Linking

Linking

- **Linking**
    - Motivation
    - What it does
    - How it works
    - Dynamic linking
- **Case study: Library interpositioning**

Example C Program

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

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

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

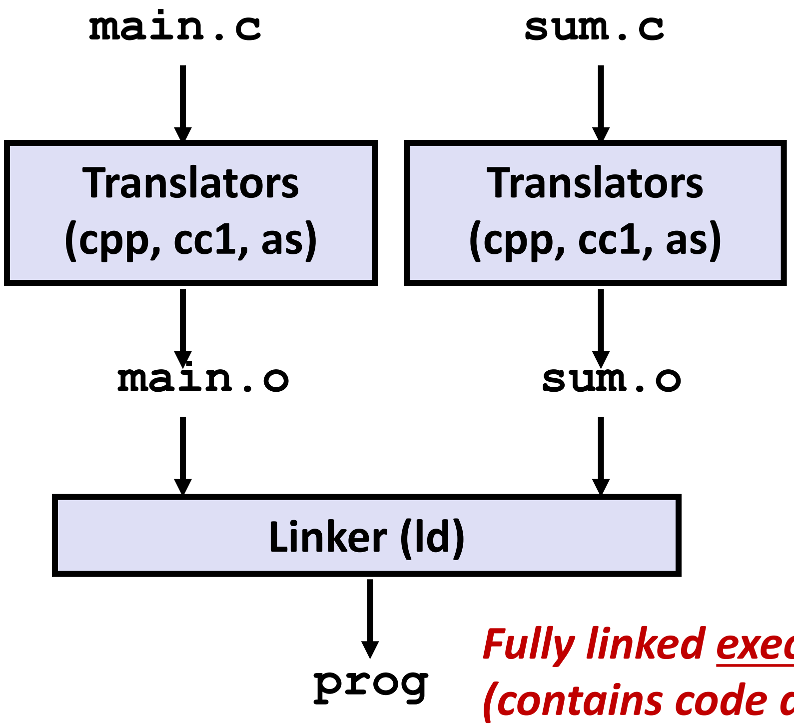
main.c

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

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

sum.c

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 <u>relocatable</u> object files

Fully linked <u>executable</u> 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

