Linking

Introduction to Computer Systems
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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**

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;
}
```

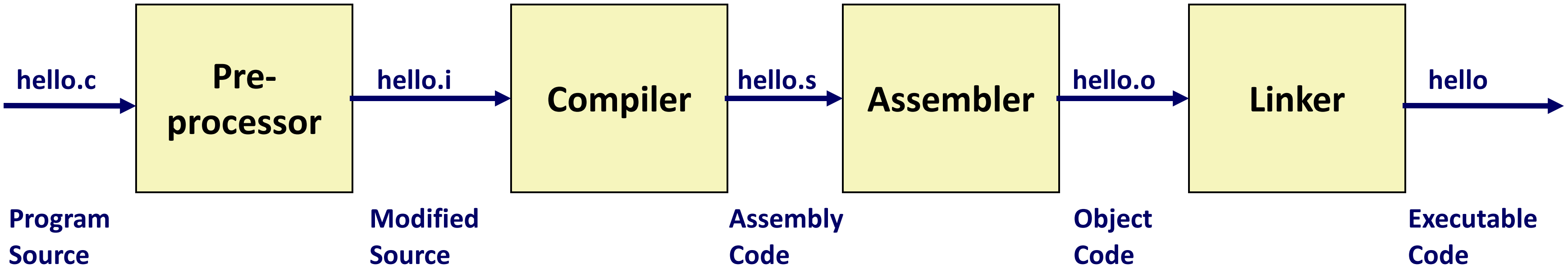
main.c

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

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

sum.c

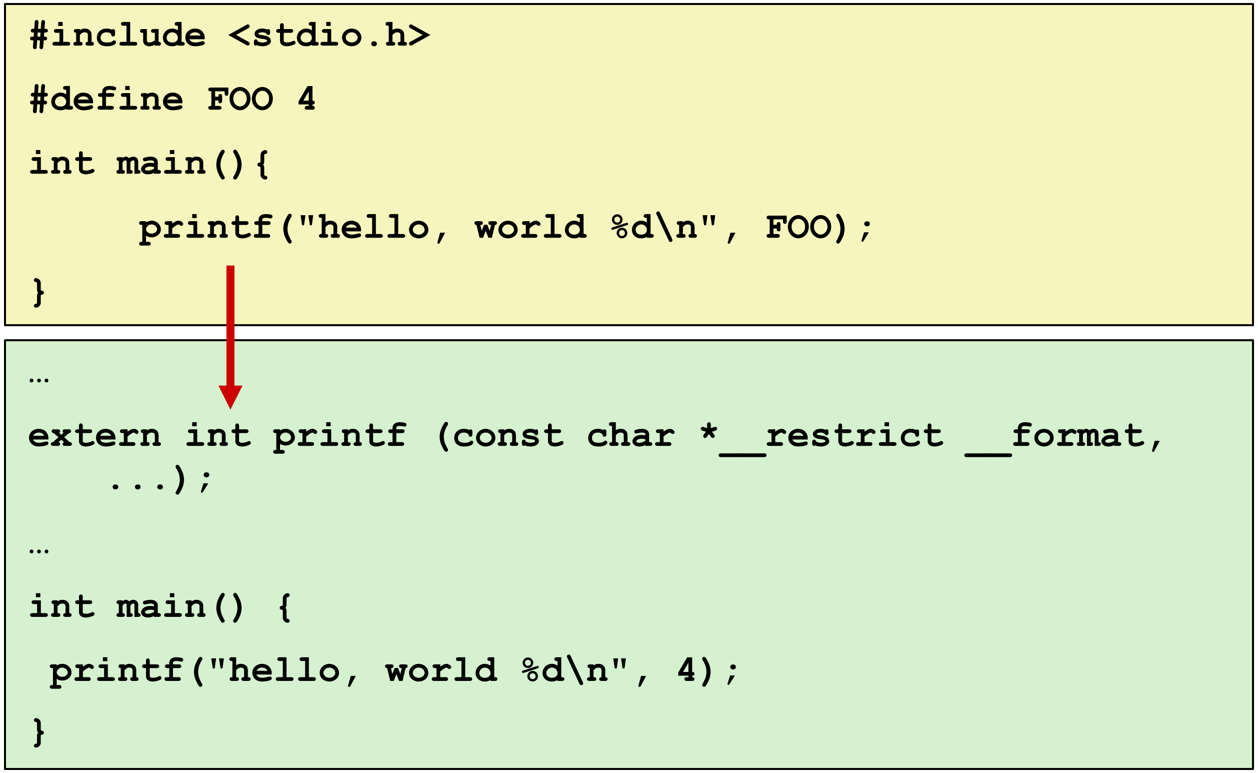
Compiler Driver, GCC as an Example

- **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);
}
```

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
```

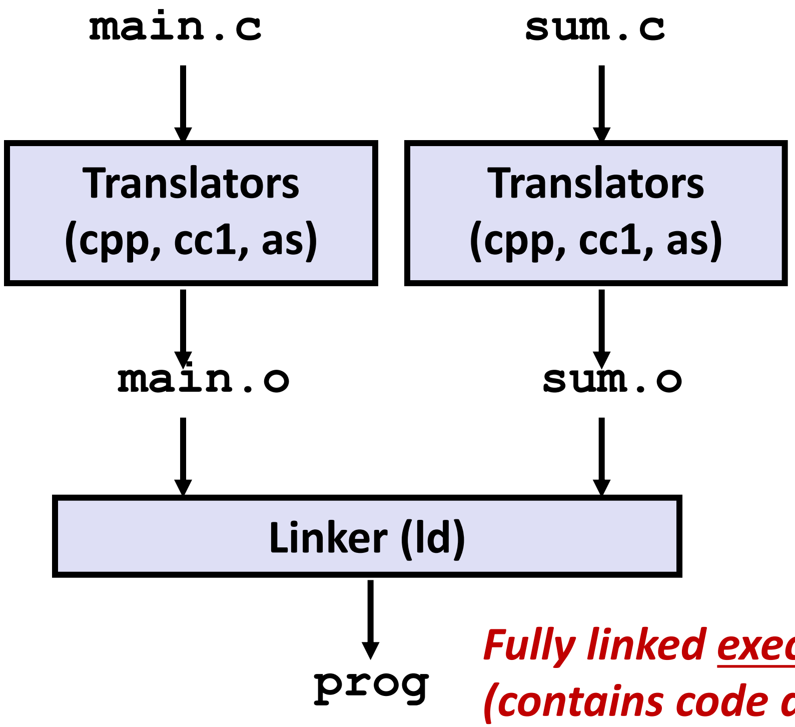
Assembler

- **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
```

(Static) Linking

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



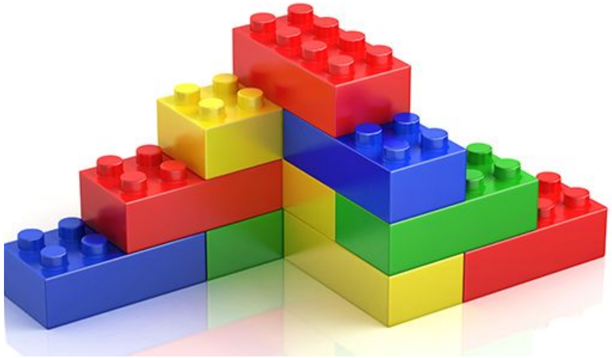
Source files

Separately compiled relocatable object files

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

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

What Do Linkers Do?

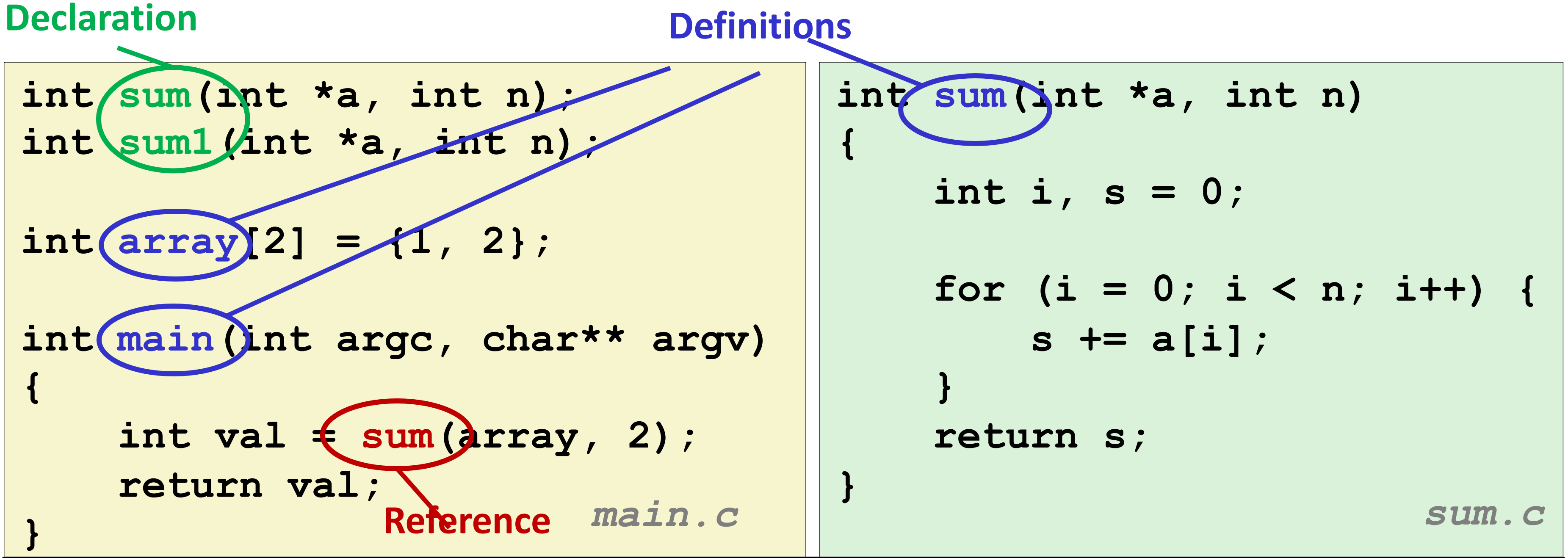
- Step 1: Symbol resolution

  - 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



Declaration

Definitions

Reference

```
int sum(int *a, int n);
int sum1(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

