Standard binary format for object files**
- **One unified format for**
  - Relocatable object files (`.o`),
  - Executable object files (`a.out`)
  - Shared object files (`.so`)
- **Generic name: ELF binaries**
- **First appeared in System V Release 4 Unix, c. 1989**
- **Linux switched to ELF c. 1995, BSD later at c. 1998-2000**

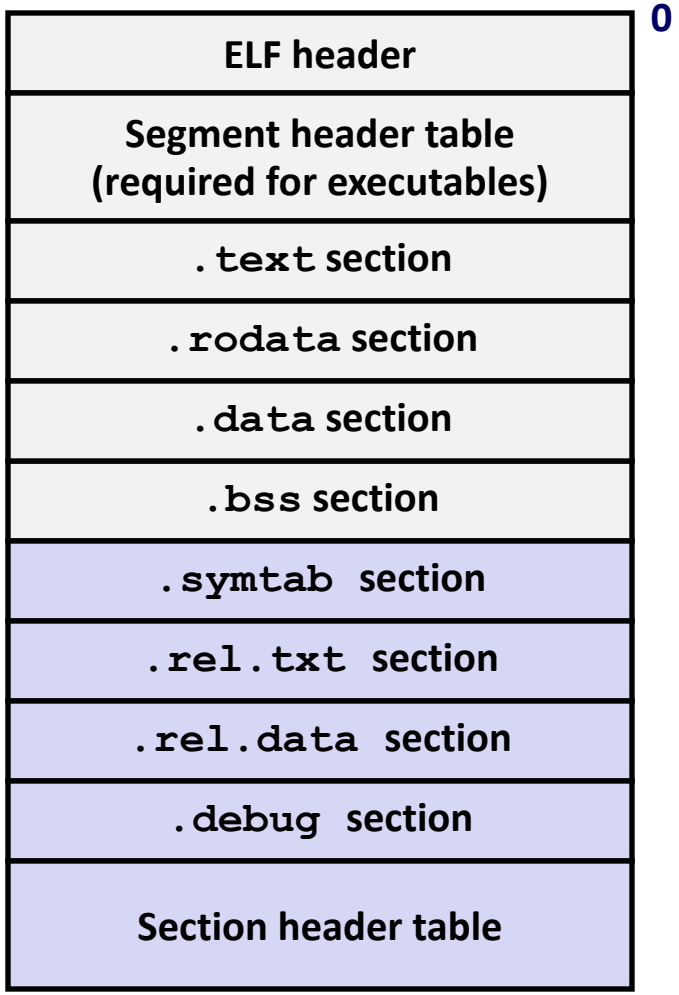
ELF Object File Format

- **ELF header**
  - Word size, byte ordering, file type (.o, exec, .so), machine type, etc.
- **Segment header table**
  - Page size, virtual address memory segments (sections), segment sizes.
- **`.text` section**
  - Code
- **`.rodata` section**
  - Read only data: jump tables, string constants, ...
- **`.data` section**
  - Initialized global variables
- **`.bss` section**
  - Uninitialized global variables
  - "Block Started by Symbol"
  - "Better Save Space"
  - Has section header but occupies no space



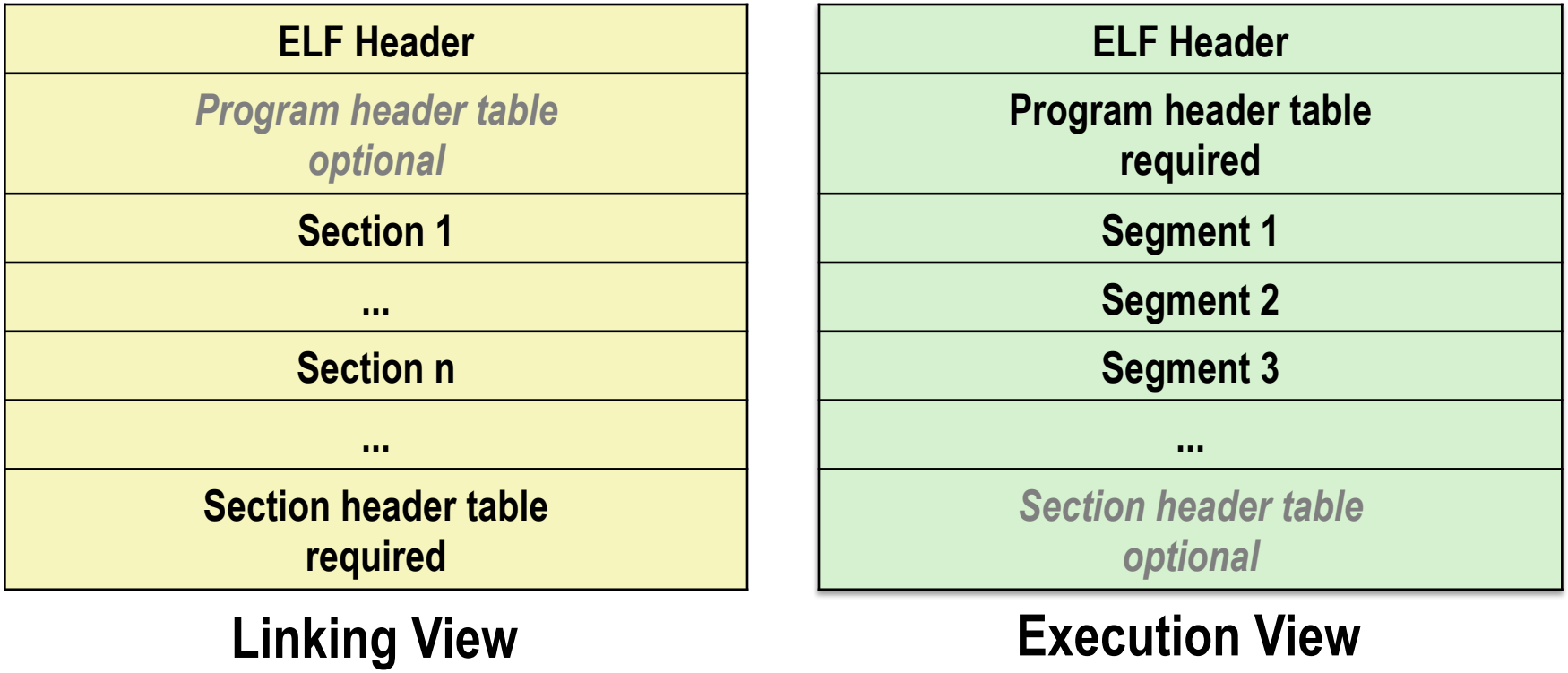
ELF Object File Format (cont.)