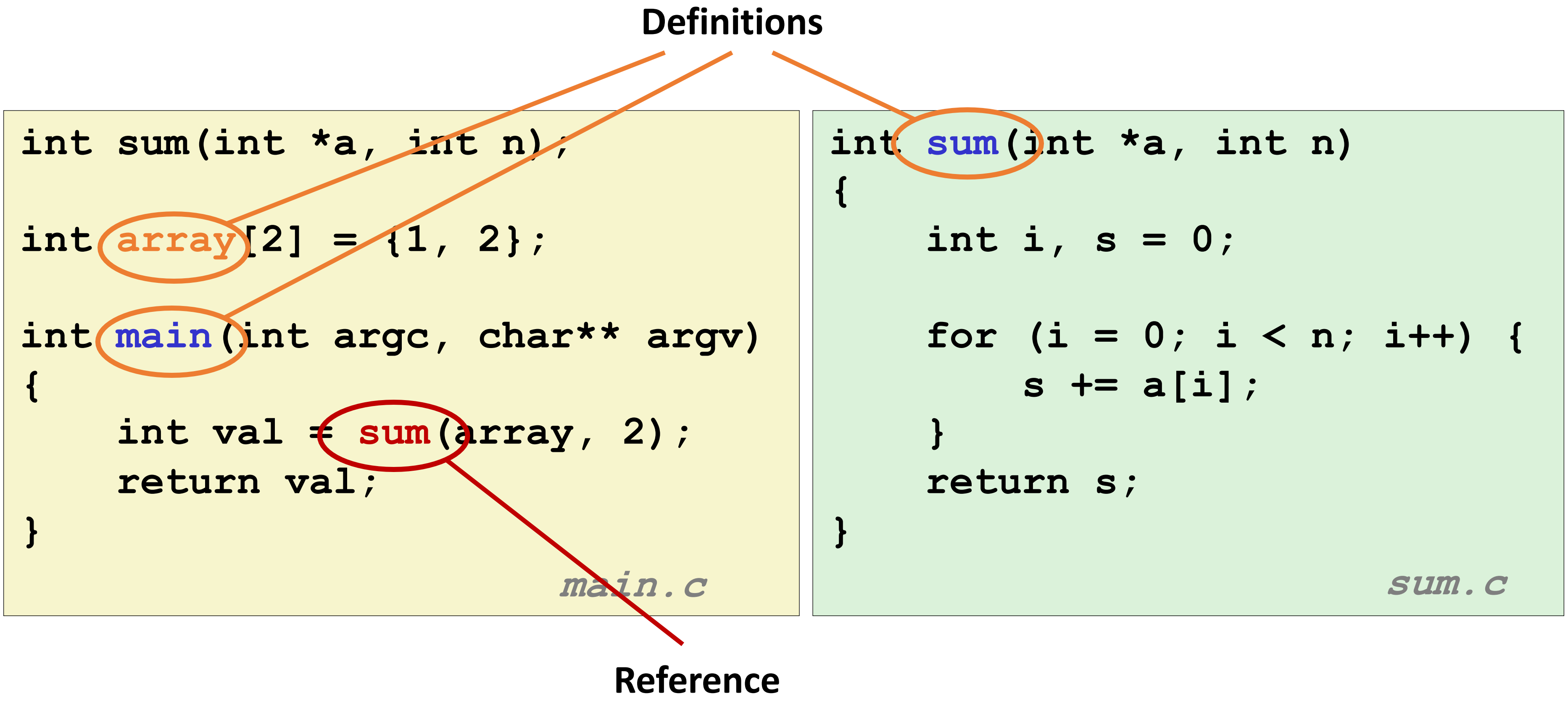
Why Linkers? (cont)