```
# 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
```

Assembler will not create the entry for function declarations (sum1 in main.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

Executable and Linkable Format (ELF)

- **Standard binary format for object files**

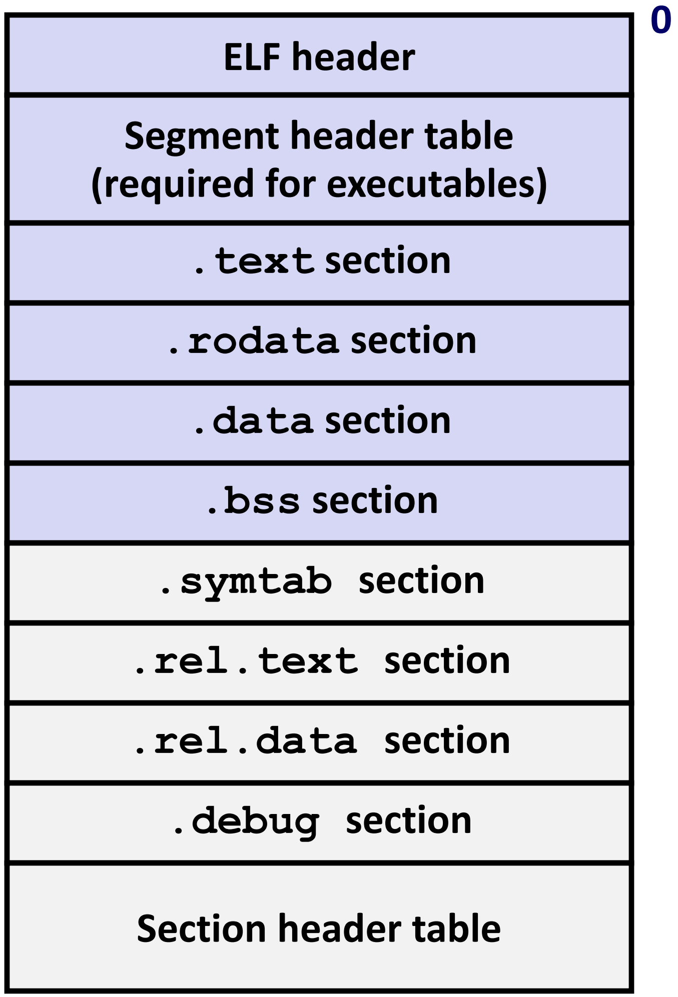
- **One unified format for**
  - Relocatable object files (`.o`),
  - Executable object files (`a.out`)
  - Shared object files (`.so`)

- **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



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ELF header

Segment header table (required for executables)

`.text` section

`.rodata` section

`.data` section

`.bss` section

`.symtab` section

`.rel.text` section

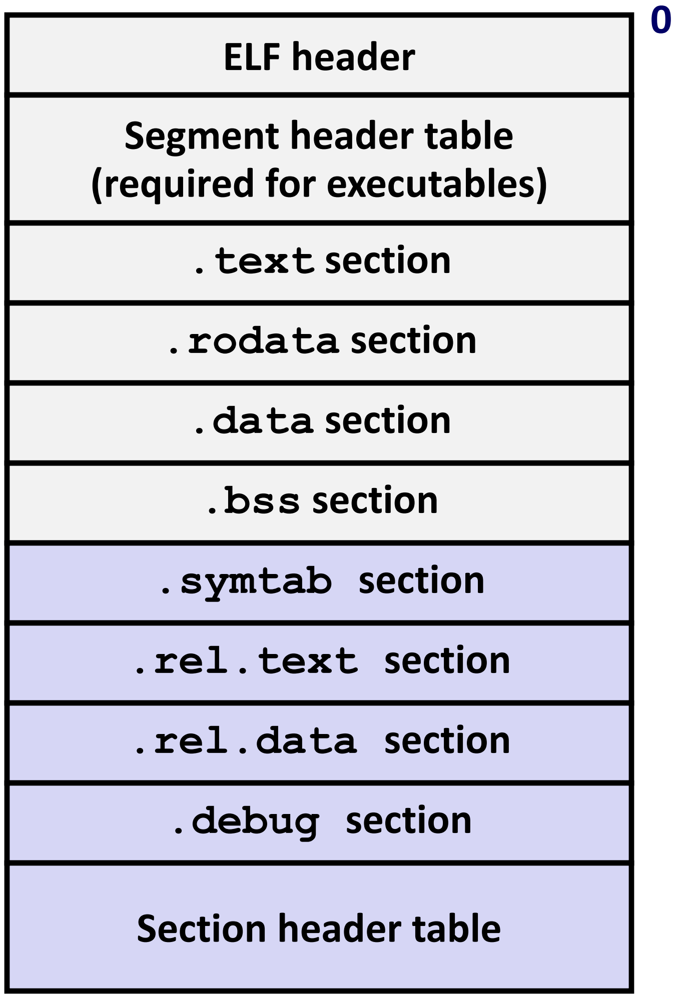
`.rel.data` section

`.debug` section

Section header table

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



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ELF header

Segment header table
(required for executables)

`.text` section

`.rodata` section

`.data` section

`.bss` section

`.symtab` section

`.rel.text` section

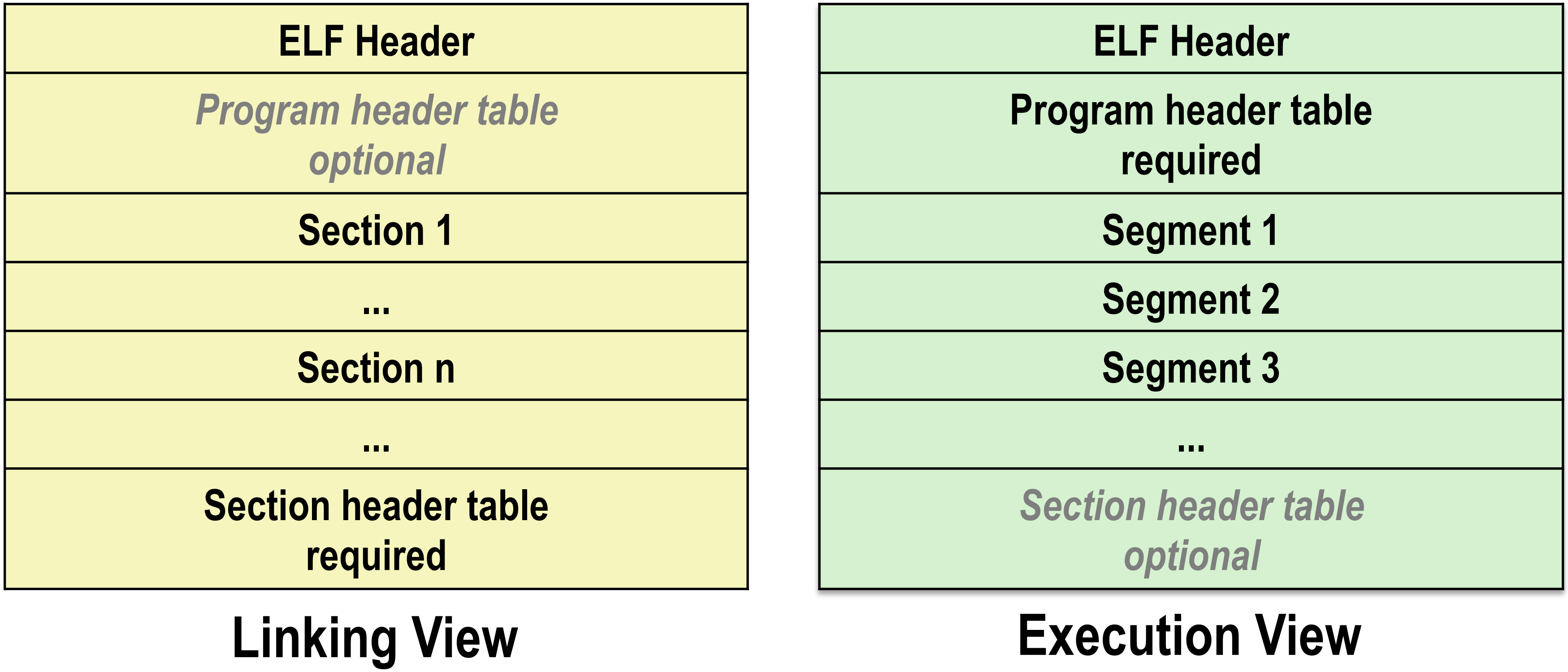
`.rel.data` section

`.debug` section

Section header table

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*.**



ELF Header

Program header table
optional

Section 1

...

Section n

...

Section header table
required

Linking View

ELF Header

Program header table
required

Segment 1

Segment 2

Segment 3

...

Section header table
optional

Execution View

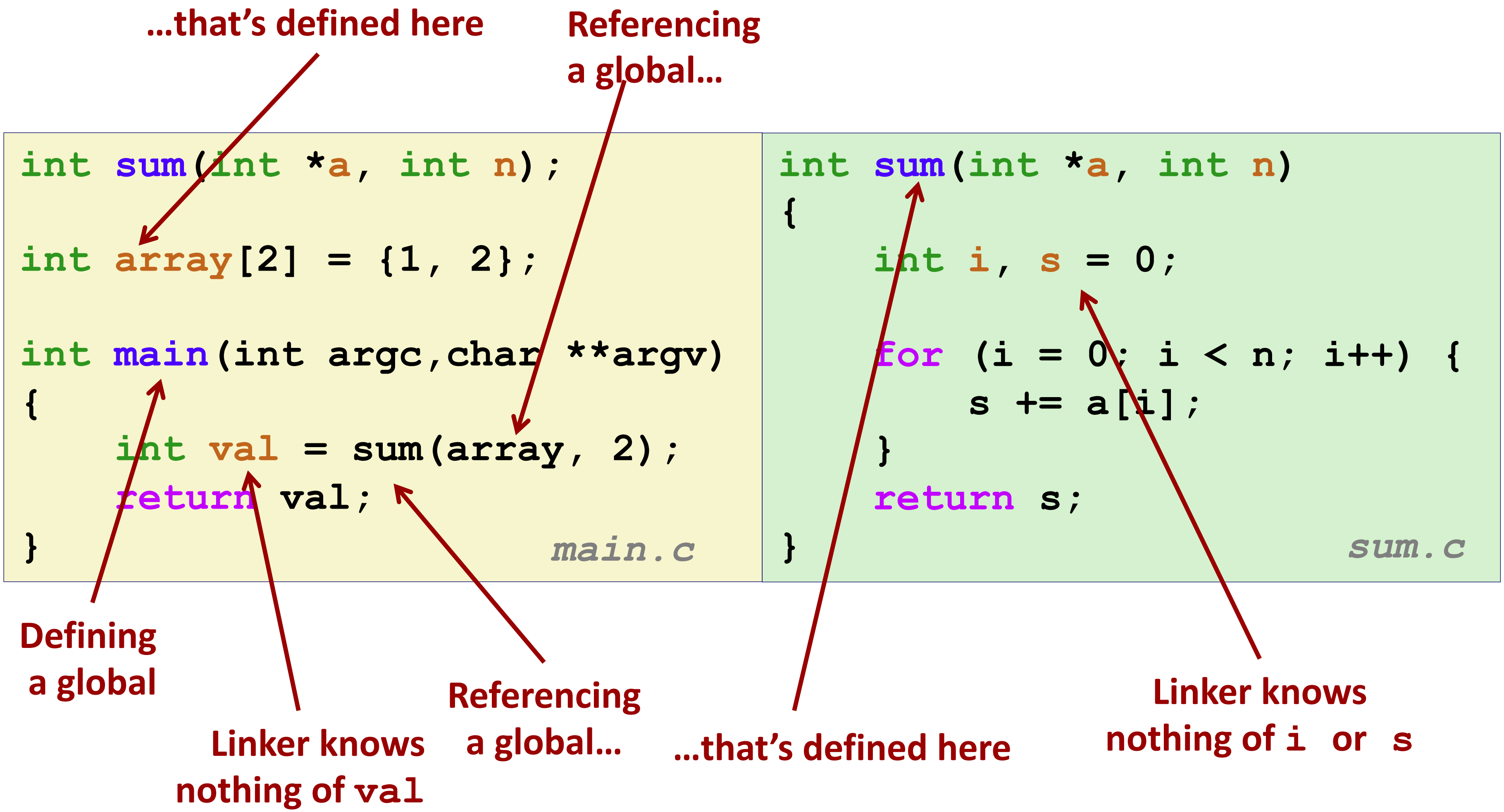
Linker Symbols

- **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**

Step 1: Symbol Resolution