- **`.symtab` section**
  - Symbol table
  - Procedure and static variable names
  - Section names and locations
- **`.rel.text` section**
  - Relocation info for `.text` section
  - Addresses of instructions that will need to be modified in the executable
  - Instructions for modifying.
- **`.rel.data` section**
  - Relocation info for `.data` section
  - Addresses of pointer data that will need to be modified in the merged executable
- **`.debug` section**
  - Info for symbolic debugging (`gcc -g`)
- **Section header table**
  - Offsets and sizes of each section



Parallel Views of a ELF File

- ***Program header table/Segments*** **is used to build a process image (execute a program); relocatable files don't need it.**
- **Files used during linking must have a *section header table/Sections*.**



Linker Symbols

- **Global symbols**
  - Symbols defined by module *m* that can be referenced by other modules.
  - E.g.: non-**`static`** C functions and non-**`static`** global variables.

- **External symbols**
  - Global symbols that are referenced by module *m* but defined by some other module.

- **Local symbols**
  - Symbols that are defined and referenced exclusively by module *m*.
  - E.g.: C functions and global variables defined with the **`static`** attribute.
  - **Local linker symbols are *not* local program variables**

Symbol Table

- Symbol tables are built by assembler, using symbols exported by the compiler into the assembly language .s file.
- An ELF symbol table is contained in the *.symbol* section. It contains an array of entries.

source code of glibc/elf/elf.h

```
529 typedef struct
530 {
531   Elf64_Word st_name; /* Symbol name (string tbl index) */
532   unsigned char st_info; /* Symbol type and binding */
533   unsigned char st_other; /* Symbol visibility */
534   Elf64_Section st_shndx; /* Section index */
535   Elf64_Addr st_value; /* Symbol value */
536   Elf64_Xword st_size; /* Symbol size */
537 } Elf64_Sym;
```

Element of Symbol Table Structure

- **st_name(name)**
  - Byte offset into the string table, which holds the name of the symbols.
- **st_value(value)**
  - gives the alignment constraints for COMMON symbols.
  - In other relocatable files, it holds a section offset for a defined symbol
  - In executable and shared object files, st_value holds a virtual address.
- **st_size(size)**
  - A data object's size is the number of bytes contained in the object.
  - Holds 0 if the symbol has no size or an unknown size.
- **st_info (type & binding)**
  - st_type is usually data or function.
  - Binding field indicates whether the symbol is local, global or week.
- **st_shndx(section)**
  - holds the relevant section header table index.
  - Every symbol table entry is defined in relation to some section.

Pseudo Sections for Section Header Index (*st_shndx*)

- **Every symbol table entry is defined in relation to some section. *st_shndx* holds the relevant section header table index.**
- **Some section indexes indicate special meanings.**
- **SHN_ABS(st_shndx == 0xfff1)**
  - Absolute values for the corresponding reference.
  - Symbols are not affected by relocation.
- **SHN_UNDEF(st_shndx == 0x0)**
  - The symbol is undefined. When the link editor combines this object file with another that defines the indicated symbol, this file's references to the symbol will be linked to the actual definition..
- **SHN_COMMON(st_shndx == 0xfff2)**
  - Uninitialized data objects that are not yet allocated. The link editor will allocate space for the symbol at an address that is a multiple of ***st_value***.
  - E.g. FORTRAN common block or unallocated C external variables.

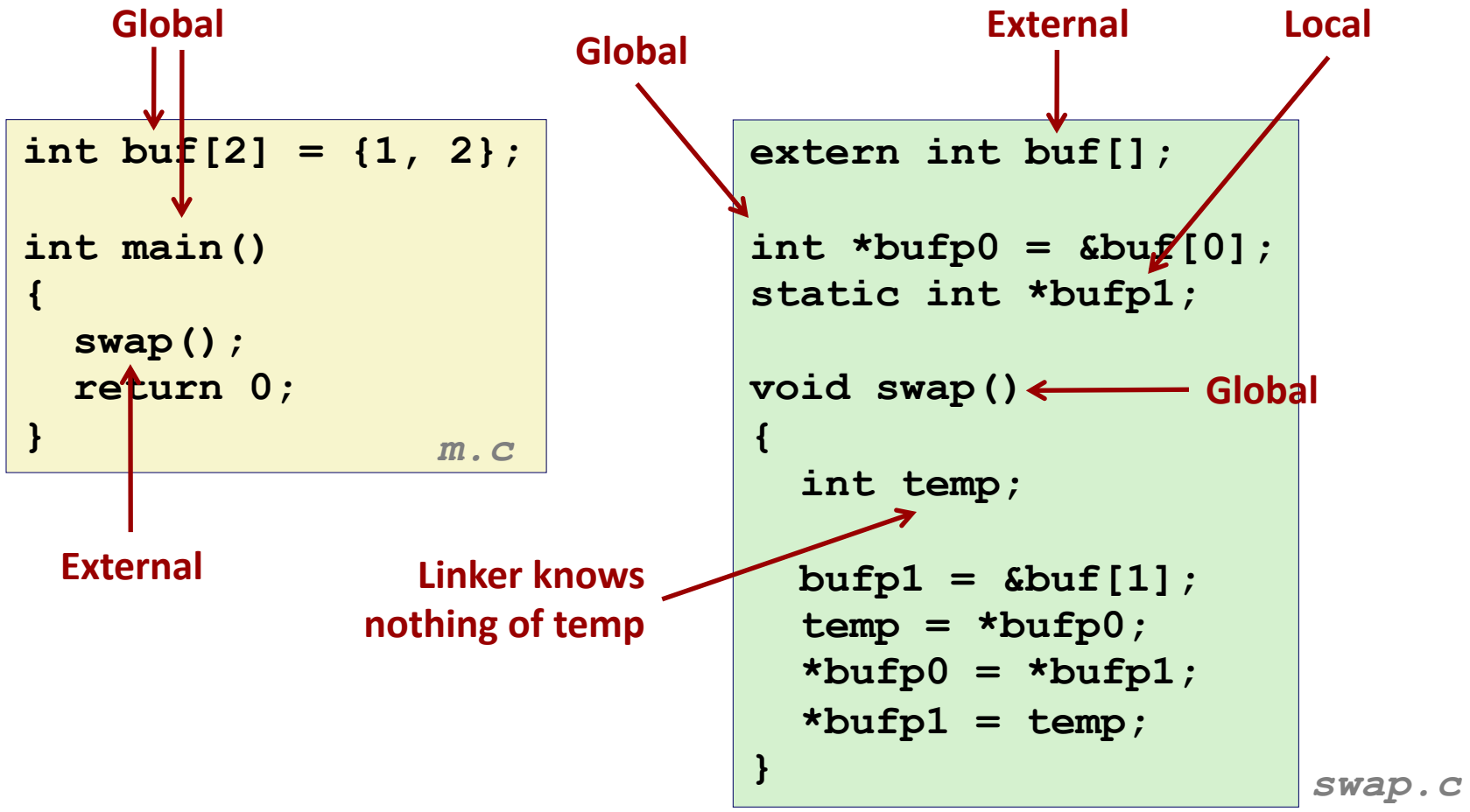
Section *COMMON* vs. Section *.bss*

- Distinction between COMMON and .bss is subtle.
- Modern versions of GCC assign symbols in relocatable object files to COMMON and .bss using the following conventions.