- **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



Definitions

```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

Reference

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
  - dynamic library

Executable and Linkable Format (ELF)

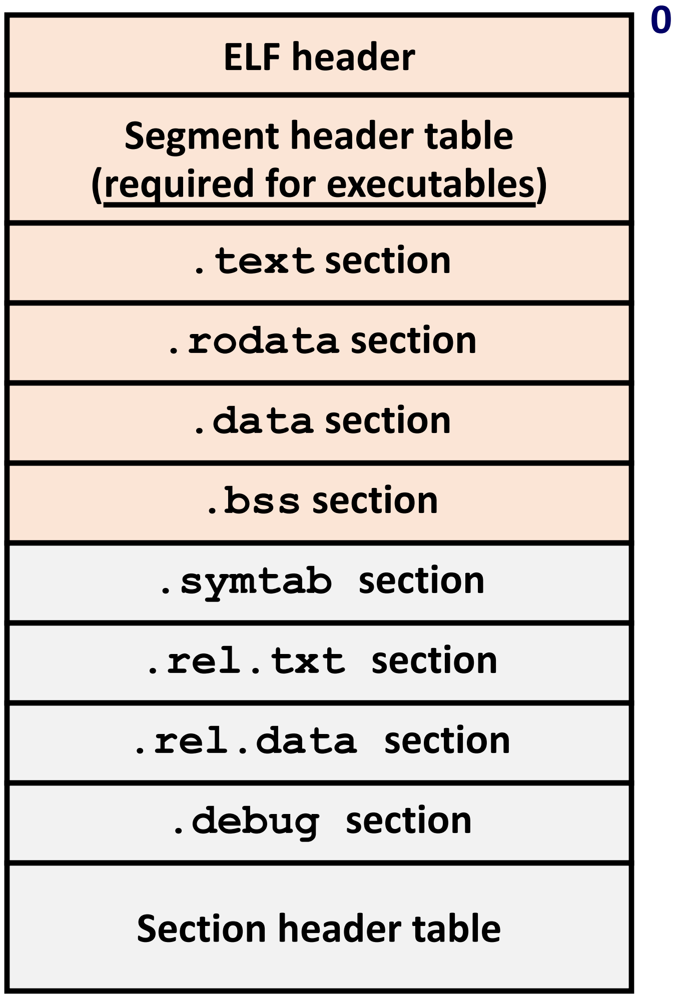
- **Standard binary format for object files**

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

- **Generic name: ELF binaries**

ELF Object File Format

- **Elf header**
  - Word size, byte ordering, file type (.o, exec, .so), machine type, etc. section size and location.
- **Segment header table**
  - Page size, virtual addresses 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 static variables, global and static variables initialized as 0
  - "Block Started by Symbol"
  - "Better Save Space"
  - Has section header but occupies no space in disk; initialize the variables in memory as 0 at run time



0

ELF header

Segment header table
(required for executables)

`.text` section

`.rodata` section

`.data` section

`.bss` section

`.symtab` section

`.rel.txt` section

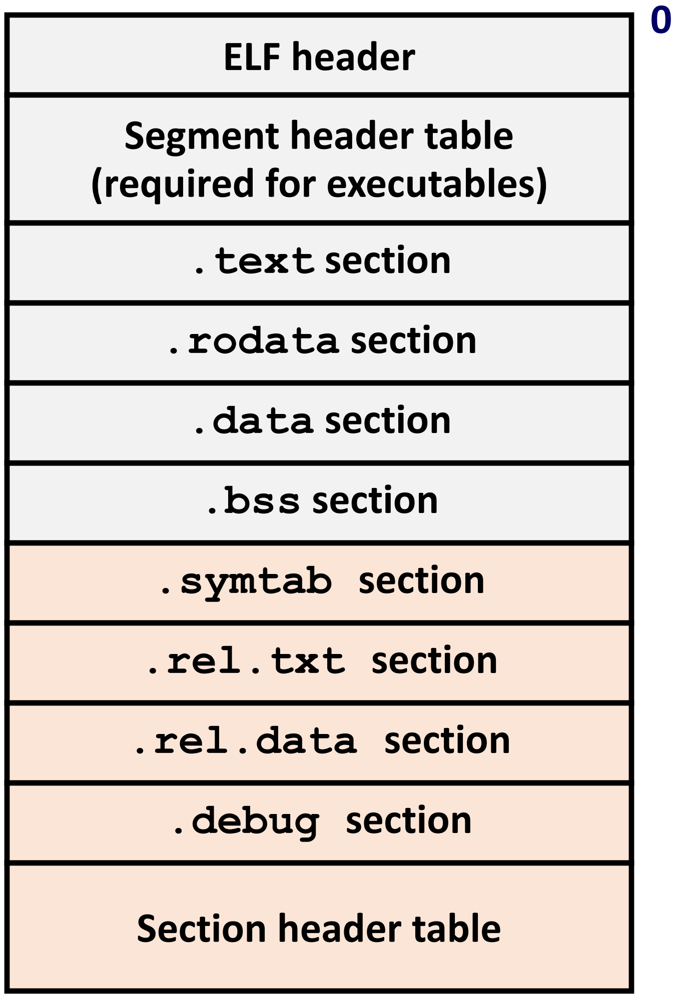
`.rel.data` section

`.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



A few more

```c
int mem_ __attribute__ ((section
("fixedloc")));