```
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

…that's defined here

Referencing a global…

Defining a global

Linker knows nothing of `val`

Referencing a global…

…that's defined here

Linker knows nothing of `i` or `s`

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

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`

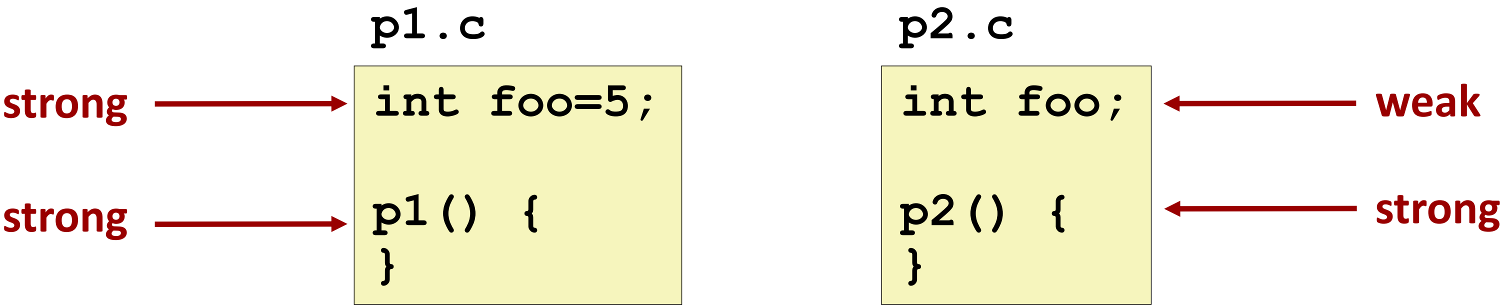
```
static int x = 15;

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`.

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.**



strong

strong

p1.c

```
int foo=5;

p1() {
}
```

p2.c

```
int foo;

p2() {
}
```

weak

strong

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`

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.

Nightmare scenario: two identical weak structs, compiled by different compilers with different alignment rules.

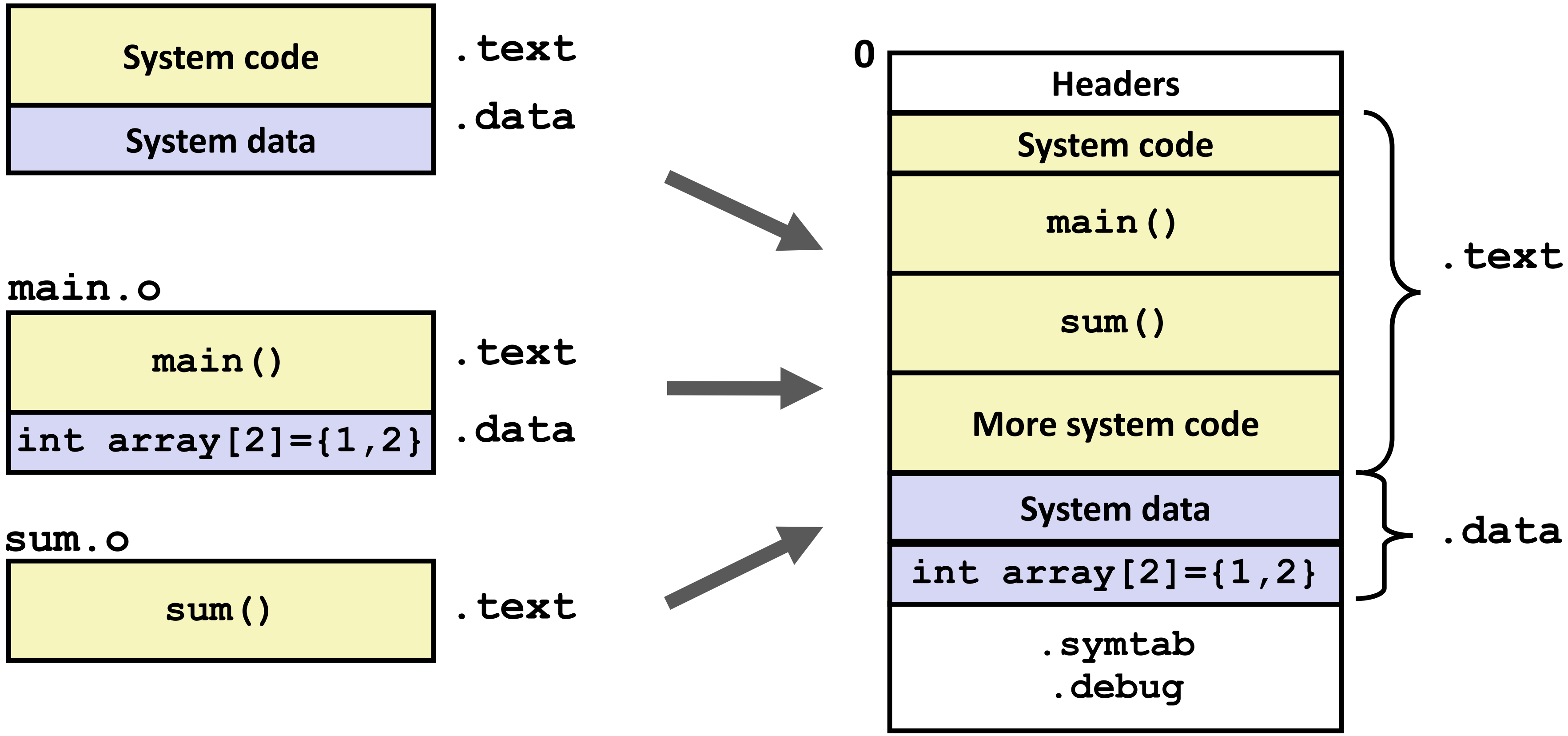
Rules for avoiding type mismatches

- **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 arguments**
  - `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!

Step 2: Relocation

Relocatable Object Files

Executable Object File



System code

System data

.text

.data

main.o

main()

int array[2]={1,2}

.text

.data

sum.o

sum()

.text

0

Headers

System code

main()

sum()

More system code

System data

int array[2]={1,2}

.symtab
.debug

.text

.data

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 reference with unknown location.