	Global Variables	Static Variables
Uninitialized	COMMON	.bss
Initialized to Zero	.bss	.bss
Initialized to Non-Zero	.data	.data

- Variables may be in COMMON or .bss in relocatable object files, both in .bss in executable files.

Symbol Table Entries (Fig. 7-5 in textbook)



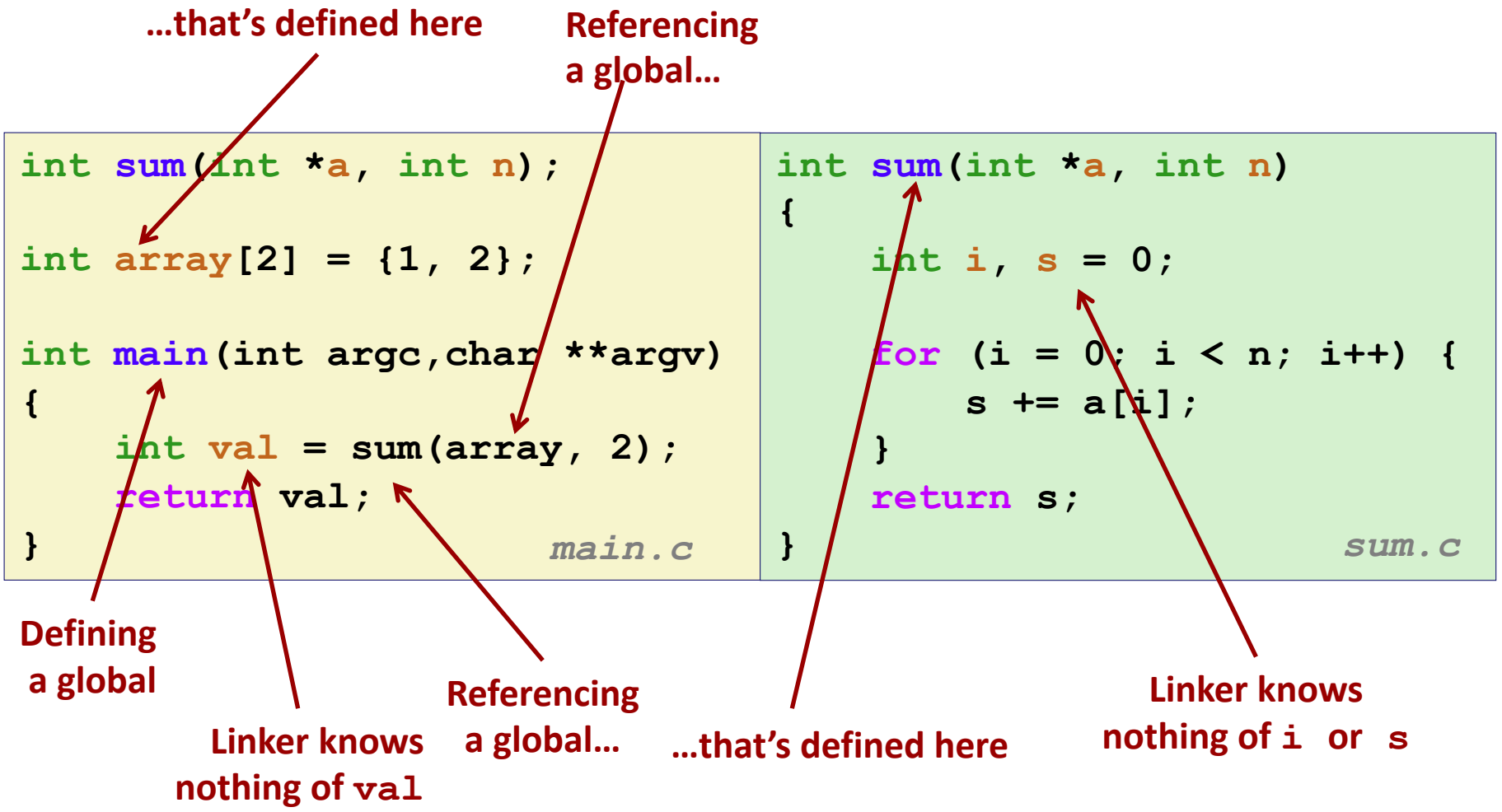
Symbol Table Entries (Fig. 7-5 in textbook)

```
# objdump -r -d -t m.o | head -n 15
m.o:     file format elf64-x86-64
SYMBOL TABLE:
0000000000000000 l    df *ABS*  0000000000000000 m.c
0000000000000000 l    d  .text  0000000000000000 .text
0000000000000000 l    d  .data  0000000000000000 .data
0000000000000000 l    d  .bss   0000000000000000 .bss
0000000000000000 l    d  .note.GNU-stack0000000000000000 .note.GNU-stack
0000000000000000 l    d  .eh_frame      0000000000000000 .eh_frame
0000000000000000 l    d  .comment       0000000000000000 .comment
0000000000000000 g     O .data  0000000000000008 buf
0000000000000000 g     F .text  0000000000000015 main
0000000000000000         *UND*  0000000000000000 swap

# readelf -s m.o
Symbol table '.symtab' contains 11 entries:
   Num:    Value          Size Type    Bind   Vis      Ndx Name
     0: 0000000000000000     0 NOTYPE  LOCAL  DEFAULT  UND
     1: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS m.c
     2: 0000000000000000     0 SECTION LOCAL  DEFAULT    1
     3: 0000000000000000     0 SECTION LOCAL  DEFAULT    3
     4: 0000000000000000     0 SECTION LOCAL  DEFAULT    4
     5: 0000000000000000     0 SECTION LOCAL  DEFAULT    6
     6: 0000000000000000     0 SECTION LOCAL  DEFAULT    7
     7: 0000000000000000     0 SECTION LOCAL  DEFAULT    5
     8: 0000000000000000     8 OBJECT  GLOBAL DEFAULT    3 buf
     9: 0000000000000000    21 FUNC    GLOBAL DEFAULT    1 main
    10: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND swap
```