int main(int argc,char **argv){
    printf("%p\n", &mem_);
    return val;
}
gcc -O2 mem.c -o mem -Wl,--section-
start=fixedloc=0x1230000
```

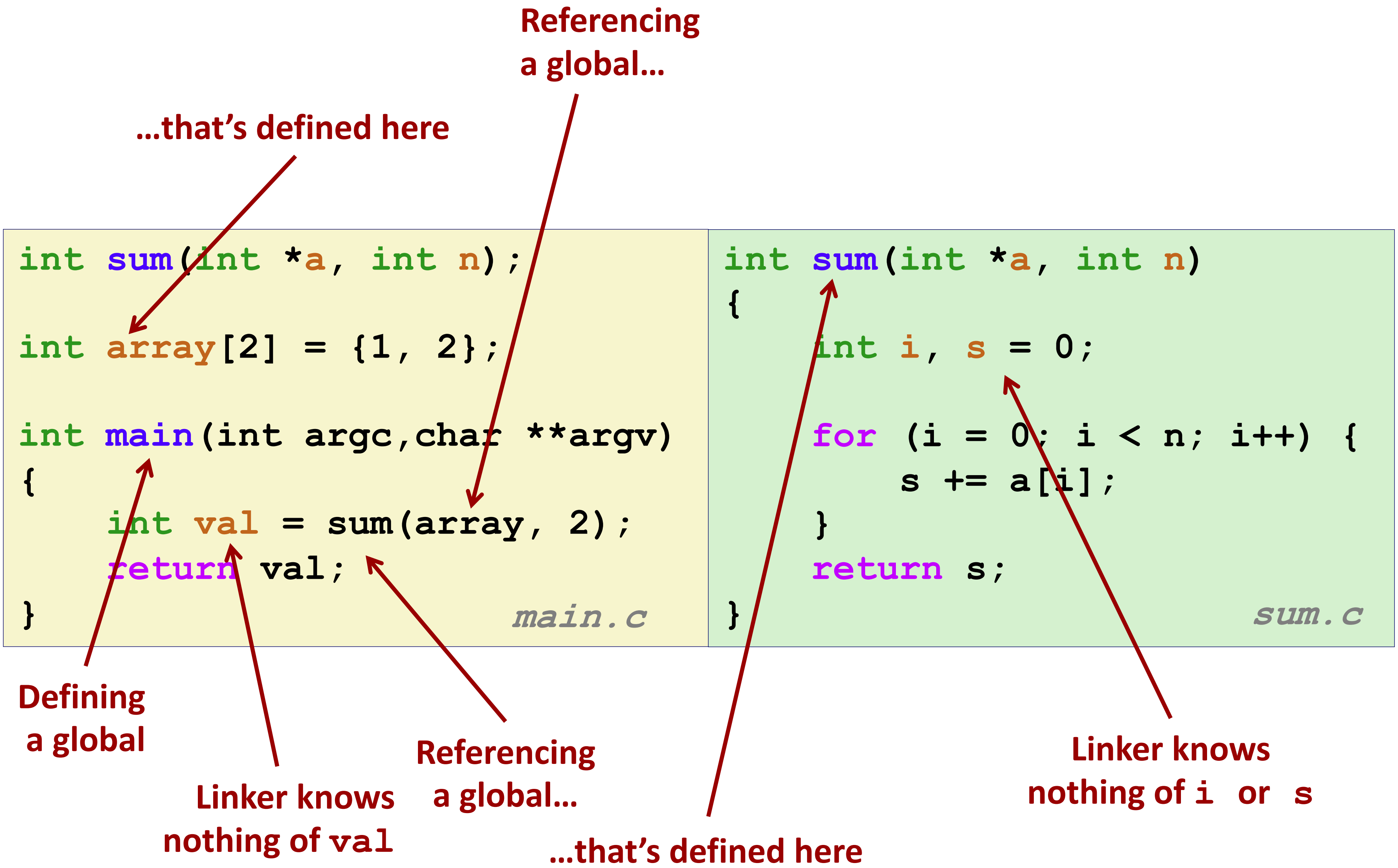
https://stackoverflow.com/questions/46662310/how-to-create-a-non-relocatable-symbol

- **Three pseudosection:**
  - ABS: symbols not relocatable
  - UNDEF: undefined symbols
  - COMMON: uninitialized global variable
- **Differences between COMMON and .bss**
  - COMMON: uninitialized global variable
  - .bss: uninitialized static variables and global or static variables which are initialized as 0

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

Referencing a global…

…that's defined here

Defining a global

Linker knows nothing of `val`

Referencing a global…

…that's defined here

Linker knows nothing of `i` or `s`

Symbol Identification

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

symbols.c:

```c
int time;

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

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

Names:

- `time`
- `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`

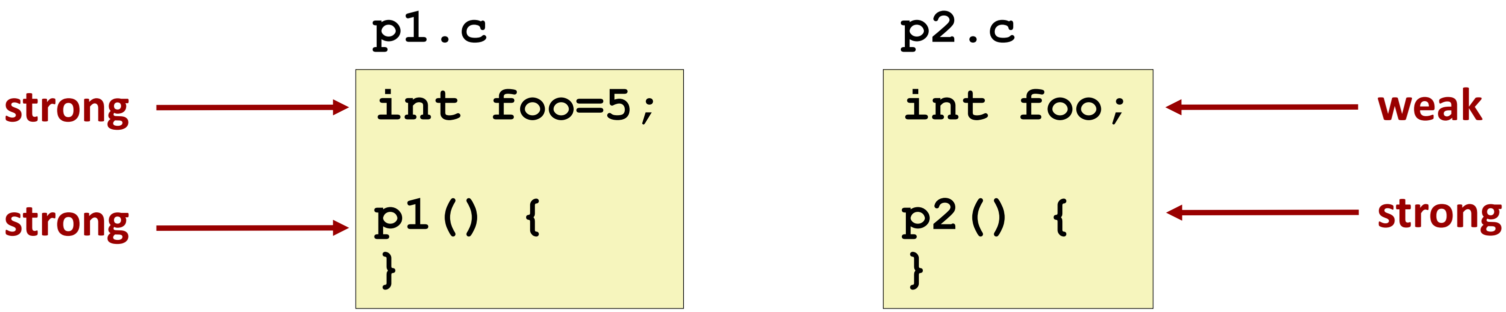
Creates local symbols in the symbol table with unique names, e.g., `x`, `x.1721` and `x.1724`.

Excersize

- **P470 Chinese Version**
  - Excersize 7.1

How Linker Resolves Duplicate Symbol Definitions

- **Program symbols are either *strong* or *weak***
  - ***Strong***: procedures and initialized globals
  - ***Weak***: uninitialized globals
    - Or ones declared with specifier **`extern`**



`p1.c`

```
int foo=5;

p1() {
}
```

`p2.c`

```
int foo;

p2() {
}
```

strong

strong

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`

- **Puzzles on the next slide**

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 both `x` and `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

```
long int x;  /* Weak symbol */

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

mismatch-main.c

```
/* Global strong symbol */
double x = 3.14;
```

mismatch-variable.c

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

My laptop: 4614253070214989087

Excersize

- **P474 Chinese Version**
  - Excersize 7.2

Global Variables

- **Avoid if you can**

- **Otherwise**
  - Use `static` if you can
  - Initialize if you define a global variable
  - Use `extern` if you reference an external global variable
    - Treated as weak symbol
    - But also causes linker error if not defined in some file

- **Compiler Help**
  - GCC -fno-common: trigger an error when multiple definition of a global variable
  - -Werror: turn all warnings into errors

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;
}
```

Calling f yields 1.

Use of .h Files (#2)