```
/* Relocation table entry with addend
(in section of type SHT_RELA). */
typedef struct
{
Elf64_Addr r_offset; /* Address */
Elf64_XWord r_info; /* Relocation type and symbol index */
Elf64_Sxword r_addend; /* Addend */
} Elf64_Rela;
#define ELF64_R_SYM(i)  ((i) >> 32)
#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.

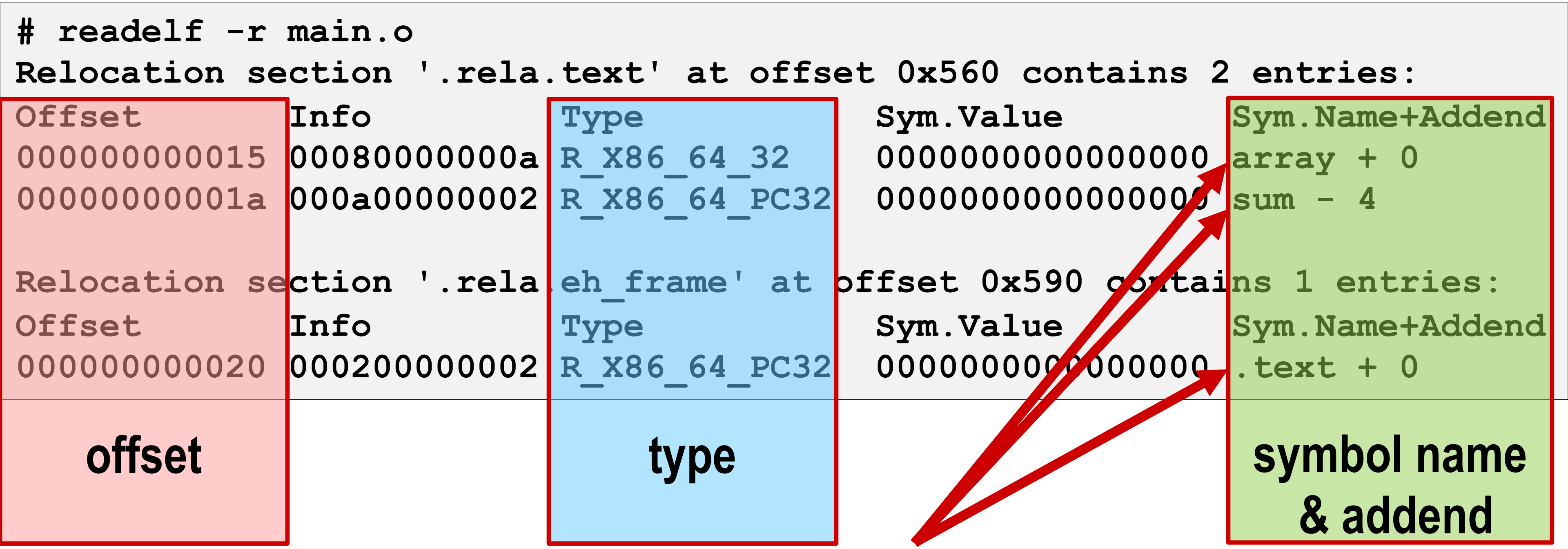
Two Most Basic Relocation Types

- 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
```

Totally 3 symbols to be relocated.

Relocation Entries (in main.o)

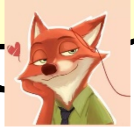
```
int array[2] = {1, 2};
int main(int argc, char** argv){
    int val = sum(array, 2);
    return val;
}                                          main.c
```

```
# 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)

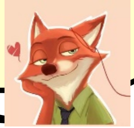
```
int array[2] = {1, 2};
int main(int argc, char** argv){
    int val = sum(array, 2);
    return val;
}                                          main.c
```

```
# 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.

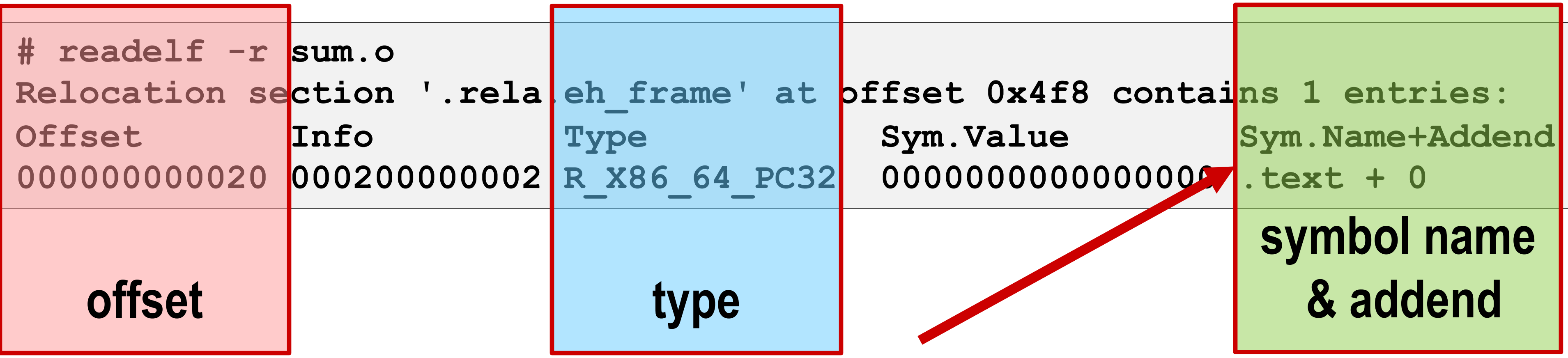
Sincerely,
Assembler



Relocation Entries (in sum.o)

```
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

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

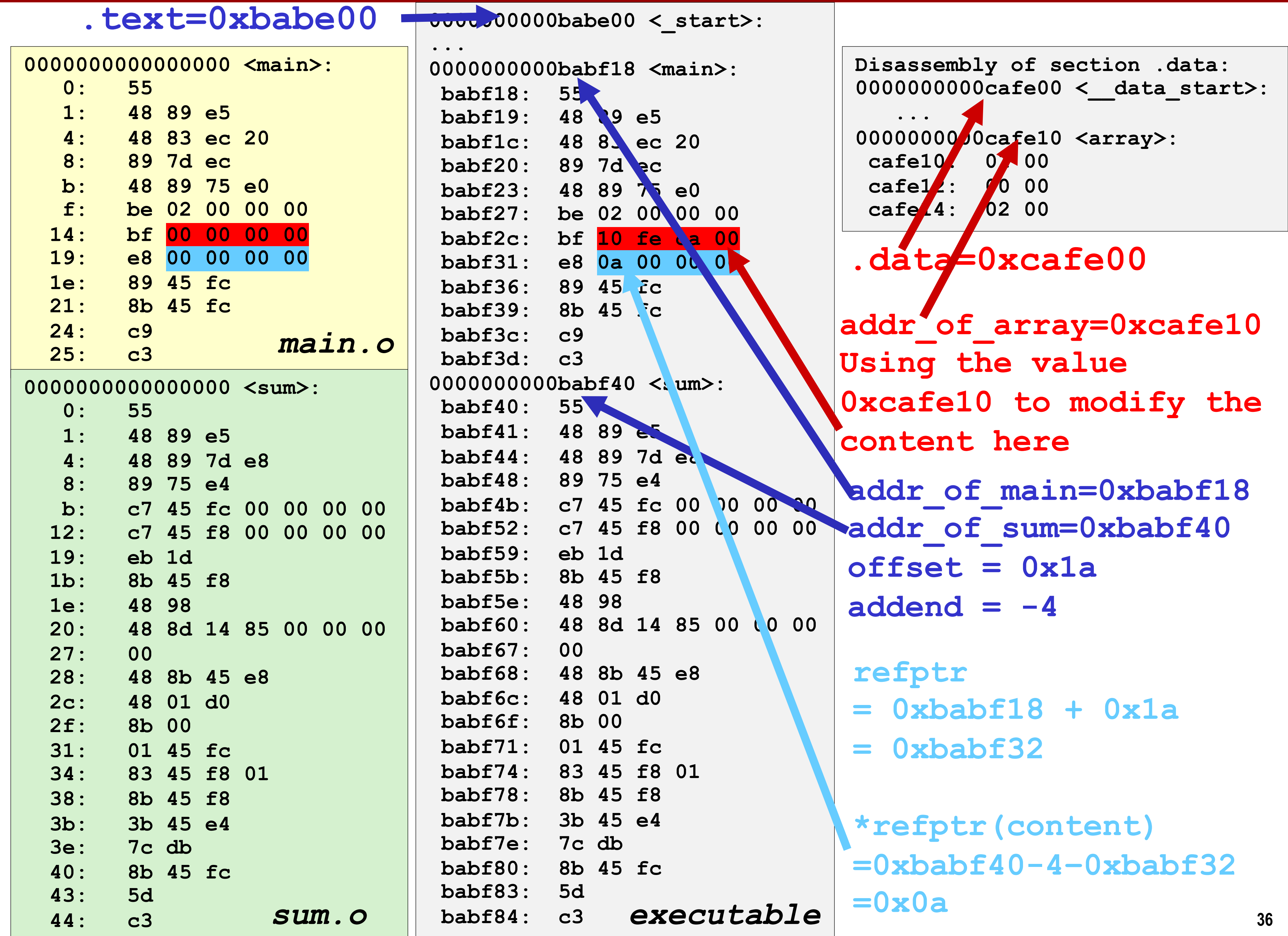
Source: `objdump -r -d main.o`

```
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
```