Symbol Table Entries (Fig. 7-5 in textbook)

```
# objdump -r -d -t swap.o | head -n 15
swap.o:     file format elf64-x86-64
SYMBOL TABLE:
0000000000000000 l    df *ABS*  0000000000000000 swap.c
0000000000000000 l    d  .text  0000000000000000 .text
0000000000000000 l    d  .data  0000000000000000 .data
0000000000000000 l    d  .bss   0000000000000000 .bss
0000000000000000 l    d  .note.GNU-stack        0000000000000000 .note.GNU-stack
0000000000000000 l    d  .eh_frame      0000000000000000 .eh_frame
0000000000000000 l    d  .comment       0000000000000000 .comment
0000000000000000 g     O .data  0000000000000008 bufp0
0000000000000000         *UND*  0000000000000000 buf
0000000000000008       O *COM*  0000000000000008 bufp1
0000000000000000 g     F .text  000000000000003c swap

# readelf -s swap.o | tail -n 11
     1: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS swap.c
     2: 0000000000000000     0 SECTION LOCAL  DEFAULT    1
     3: 0000000000000000     0 SECTION LOCAL  DEFAULT    3
     4: 0000000000000000     0 SECTION LOCAL  DEFAULT    5
     5: 0000000000000000     0 SECTION LOCAL  DEFAULT    7
     6: 0000000000000000     0 SECTION LOCAL  DEFAULT    8
     7: 0000000000000000     0 SECTION LOCAL  DEFAULT    6
     8: 0000000000000000     8 OBJECT  GLOBAL DEFAULT    3 bufp0
     9: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND buf
    10: 0000000000000008     8 OBJECT  GLOBAL DEFAULT  COM bufp1
    11: 0000000000000000    60 FUNC    GLOBAL DEFAULT    1 swap
```

Step 1: Symbol Resolution



How Linker Resolves Duplicate Symbol Definitions (such as sum, array)?

Symbol Identification

Which **of the following names will be in the symbol table of** ***symbols.o***?

symbols.c:

```
int incr = 1;
static int foo(int a) {
  int b = a + incr;
  return b;
}

int main(int argc,
         char* argv[]) {
  printf("%d\n", foo(5));
  return 0;
}
```

Names:

- incr
- foo
- a
- argc
- argv
- b
- main
- printf
- "%d\n"

Can find this with readelf:

```
linux> readelf -s symbols.o
```

Local Symbols

- **Local non-static C variables vs. local static C variables**
  - local non-static C variables: stored on the stack
  - local static C variables: stored in either `.bss`, or `.data`

```
static int x = 15;

int f() {
    static int x = 17;
    return x++;
}

int g() {
    static int x = 19;
    return x += 14;
}

int h() {
    return x += 27;
}
```

static-local.c

Compiler allocates space in `.data` for each definition of `x`

Creates local symbols in the symbol table with unique names, e.g., `x`, `x.1721` and `x.1724`.

Resolving Global Symbols

- When unable to find a definition for the reference symbol in any of its input modules, it prints an error message and terminates.

```
void foo(void);
int main() {
  foo();
  return 0;
}
```
linkerror.c

```
# gcc -Wall -Og -S linkerror.c
# as -o linkerror.o linkerror.s
```

Compiler and assembler runs without a hitch.

```
# gcc -Wall -Og -o linkerror linkerror.o
linkerror.o: In function `main':
linkerror.c:(.text+0x5): undefined reference to `foo'
collect2: error: ld returned 1 exit status
```

Linker terminates when it cannot resolve the reference to function foo.

Name Mangling

- Override in C++/Java

Name	Referent
“A”	<class A>
“print”	<overload set>

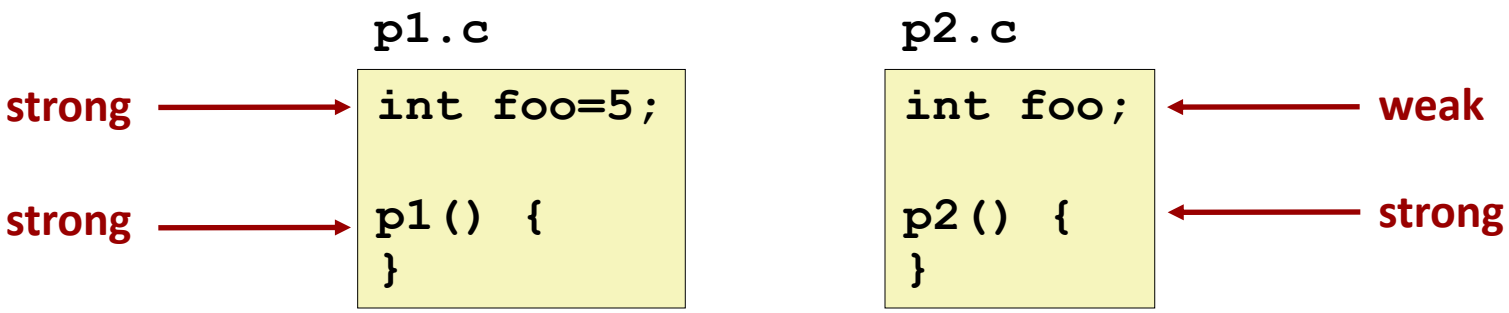
Signature	Referent
void(int)	<print 1>
void(char)	<print 2>
void(String)	<print 3>

- name mangling encodes the function‘s signature(argument and return types) into a textual form.

```
void print(int i, float f)
 => "_Z5printif"        (g++)
 => "?print@@YAXHM@Z"   (msvc++)
void print(float f, int i)
 => "_Z5printfi"        (g++)
 => "?print@@YAXMH@Z"   (msvc++)
```

How Linker Resolves Duplicate Symbol Names

- **Program symbols are either *strong* or *weak***
  - ***Strong***: procedures and initialized global variables
  - ***Weak***: uninitialized global variables
    - Or ones declared with specifier **`extern`**
- **Compiler exports such kind of information and assembler encodes it implicitly in the symbol table of ELF files.**



Linker's Symbol Rules

- **Rule 1: Multiple strong symbols are not allowed**
  - Each item can be defined only once
  - Otherwise: Linker error
- **Rule 2: Given a strong symbol and multiple weak symbols, choose the strong symbol**
  - References to the weak symbol resolve to the strong symbol
- **Rule 3: If there are multiple weak symbols, pick an arbitrary one**
  - Can override this with `gcc -fno-common`

Convention between Compiler and Linker

- **Compiler may assign symbols to either COMMON or .bss**
  - Uninitialized global names is assigned to COMMON.
  - -fno-common GCC option force uninitialized global names to be assigned in .bss section.
  - __attribute__((weak)) force global names to be weak.