c1.c

```
#i~~nclude "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

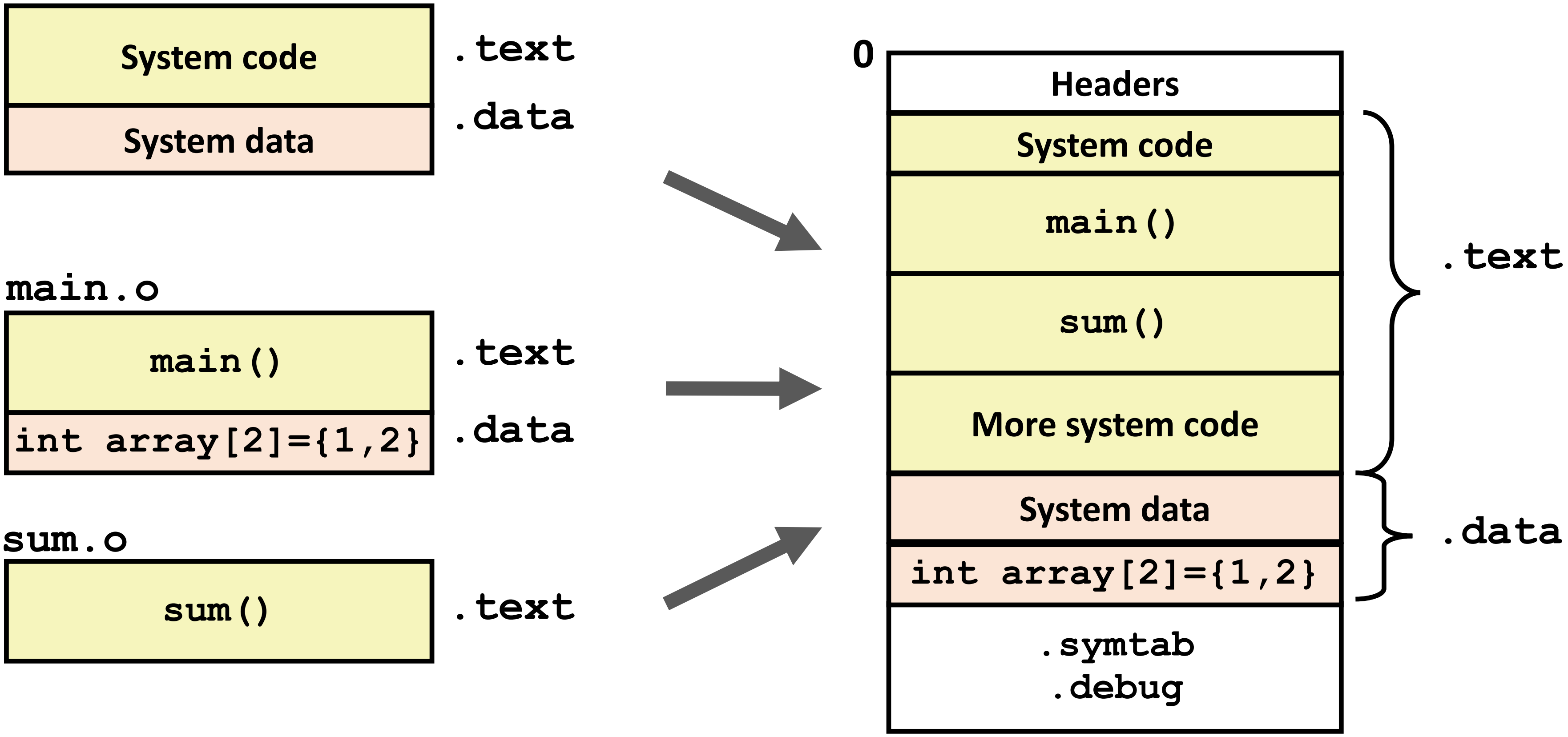
```
#define INITIALIZE
#include <stdio.h>
#~~include "global.h"~~

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;
```

Step 2: Relocation

Relocatable Object Files

Executable Object File



Relocation Entries

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

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

```
entry:
r.offset = 0xf
r.symbol = sum
r.type = R_X86_64_PC32
r.addend = -4
```

R_X86_64_32: 32 bits absolute address
R_X86_64_PC32: 32 bits PC relative address

```
0000000000000000 <main>:
   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        # %edi = &array
                        a: R_X86_64_32 array            # Relocation entry

   e:   e8 00 00 00 00          callq  13 <main+0x13>   # sum(),13(hex)=18(dec)
                        f: R_X86_64_PC32 sum-0x4        # Relocation entry
  13:   48 83 c4 08             add    $0x8,%rsp
  17:   c3                      retq
                                                                main.o
```

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

Relocated .text section

```
0000000000004004d0 <main>:
  4004d0:       48 83 ec 08       sub    $0x8,%rsp
  4004d4:       be 02 00 00 00    mov    $0x2,%esi
  4004d9:       bf 18 10 60 00    mov    $0x601018,%edi  # %edi = &array
  4004de:       e8 05 00 00 00    callq  4004e8 <sum>    # sum()
  4004e3:       48 83 c4 08       add    $0x8,%rsp
  4004e7:       c3                retq