.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

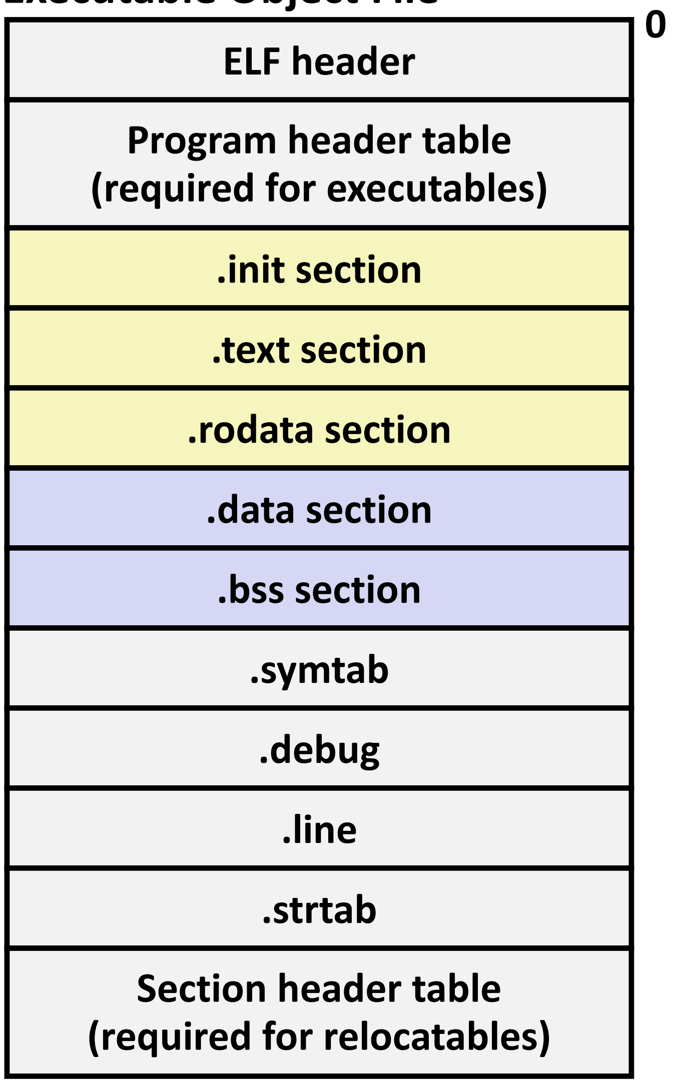
addr_of_main=0xbabf18
addr_of_sum=0xbabf40
offset = 0x1a
addend = -4

refptr
= 0xbabf18 + 0x1a
= 0xbabf32

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

Loading Executable Object Files

Executable Object File



0

ELF header

Program header table
(required for executables)

.init section

.text section

.rodata section

.data section

.bss section

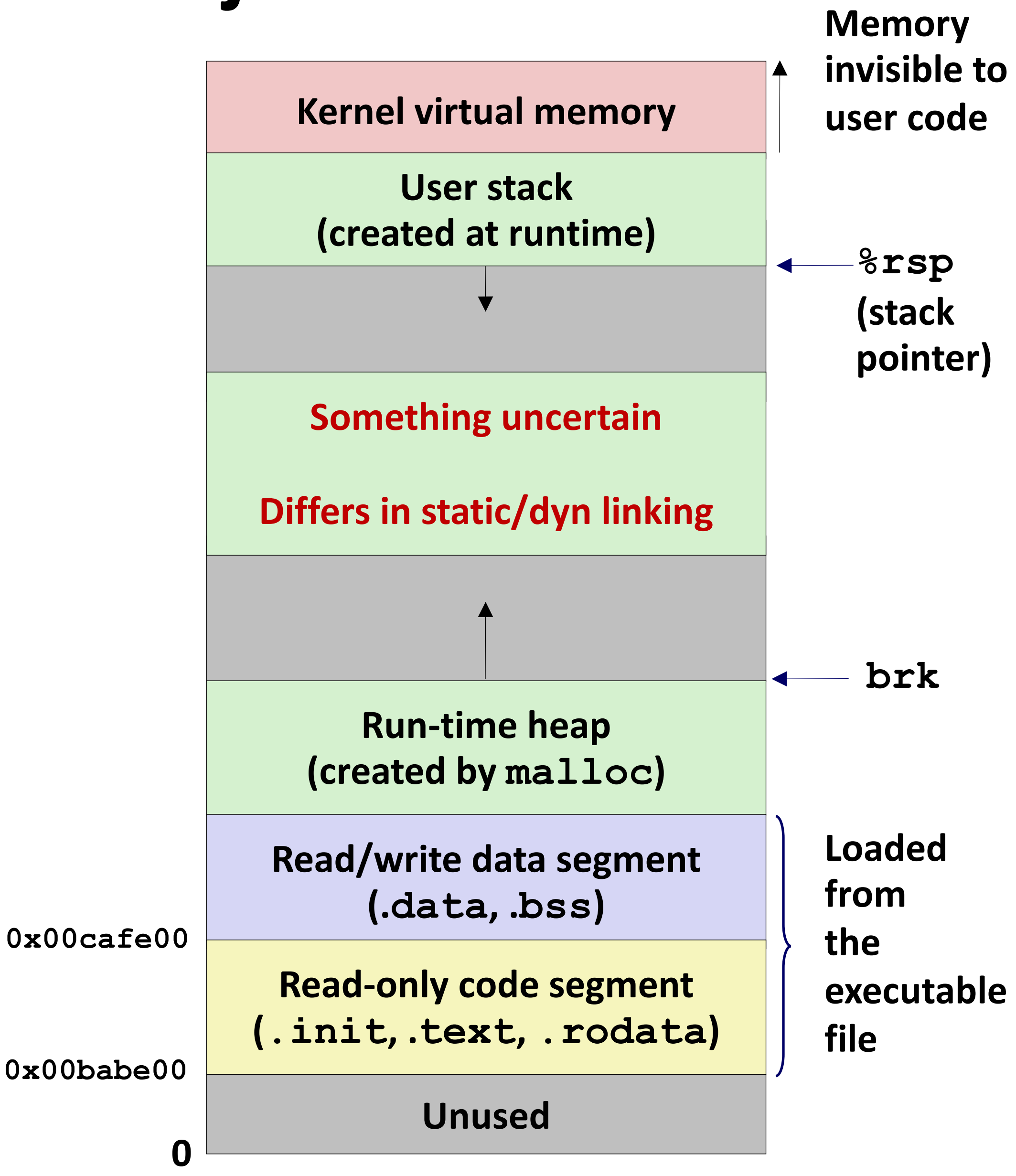
.symtab

.debug

.line

.strtab

Section header table
(required for relocatables)



Memory invisible to user code

Kernel virtual memory

User stack
(created at runtime)

%rsp
(stack pointer)

Something uncertain

Differs in static/dyn linking

brk

Run-time heap
(created by malloc)

Read/write data segment
(.data, .bss)

0x00cafe00

Read-only code segment
(.init, .text, .rodata)

0x00babe00

Unused

0

Loaded from the executable file

Libraries: Packaging a Set of Functions

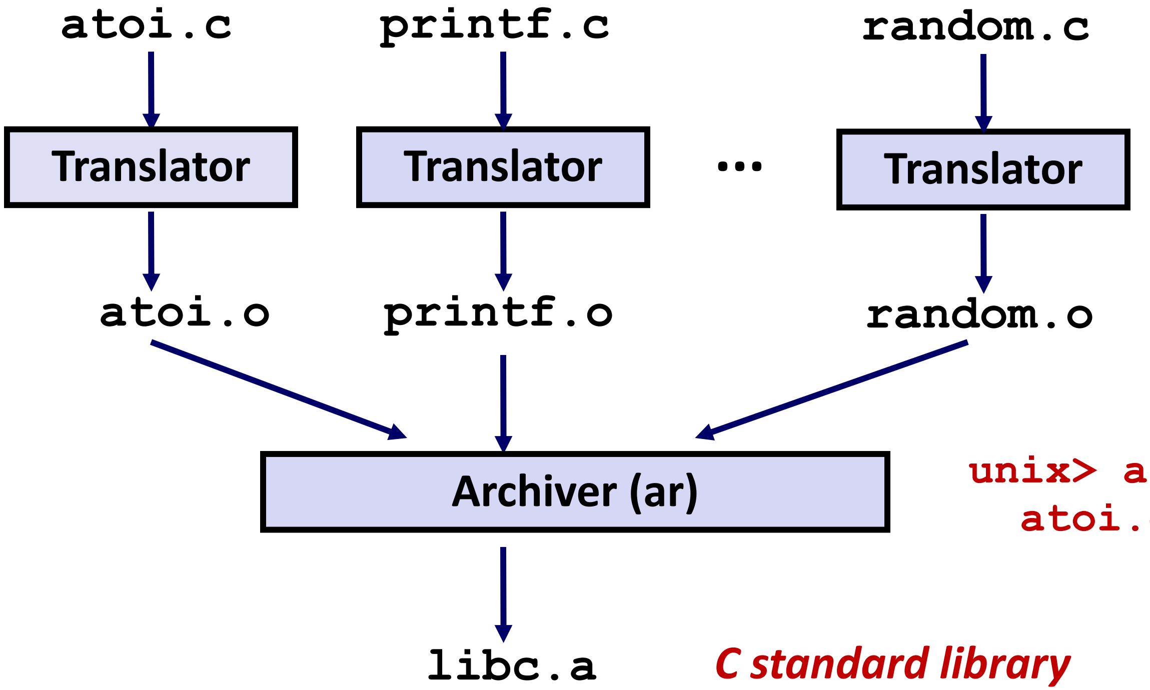
- **How to package functions commonly used by programmers?**
  - Math, I/O, memory management, string manipulation, etc.