- **Sometimes, linker allows multiple modules to define global symbols with the same name.**
  - The link editor honors the global definition and ignores the weak ones.
  - Similarly, the link editor honors the COMMON definition and ignores the weak ones.

What if you mess up?

```
int x=7;
p1() {}
```

```
extern int x;
p2() {}
```

Correct program.
Only one definition of **x**, **p1**, **p2**

```
int x=7;
p1() {}
```

```
int x=0;
p1() {}
```

Link error: two definitions of **x** and **p1**

```
int x;
p1() {}
```

```
int x;
p2() {}
```

Compiler-dependent. Might be considered either one or two definitions of **x**.

```
int x=7;
int y=5;
p1() {}
```

```
extern double x;
p2() {}
```

Undefined behavior. No link error.
Writes to **x** in **p2** may overwrite **y**!

```
char p1[]
  = 0xC3;
```

```
extern void p1();
p2() { p1(); }
```

Undefined behavior. No link error.
Call to p1 may crash!

Linker checks for two definitions of one symbol.
Linker *does not* check types of references.

Linker Puzzles

```
int x;
p1() {}
```

```
p1() {}
```

Link time error: two strong symbols (**p1**)

```
int x;
p1() {}
```

```
int x;
p2() {}
```

References to **x** will refer to the same uninitialized int. Is this what you really want?

```
int x;
int y;
p1() {}
```

```
double x;
p2() {}
```

Writes to **x** in **p2** might overwrite **y**!
Evil!

```
int x=7;
int y=5;
p1() {}
```

```
double x;
p2() {}
```

Writes to **x** in **p2** might overwrite **y**!
Nasty!

```
int x=7;
p1() {}
```

```
int x;
p2() {}
```

References to **x** will refer to the same initialized variable.

Important: Linker does not do type checking.

Type Mismatch Example

```c
extern long int x;

int main(int argc,
         char *argv[]) {
    printf("%ld\n", x);
    return 0;
}
```

mismatch-main.c

```c
double x = 3.14;
```

mismatch-variable.c

- Compiles without any errors or warnings
- What gets printed?

```
-bash-4.2$ ./mismatch
4614253070214989087
```

Detecting the Type Mismatch Example

```
extern long int x;
```
mismatch.h

```
#include "mismatch.h"

int main(int argc,
         char *argv[]) {
    printf("%ld\n", x);
    return 0;
}
```
mismatch-main.c

```
#include "mismatch.h"

double x = 3.14;
```
mismatch-variable.c

- Now we get an error … from the *compiler*, not the linker.

```
mismatch-variable.c:3:8: conflicting types for ‘x’
mismatch.h:1:17: previous declaration of ‘x’
```

Rules for avoiding type mismatches

- **Avoid global variables as much as possible**
- **Use `static` as much as possible**
- **Declare *everything* that's not `static` in a header file**
  - Make sure to include the header file everywhere it's relevant
  - Including the files that define those symbols
- **Always put `extern` on declarations in header files**
  - Unnecessary but harmless for function declarations
  - Avoids the quirky behavior of extern-less global variables
- **Always write (void) when a function takes no args**
  - `extern void no_args(void);`
  - Leaving out the **`void`** means "I'm *not saying* what argument list this function takes." Turns off argument type checking!

Use of `extern` in .h Files (#1)

c1.c

```
#include "global.h"

int f() {
  return g+1;
}
```

global.h

```
extern int g;
int f();
```

c2.c

```
#include <stdio.h>
#include "global.h"

int g = 0;

int main(int argc, char argv[]) {
  int t = f();
  printf("Calling f yields %d\n", t);
  return 0;
}
```

Use of .h Files (#2)

c1.c

```
#include "global.h"

int f() {
  return g+1;
}
```

global.h

```
extern int g;
static int init = 0;
```

```
#else
  extern int g;
  static int init = 0;
#endif
```

c2.c

```
#define INITIALIZE
#include <stdio.h>
#include "global.h"

int main(int argc, char** argv) {
  if (init)
    // do something, e.g., g=31;
  int t = f();
  printf("Calling f yields %d\n", t);
  return 0;
}
```

```
int g = 23;
static int init = 1;
```

Linking Example

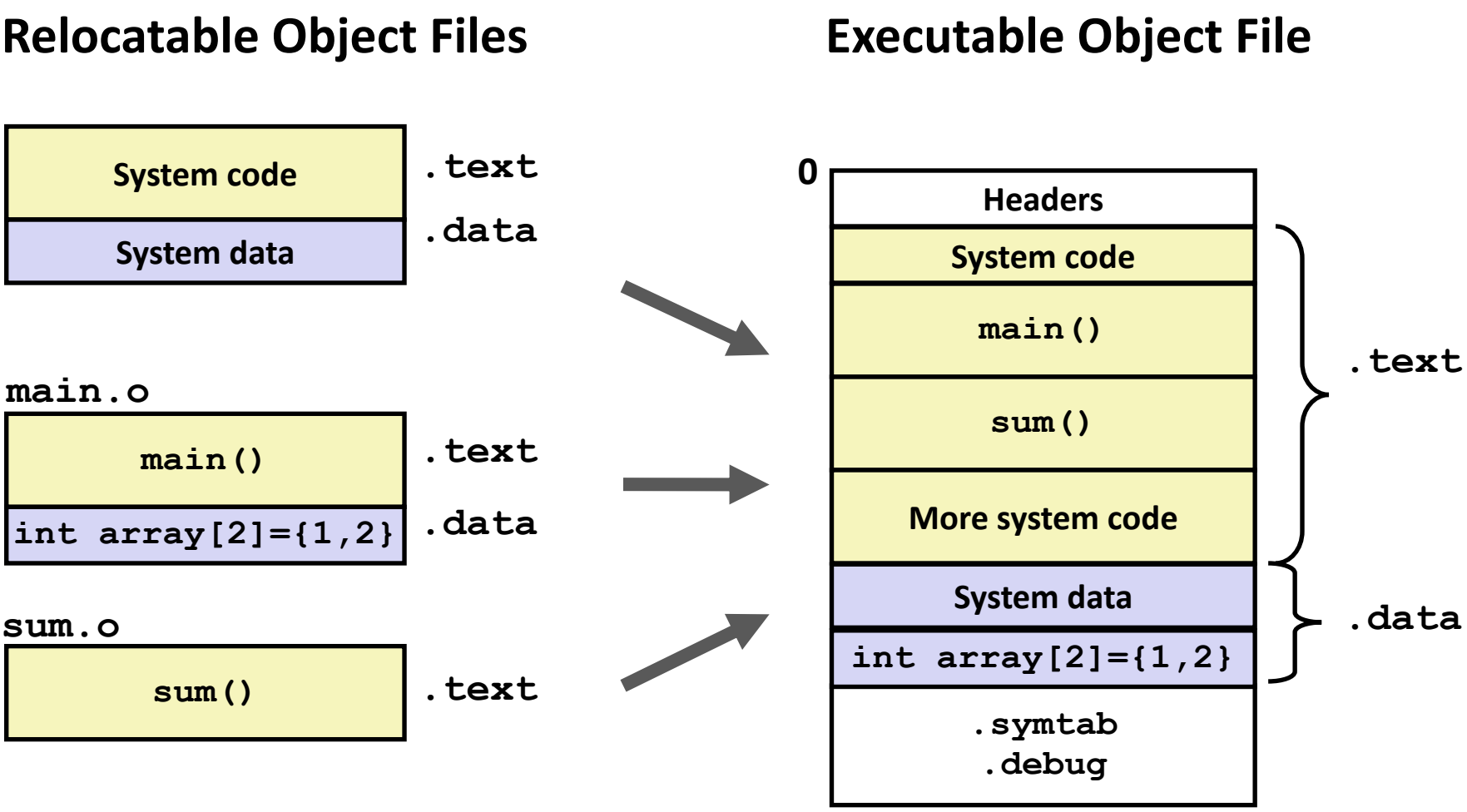
```c
int sum(int *a, int n);

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

int main(int argc,char **argv)
{
    int val = sum(array, 2);
    return val;
}
```