0000000000004004e8 <sum>:
  4004e8:       b8 00 00 00 00          mov    $0x0,%eax
  4004ed:       ba 00 00 00 00          mov    $0x0,%edx
  4004f2:       eb 09                   jmp    4004fd <sum+0x15>
  4004f4:       48 63 ca                movslq %edx,%rcx
  4004f7:       03 04 8f                add    (%rdi,%rcx,4),%eax
  4004fa:       83 c2 01                add    $0x1,%edx
  4004fd:       39 f2                   cmp    %esi,%edx
  4004ff:       7c f3                   jl     4004f4 <sum+0xc>
  400501:       f3 c3                   repz retq
```

`callq` instruction uses PC-relative addressing for sum():

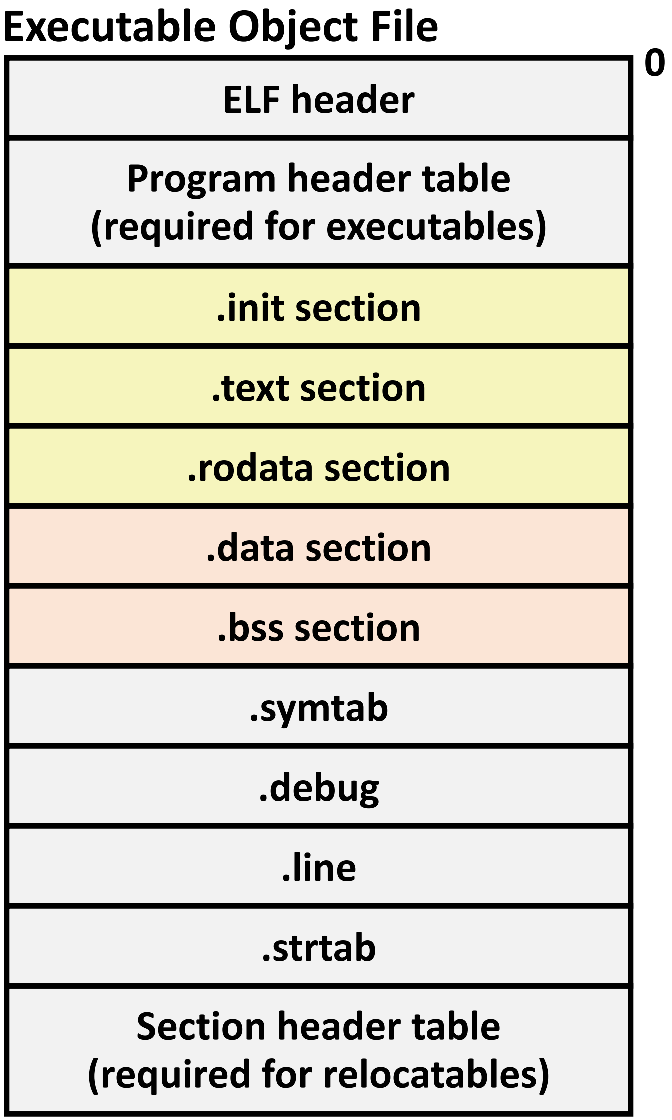
`0x4004e8` = `0x4004e3` + `0x5`

Source: `objdump -d prog`

Excersize

- **P482 Chinese Version**
  - Excersize 7.4
  - Excersize 7.5

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)

Read-only code segment