- **Awkward, given the linker framework so far:**
  - **Option 1:** Put all functions into a single source file
    - Programmers link big object file into their programs
    - Space and time inefficient
  - **Option 2:** Put each function in a separate source file
    - Programmers explicitly link appropriate binaries into their programs
    - More efficient, but burdensome on the programmer

Old-fashioned Solution: Static Libraries

- **Static libraries (`.a` archive files)**
  - Concatenate related relocatable object files into a single file with an index (called an *archive*).
  - Enhance linker so that it tries to resolve unresolved external references by looking for the symbols in one or more archives.
  - If an archive member file resolves reference, link it into the executable.

Creating Static Libraries



```
unix> ar rs libc.a \
  atoi.o printf.o … random.o
```

C standard library

- Archiver allows incremental updates
- Recompile function that changes and replace .o file in archive.

Commonly Used Libraries

`libc.a` (the C standard library)

- 4.6 MB archive of 1496 object files. (differs in different versions)
- I/O, memory allocation, signal handling, string handling, data and time, random numbers, integer math

`libm.a` (the C math library)

- 2 MB archive of 444 object files. (differs in different versions)
- floating point math (sin, cos, tan, log, exp, sqrt, …)

```
% ar -t /usr/lib/libc.a | sort
…
fork.o
…
fprintf.o
fpu_control.o
fputc.o
freopen.o
fscanf.o
fseek.o
fstab.o
…
```

```
% ar -t /usr/lib/libm.a | sort
…
e_acos.o
e_acosf.o
e_acosh.o
e_acoshf.o
e_acoshl.o
e_acosl.o
e_asin.o
e_asinf.o
e_asinl.o
…
```

Linking with Static Libraries

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

int x[2] = {1, 2};
int y[2] = {3, 4};
int z[2];

int main(int argc, char**
argv)
{
    addvec(x, y, z, 2);
    printf("z = [%d %d]\n”,
           z[0], z[1]);
    return 0;
}
```

main2.c

libvector.a

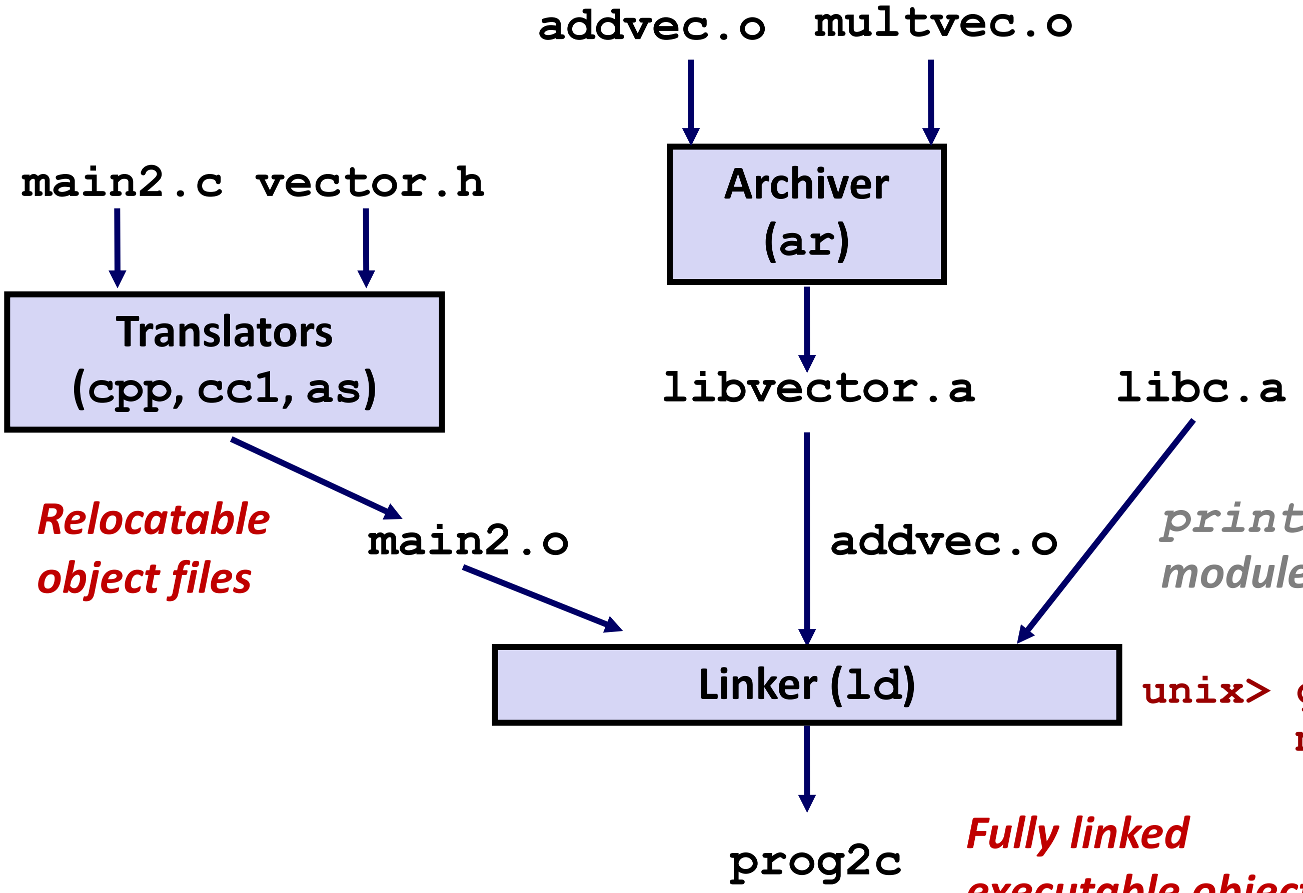
```
void addvec(int *x, int *y,
            int *z, int n) {
    int i;

    for (i = 0; i < n; i++)
        z[i] = x[i] + y[i];
}
```

addvec.c

```
void multvec(int *x, int *y,
             int *z, int n)
{
    int i;

    for (i = 0; i < n; i++)
        z[i] = x[i] * y[i];
}
```

multvec.c

Linking with Static Libraries



`addvec.o` `multvec.o`

Archiver (`ar`)

`main2.c` `vector.h`

Translators (`cpp`, `cc1`, `as`)

`libvector.a` `libc.a`

Static libraries

Relocatable object files

`main2.o`

`addvec.o`

`printf.o` and any other modules called by `printf.o`

Linker (`ld`)

```
unix> gcc -static -o prog2c \
      main2.o -L. -lvector
```

`prog2c`

Fully linked executable object file

(861,232 bytes)

“c” for “compile-time”

Using Static Libraries

- **Linker's algorithm for resolving external references:**
  - Scan `.o` files and `.a` files in the command line order.
  - During the scan, keep a list of the current unresolved references.
  - As each new `.o` or `.a` file, *obj*, is encountered, try to resolve each unresolved reference in the list against the symbols defined in *obj*.
  - If any entries in the unresolved list at end of scan, then error.

- **Problem:**
  - Command line order matters!
  - Moral: put libraries at the end of the command line.