main.c

```c
int sum(int *a, int n)
{
    int i, s = 0;

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

sum.c

Step 2: Relocation



2-Step Relocation in Static Linking

- **Relocating sections and symbol definitions**
  - Merges all sections of the same type into a new aggregate section of the same type.
  - Assigns run-time memory addresses to
    - The new aggregate section.
    - Each section defined by the input modules.
    - Each symbol defined by the input modules.
- **Relocating symbol references with sections**
  - Modifies every symbol reference in the bodies of the code and data sections so that they point to the correct run-time addresses.
  - It relies on data structures in the relocatable modules known as **relocation entries.**

Relocation Entries

- A *relocation entry* generates from eference with unkown location.

```
    /* Relocation table entry with addend
    (in section of type SHT_RELA). */
660 typedef struct
661 {
662 Elf64_Addr r_offset; /* Address */
663 Elf64_XWord r_info; /* Relocation type and symbol index */
664 Elf64_Sxword r_addend; /* Addend */
665 } Elf64_Rela;
673 #define ELF64_R_SYM(i)   ((i) >> 32)
674 #define ELF64_R_TYPE(i) ((i) & 0xffffffff)
```

- *r_offset* is the section offset of the reference that will be modified.
- *ELF_64_R_SYM* identifies the symbol that the reference should point to.
- *ELF_64_R_TYPE* tells the linker how to modify the new reference.
- *r_addend* is a constant used for offset adjustment in some kind of relocation.

Two Most Basic Relocation Types

- **R_X86_64_PC32**
  - Relocates a reference that uses a 32-bit PC-relative address.
- **R_X86_64_32/R_X86_64_32S**
  - Relocates a reference that uses a 32-bit absolute address.

```
for each section s {
    foreach relocation entry r {
        refptr = s + r.offset;  /* ptr to reference to be relocated */

        /* Relocate a PC-relative reference */
        if (r.type == R_X86_64_PC32){
            refaddr = ADDR(s) + r.offset; /* ref's run-time address */
            *refptr = (unsigned) (ADDR(r.symbol) + r.addend - refaddr);
        }

        /* Relocate an absolute reference */
        if (r.type ==R_X86_64_32)
            *refptr = (unsigned) (ADDR(r.symbol) + r.addend);
    }
}
```

Relocation Entries

```c
int array[2] = {1, 2};
int main(int argc, char** argv){
    int val = sum(array, 2);
    return val;
}
```
main.c

```
# readelf -r main.o
Relocation section '.rela.text' at offset 0x560 contains 2 entries:
Offset          Info           Type            Sym.Value        Sym.Name+Addend
000000000015  00080000000a R_X86_64_32       0000000000000000 array + 0
00000000001a  000a00000002 R_X86_64_PC32     0000000000000000 sum - 4

Relocation section '.rela.eh_frame' at offset 0x590 contains 1 entries:
Offset          Info           Type            Sym.Value        Sym.Name+Addend
000000000020  000200000002 R_X86_64_PC32     0000000000000000 .text + 0
```

offset

type

symbol name & addend

Totally 3 symbols to be relocated.

Relocation Entries (in main.o)

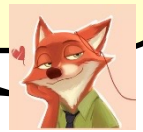
```c
int array[2] = {1, 2};
int main(int argc, char** argv){
    int val = sum(array, 2);
    return val;
}
```
main.c

```
# readelf -r main.o
Relocation section '.rela.text' at offset 0x560 contains 2 entries:
Offset          Info           Type            Sym.Value        Sym.Name+Addend
000000000015  00080000000a R_X86_64_32       0000000000000000 array + 0
00000000001a  000a00000002 R_X86_64_PC32     0000000000000000 sum - 4
```

Dear Linker,

Please patch the .rela.text section at offsets 0x15. Patch in a 32-bit value like following steps. When you determine the addr of .data, compute [addr of array] + [addend, which equals 0] and place the result at the prescribed place.

Sincerely,
Assembler



Relocation Entries (in main.o)

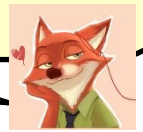
```c
int array[2] = {1, 2};
int main(int argc, char** argv){
    int val = sum(array, 2);
    return val;
}
```
main.c

```
# readelf -r main.o
Relocation section '.rela.text' at offset 0x560 contains 2 entries:
Offset          Info           Type            Sym.Value        Sym.Name+Addend
000000000015 00080000000a R_X86_64_32       0000000000000000 array + 0
00000000001a 000a00000002 R_X86_64_PC32     0000000000000000 sum - 4
```

Dear Linker,

Please patch the .rela.text section at offsets 0x1a. Patch in a 32-bit "PC-relative" value like following steps. When you determine the addr of sum, compute [addr of sum] + [addend, which equals -4] – [addr of section + offset]and place the result at the prescribed place.

Sincerely,
Assembler



Relocation Entries (in sum.o)

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

sum.c

```
# readelf -r sum.o
Relocation section '.rela.eh_frame' at offset 0x4f8 contains 1 entries:
Offset          Info           Type            Sym.Value        Sym.Name+Addend
000000000020  000200000002 R_X86_64_PC32     0000000000000000 .text + 0
```

offset

type

symbol name & addend

1 symbol to be relocated (.text)

Original Object File of main.o

```c
int array[2] = {1, 2};
int main(int argc, char** argv){
    int val = sum(array, 2);
    return val;
}
```
main.c

Source: `objdump -r -d main.o`

```
0000000000000000 <main>:
   0:   55                      push   %rbp
   1:   48 89 e5                mov    %rsp,%rbp
   4:   48 83 ec 20             sub    $0x20,%rsp
   8:   89 7d ec                mov    %edi,-0x14(%rbp)
   b:   48 89 75 e0             mov    %rsi,-0x20(%rbp)
   f:   be 02 00 00 00          mov    $0x2,%esi
  14:   bf 00 00 00 00          mov    $0x0,%edi        # %edi = &array
                        15: R_X86_64_32 array          # Relocation entry
  19:   e8 00 00 00 00          callq  1e <main+0x1e>   # sum()
                        1a: R_X86_64_PC32 sum-0x4      # Relocation entry
  1e:   89 45 fc                mov    %eax,-0x4(%rbp)
  21:   8b 45 fc                mov    -0x4(%rbp),%eax
  24:   c9                      leaveq
  25:   c3                      retq
```

Original Object File of sum.o

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

```
0000000000000000 <sum>:
   0:   55                          push   %rbp
   1:   48 89 e5                    mov    %rsp,%rbp
   4:   48 89 7d e8                 mov    %rdi,-0x18(%rbp)
   8:   89 75 e4                    mov    %esi,-0x1c(%rbp)
   b:   c7 45 fc 00 00 00 00        movl   $0x0,-0x4(%rbp)
  12:   c7 45 f8 00 00 00 00        movl   $0x0,-0x8(%rbp)
  19:   eb 1d                       jmp    38 <sum+0x38>
  1b:   8b 45 f8                    mov    -0x8(%rbp),%eax
  1e:   48 98                       cltq
  20:   48 8d 14 85 00 00 00        lea    0x0(,%rax,4),%rdx
  27:   00
  28:   48 8b 45 e8                 mov    -0x18(%rbp),%rax
  2c:   48 01 d0                    add    %rdx,%rax
  2f:   8b 00                       mov    (%rax),%eax
  31:   01 45 fc                    add    %eax,-0x4(%rbp)
  34:   83 45 f8 01                 addl   $0x1,-0x8(%rbp)
  38:   8b 45 f8                    mov    -0x8(%rbp),%eax
  3b:   3b 45 e4                    cmp    -0x1c(%rbp),%eax
  3e:   7c db                       jl     1b <sum+0x1b>
  40:   8b 45 fc                    mov    -0x4(%rbp),%eax
  43:   5d                          pop    %rbp
  44:   c3                          retq
```

A Little Bit of Preparation for Linking

- Linking script can be used to configure your linking process.
- start address of sections could be specified
  - .text starts at 0xbabe00
  - .data starts at 0xcafe00
- Using:

gcc a.lds –o m main.o sum.o

```
SECTIONS
{
   .text 0x00BABE00:
   {
      *(.text)
   }
   . = ALIGN(0);
   .data 0x00CAFE00:
   {
      *(.data)
   }
}
```

a.lds

.text=0xbabe00

```
0000000000000000 <main>:
   0:   55
   1:   48 89 e5
   4:   48 83 ec 20
   8:   89 7d ec
   b:   48 89 75 e0
   f:   be 02 00 00 00
  14:   bf 00 00 00 00
  19:   e8 00 00 00 00
  1e:   89 45 fc
  21:   8b 45 fc
  24:   c9
  25:   c3
```

main.o

```
0000000000000000 <sum>:
   0:   55
   1:   48 89 e5
   4:   48 89 7d e8
   8:   89 75 e4
   b:   c7 45 fc 00 00 00 00
  12:   c7 45 f8 00 00 00 00
  19:   eb 1d
  1b:   8b 45 f8
  1e:   48 98
  20:   48 8d 14 85 00 00 00
  27:   00
  28:   48 8b 45 e8
  2c:   48 01 d0
  2f:   8b 00
  31:   01 45 fc
  34:   83 45 f8 01
  38:   8b 45 f8
  3b:   3b 45 e4
  3e:   7c db
  40:   8b 45 fc
  43:   5d
  44:   c3
```

sum.o

```
0000000000babe00 <_start>:
...
0000000000babf18 <main>:
 babf18:   55
 babf19:   48 89 e5
 babf1c:   48 83 ec 20
 babf20:   89 7d ec
 babf23:   48 89 75 e0
 babf27:   be 02 00 00 00
 babf2c:   bf 10 fe ca 00
 babf31:   e8 0a 00 00 00
 babf36:   89 45 fc
 babf39:   8b 45 fc
 babf3c:   c9
 babf3d:   c3
0000000000babf40 <sum>:
 babf40:   55
 babf41:   48 89 e5
 babf44:   48 89 7d e8
 babf48:   89 75 e4
 babf4b:   c7 45 fc 00 00 00 00
 babf52:   c7 45 f8 00 00 00 00
 babf59:   eb 1d
 babf5b:   8b 45 f8
 babf5e:   48 98
 babf60:   48 8d 14 85 00 00 00
 babf67:   00
 babf68:   48 8b 45 e8
 babf6c:   48 01 d0
 babf6f:   8b 00
 babf71:   01 45 fc
 babf74:   83 45 f8 01
 babf78:   8b 45 f8
 babf7b:   3b 45 e4
 babf7e:   7c db
 babf80:   8b 45 fc
 babf83:   5d
 babf84:   c3
```

executable