```
unix> gcc -static -o prog2c -L. -lvector main2.o
main2.o: In function `main':
main2.c:(.text+0x19): undefined reference to `addvec'
collect2: error: ld returned 1 exit status
```

Modern Solution: Shared Libraries

- **Static libraries have the following disadvantages:**
  - Duplication in the stored executables (every function needs libc)
  - Duplication in the running executables
  - Minor bug fixes of system libraries require each application to explicitly relink
    - Rebuild everything with glibc?
    - https://security.googleblog.com/2016/02/cve-2015-7547-glibc-getaddrinfo-stack.html

- **Modern solution: Shared Libraries**
  - Object files that contain code and data that are loaded and linked into an application *dynamically,* at either *load-time* or *run-time*
  - Also called: dynamic link libraries, DLLs, `.so` files

Shared Libraries (cont.)

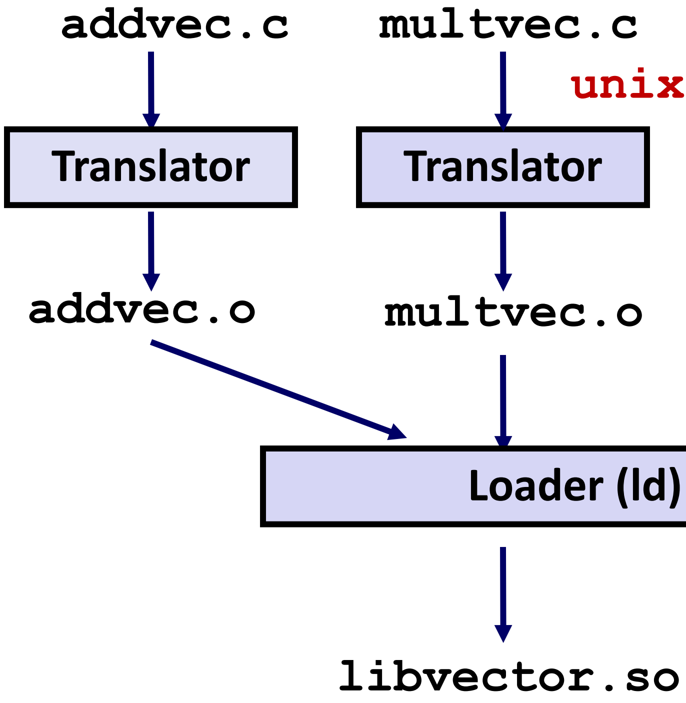
- **Dynamic linking can occur when executable is first loaded and run (load-time linking).**
  - Common case for Linux, handled automatically by the dynamic linker (`ld-linux.so`).
  - Standard C library (`libc.so`) usually dynamically linked.

- **Dynamic linking can also occur after program has begun (run-time linking).**
  - In Linux, this is done by calls to the `dlopen()` interface.
    - Distributing software.
    - High-performance web servers.
    - Runtime library interpositioning.

There…… is… no…hur...ry.
We…love…lazy…binding…

- **Shared library routines can be shared by multiple processes.**
  - More on this when we learn about virtual memory

Dynamic Library Example

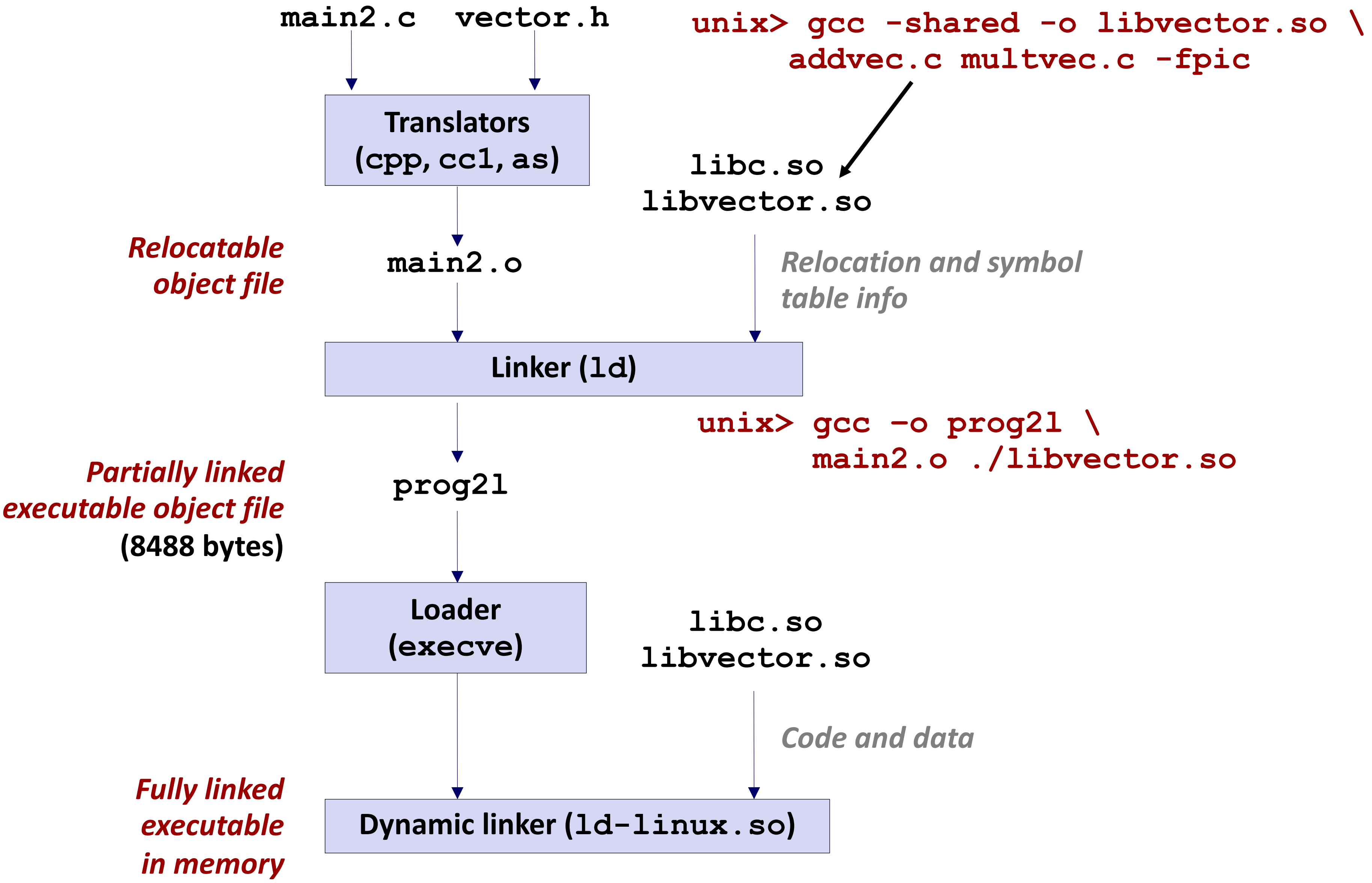


```
unix> gcc –Og –c addvec.c multvec.c -fpic
```

```
unix> gcc -shared -o libvector.so \
    addvec.o multvec.o
```

Dynamic vector library

Dynamic Linking at Load-time



main2.c vector.h

```
unix> gcc -shared -o libvector.so \
      addvec.c multvec.c -fpic
```

Translators (cpp, cc1, as)

libc.so
libvector.so

Relocatable object file

main2.o

Relocation and symbol table info

Linker (ld)

```
unix> gcc -o prog21 \
      main2.o ./libvector.so
```

Partially linked executable object file (8488 bytes)

prog21

Loader (execve)

libc.so
libvector.so

Code and data

Fully linked executable in memory

Dynamic linker (ld-linux.so)

Dynamic Linking at Run-time

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

int x[2] = {1, 2};
int y[2] = {3, 4};
int z[2];

int main(int argc, char** argv)
{
    void *handle;
    void (*addvec)(int *, int *, int *, int);
    char *error;

    /* Dynamically load the shared library that contains addvec() */
    handle = dlopen("./libvector.so", RTLD_LAZY);
    if (!handle) {
        fprintf(stderr, "%s\n", dlerror());
        exit(1);
    }
  . . .
```

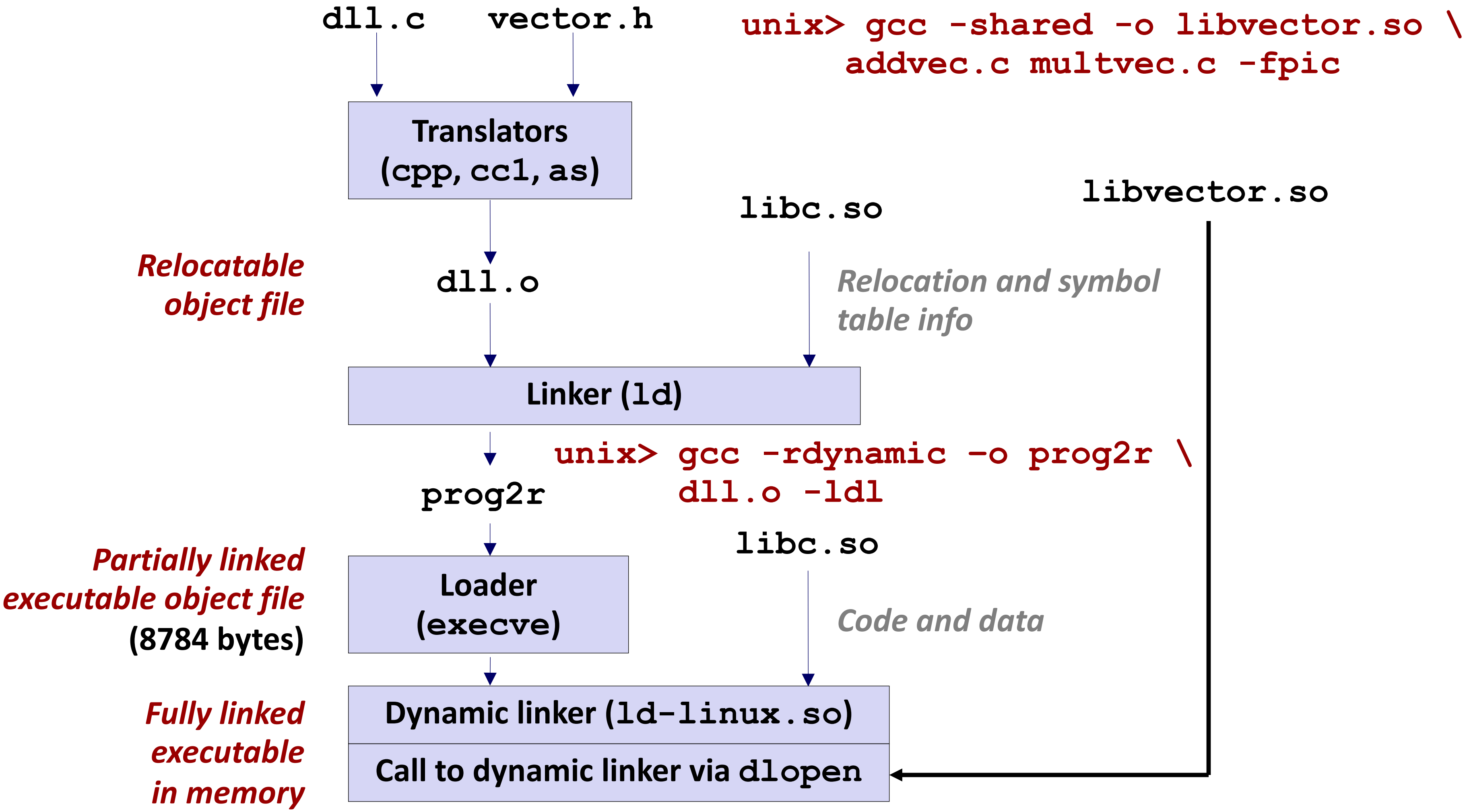
dll.c

Dynamic Linking at Run-time (cont)

```
    ...

    /* Get a pointer to the addvec() function we just loaded */
    addvec = dlsym(handle, "addvec");
    if ((error = dlerror()) != NULL) {
        fprintf(stderr, "%s\n", error);
        exit(1);
    }

    /* Now we can call addvec() just like any other function */
    addvec(x, y, z, 2);
    printf("z = [%d %d]\n", z[0], z[1]);

    /* Unload the shared library */
    if (dlclose(handle) < 0) {
        fprintf(stderr, "%s\n", dlerror());
        exit(1);
    }
    return 0;
}
```

dll.c

Dynamic Linking at Run-time



```
unix> gcc -shared -o libvector.so \
      addvec.c multvec.c -fpic
```

```
unix> gcc -rdynamic -o prog2r \
      dll.o -ldl
```

What dynamic libraries are required?