```
Disassembly of section .data:
0000000000cafe00 <__data_start>:
    ...
0000000000cafe10 <array>:
 cafe10:   01 00
 cafe12:   00 00
 cafe14:   02 00
```

.data=0xcafe00

addr_of_array=0xcafe10
Using the value 0xcafe10 to modify the content here

addr_of_main=0xbabf18
addr_of_sum=0xbabf40
offset = 0x1a
addend = -4

refptr
= 0xbabf18 + 0x1a
= 0xbabf32

*refptr(content)
=0xbabf40-4-0xbabf32
=0x0a

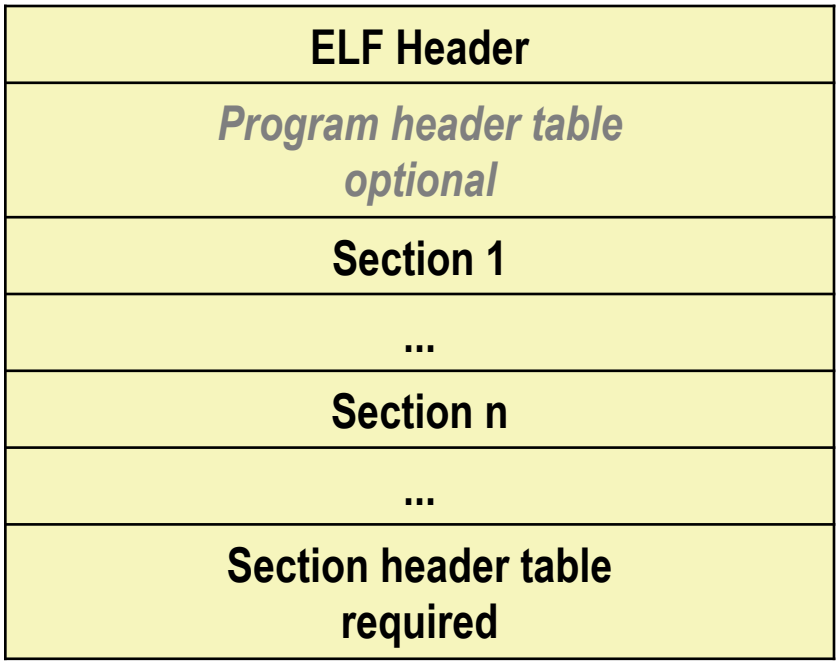
```
0000000000babe00 <_start>:
...
0000000000babf18 <main>:
 babf18:  55
 babf19:  48 89 e5
 babf1c:  48 83 ec 20
 babf20:  89 7d ec
 babf23:  48 89 75 e0
 babf27:  be 02 00 00 00
 babf2c:  bf 10 fe ca 00
 babf31:  e8 0a 00 00 00
 babf36:  89 45 fc
 babf39:  8b 45 fc
 babf3c:  c9
 babf3d:  c3
0000000000babf40 <sum>:
 babf40:  55
 babf41:  48 89 e5
 babf44:  48 89 7d e8
 babf48:  89 75 e4
 babf4b:  c7 45 fc 00 00 00 00
 babf52:  c7 45 f8 00 00 00 00
 babf59:  eb 1d
 babf5b:  8b 45 f8
 babf5e:  48 98
 babf60:  48 8d 14 85 00 00 00
 babf67:  00
 babf68:  48 8b 45 e8
 babf6c:  48 01 d0
 babf6f:  8b 00
 babf71:  01 45 fc
 babf74:  83 45 f8 01
 babf78:  8b 45 f8
 babf7b:  3b 45 e4
 babf7e:  7c db
 babf80:  8b 45 fc
 babf83:  5d
 babf84:  c3
```

```
0000000000babe00 <_start>:
...
0000000000babf18 <sum>:
  babf18:        55
  babf19:        48 89 e5
  babf1c:        48 89 7d e8
  babf20:        89 75 e4
  babf23:        c7 45 fc 00 00 00 00
  babf2a:        c7 45 f8 00 00 00 00
  babf31:        eb 1d
  babf33:        8b 45 f8
  babf36:        48 98
  babf38:        48 8d 14 85 00 00 00
  babf3f:        00
  babf40:        48 8b 45 e8
  babf44:        48 01 d0
  babf47:        8b 00
  babf49:        01 45 fc
  babf4c:        83 45 f8 01
  babf50:        8b 45 f8
  babf53:        3b 45 e4
  babf56:        7c db
  babf58:        8b 45 fc
  babf5b:        5d
  babf5c:        c3
  babf5d:        00 00
0000000000babf60 <main>:
  babf60:        55
  babf61:        48 89 e5
  babf64:        48 83 ec 20
  babf68:        89 7d ec
  babf6b:        48 89 75 e0
  babf6f:        be 02 00 00 00
  babf74:        bf 10 fe ca 00
  babf79:        e8 9a ff ff ff
  babf7e:        89 45 fc
  babf81:        8b 45 fc
  babf84:        c9
```

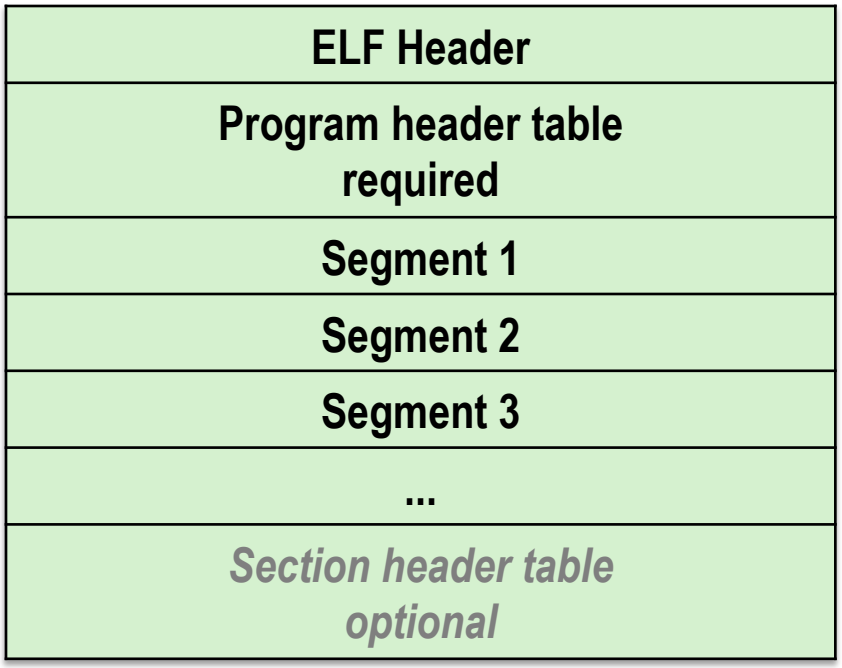
It differs with linking order

Recall: Parallel Views of a ELF File

- ***Program header table/Segments*** **is used to build a process image (execute a program); relocatable files don't need it.**
- **Files used during linking must have a *section header table/Sections*; other object files may or may not have one.**



Linking View



Execution View

Program Headers

- ELF executables are easy to load into memory, with contiguous chunks mapped to contiguous memory segments. It is described by the program header table.

```
#  objdump -x m

......
LOAD off 0x00000000001abe00 vaddr 0x0000000000babe00 paddr 0x0000000000babe00 align 2**21
  filesz 0x000000000000032c memsz 0x000000000000032c flags r-x
LOAD off 0x00000000002afe00 vaddr 0x0000000000cafe00 paddr 0x0000000000cafe00 align 2**21
  filesz 0x0000000000000018 memsz 0x0000000000000020 flags rw-
```

```
Off: offset in object file      vaddr/paddr: memory address     align: alignment requirement
Filesz:segment size in obj      memsz: segment size in mem      flags: runtime permissions
```

- .text starts from 0x00babe00 and .data starts from 0x00cafe00 as we specified before in the link script.
- According to the flags, .text is executable and .data is writable.

Loading Executable Object Files