- **.interp section**
  - Specifies the dynamic linker to use (i.e., `ld-linux.so`)
- **.dynamic section**
  - Specifies the names, etc of the dynamic libraries to use
  - Follow an example of `prog`

```
(NEEDED)                   Shared library: [libm.so.6]
```

- **Where are the libraries found?**
  - Use "`ldd`" to find out:

```
unix> ldd prog
  linux-vdso.so.1 =>  (0x00007ffcf2998000)
  libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007f99ad927000)
  /lib64/ld-linux-x86-64.so.2 (0x00007f99adcef000)
```

Static vs. Dynamic Linking Tradeoffs

Static:

- Does not need to look up libraries at runtime
- Does not need extra PLT indirection
- Consumes more memory with copies of each library in every program

Dynamic:

- Less disk space/memory (7K vs 571K for hello world)
- Shared libraries already in memory and in hot cache
- Incurs lookup and indirection overheads

Linking Summary

- **Linking is a technique that allows programs to be constructed from multiple object files.**

- **Linking can happen at different times in a program’s lifetime:**
  - Compile time (when a program is compiled)
  - Load time (when a program is loaded into memory)
  - Run time (while a program is executing)

- **Understanding linking can help you avoid nasty errors and make you a better programmer.**

Case Study: Library Interpositioning

- **Documented in Section 7.13 of textbook**
- **Library interpositioning : powerful linking technique that allows programmers to intercept calls to arbitrary functions**
- **Interpositioning can occur at:**
  - Compile time: When the source code is compiled.
  - Link time: When the relocatable object files are statically linked to form an executable object file.
  - Load/run time: When an executable object file is loaded into memory, dynamically linked, and then executed.

Some Interpositioning Applications

- **Security**
  - Confinement (sandboxing)
  - Behind the scenes encryption
- **Debugging**
  - In 2014, two Facebook engineers debugged a treacherous 1-year old bug in their iPhone app using interpositioning
  - Code in the SPDY networking stack was writing to the wrong location
  - Solved by intercepting calls to POSIX write functions (write, writev, pwrite)

Source: Facebook engineering blog post at:

https://code.facebook.com/posts/313033472212144/debugging-file-corruption-on-ios/

Some Interpositioning Applications

- **Monitoring and Profiling**
  - Count number of calls to functions
  - Characterize call sites and arguments to functions
  - Malloc tracing
    - Detecting memory leaks
    - **Generating address traces**
- **Error Checking**
  - C Programming Lab used customized versions of malloc/free to do careful error checking
  - Other labs (malloc, shell, proxy) also use interpositioning to enhance checking capabilities

Example program

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

int main(int argc,
         char *argv[])
{
  int i;
  for (i = 1; i < argc; i++) {
    void *p =
          malloc(atoi(argv[i]));
    free(p);
  }
  return(0);
}
                              int.c
```

- **Goal: trace the addresses and sizes of the allocated and freed blocks, without breaking the program, and without modifying the source code.**

- **Three solutions: interpose on the library `malloc` and `free` functions at compile time, link time, and load/run time.**

Compile-time Interpositioning

```c
#ifdef COMPILETIME
#include <stdio.h>
#include <malloc.h>

/* malloc wrapper function */
void *mymalloc(size_t size)
{
    void *ptr = malloc(size);
    printf("malloc(%d)=%p\n", (int)size, ptr);
    return ptr;
}

/* free wrapper function */
void myfree(void *ptr)
{
    free(ptr);
    printf("free(%p)\n", ptr);
}
#endif
```

mymalloc.c

Compile-time Interpositioning

```
#define malloc(size) mymalloc(size)
#define free(ptr) myfree(ptr)

void *mymalloc(size_t size);
void myfree(void *ptr);
```

malloc.h

```
linux> make intc
gcc -Wall -DCOMPILETIME -c mymalloc.c
gcc -Wall -I. -o intc int.c mymalloc.o
linux> make runc
./intc 10 100 1000
malloc(10)=0x1ba7010
free(0x1ba7010)
malloc(100)=0x1ba7030
free(0x1ba7030)
malloc(1000)=0x1ba70a0
free(0x1ba70a0)
linux>
```

Search for <malloc.h> leads to /usr/include/malloc.h

Search for <malloc.h> leads to

Link-time Interpositioning

```
#ifdef LINKTIME
#include <stdio.h>

void *__real_malloc(size_t size);
void __real_free(void *ptr);

/* malloc wrapper function */
void *__wrap_malloc(size_t size)
{
    void *ptr = __real_malloc(size); /* Call libc malloc */
    printf("malloc(%d) = %p\n", (int)size, ptr);
    return ptr;
}

/* free wrapper function */
void __wrap_free(void *ptr)
{
    __real_free(ptr); /* Call libc free */
    printf("free(%p)\n", ptr);
}
#endif
```

mymalloc.c

Link-time Interpositioning

```
linux> make intl
gcc -Wall -DLINKTIME -c mymalloc.c
gcc -Wall -c int.c
gcc -Wall -Wl,--wrap,malloc -Wl,--wrap,free -o intl \
    int.o mymalloc.o
linux> make runl
./intl 10 100 1000
malloc(10) = 0x91a010
free(0x91a010)
. . .
```

Search for `<malloc.h>` leads to `/usr/include/malloc.h`

- The "`-Wl`" flag passes argument to linker, replacing each comma with a space.
- The "`--wrap,malloc`" `arg` instructs linker to resolve references in a special way:
  - Refs to `malloc` should be resolved as `__wrap_malloc`
  - Refs to `__real_malloc` should be resolved as `malloc`

Load/Run-time Interpositioning

```c
#ifdef RUNTIME
#define _GNU_SOURCE
#include <stdio.h>
#include <stdlib.h>
#include <dlfcn.h>

/* malloc wrapper function */
void *malloc(size_t size)
{
    void *(*mallocp)(size_t size);
    char *error;

    mallocp = dlsym(RTLD_NEXT, "malloc"); /* Get addr of libc malloc */
    if ((error = dlerror()) != NULL) {
        fputs(error, stderr);
        exit(1);
    }
    char *ptr = mallocp(size); /* Call libc malloc */
    printf("malloc(%d) = %p\n", (int)size, ptr);
    return ptr;
}
```

mymalloc.c

Observe that DON'T have
#include <malloc.h>

Load/Run-time Interpositioning

```
/* free wrapper function */
void free(void *ptr)
{
    void (*freep)(void *) = NULL;
    char *error;

    if (!ptr)
        return;

    freep = dlsym(RTLD_NEXT, "free"); /* Get address of libc free */
    if ((error = dlerror()) != NULL) {
        fputs(error, stderr);
        exit(1);
    }
    freep(ptr); /* Call libc free */
    printf("free(%p)\n", ptr);
}
#endif
```

mymalloc.c

Load/Run-time Interpositioning

```
linux> make intr
gcc -Wall -DRUNTIME -shared -fpic -o mymalloc.so mymalloc.c -ldl
gcc -Wall -o intr int.c
linux> make runr
(LD_PRELOAD="./mymalloc.so" ./intr 10 100 1000)
malloc(10) = 0x91a010
free(0x91a010)
. . .
linux>
```

Search for `<malloc.h>` leads to `/usr/include/malloc.h`

- The `LD_PRELOAD` environment variable tells the dynamic linker to resolve unresolved refs (e.g., to `malloc`) by looking in `mymalloc.so` first.
- Type into (some) shells as:

```
env LD_PRELOAD=./mymalloc.so ./intr 10 100 1000)
```

Interpositioning Recap

- **Compile Time**
  - Apparent calls to **`malloc`**/**`free`** get macro-expanded into calls to **`mymalloc`**/**`myfree`**
  - Simple approach. Must have access to source & recompile
- **Link Time**
  - Use linker trick to have special name resolutions
    - **`malloc`** → **`__wrap_malloc`**
    - **`__real_malloc`** → **`malloc`**
- **Load/Run Time**
  - Implement custom version of **`malloc`**/**`free`** that use dynamic linking to load library **`malloc`**/**`free`** under different names
  - Can use with ANY dynamically linked binary

```
env LD_PRELOAD=./mymalloc.so gcc -c int.c)
```

Linking Recap

- **Usually: Just happens, no big deal**
- **Sometimes: Strange errors**
  - Bad symbol resolution
  - Ordering dependence of linked .o, .a, and .so files
- **For power users:**
  - Interpositioning to trace programs with & without source