```
1 LOAD  off      0x0000000000000000
        vaddr    0x0000000000400000
        paddr    0x0000000000400000
        align    2**21
2       filesz   0x000000000000069c
        memsz    0x000000000000069c
        flags    r-x
```

Read-only data segment

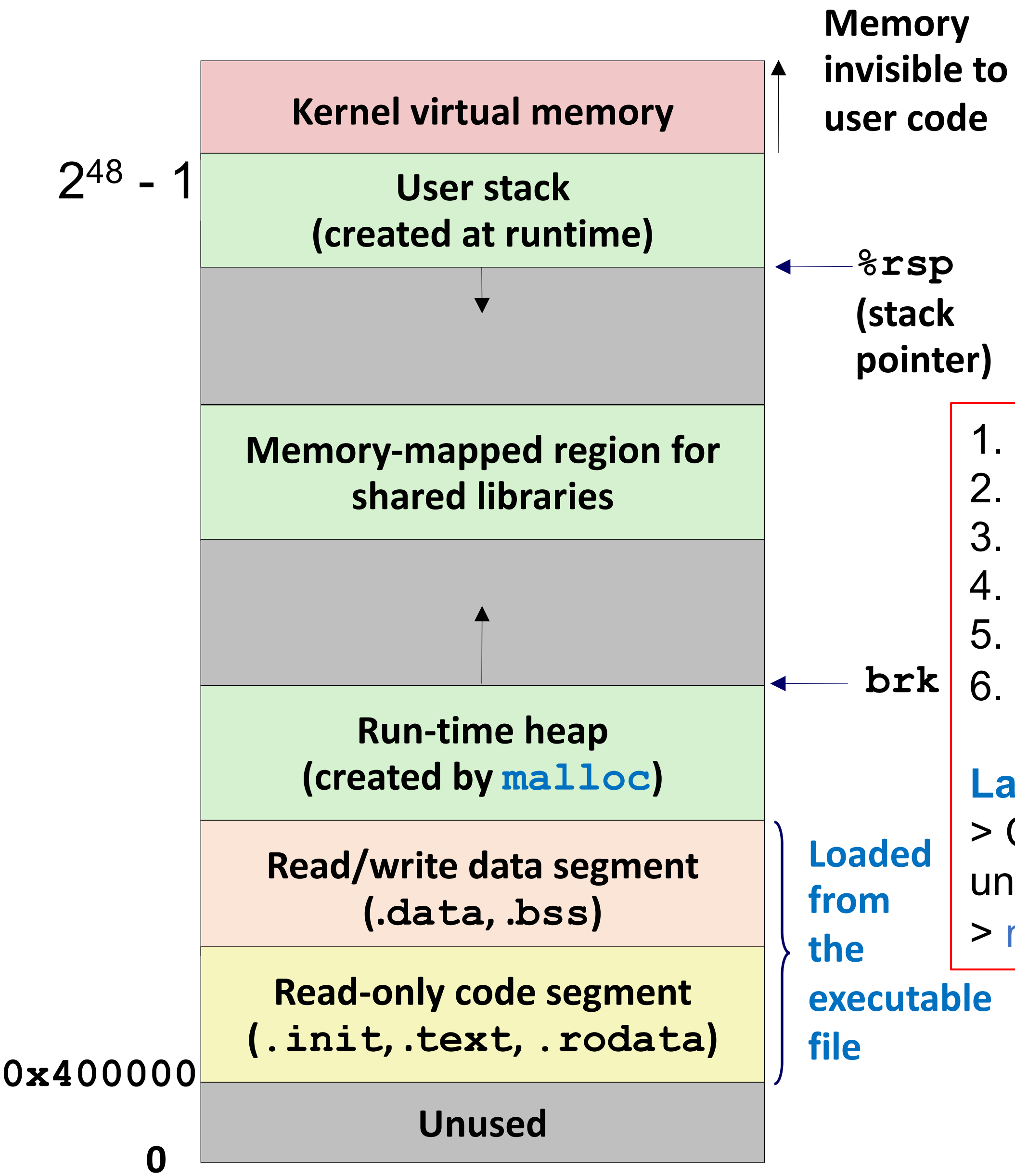
```
3 LOAD  off      0x0000000000000df8
        vaddr    0x0000000000600df8
        paddr    0x0000000000600df8
        align    2**21
4       filesz   0x0000000000000228
        memsz    0x0000000000000230
        flags    r-x
```

.bss segment not store on disk
initializes as 0 in memory

vaddr mod align = off mod align

0x600df8 mod 0x200000 = 0xdf8

Loading Executable Object Files



Kernel virtual memory

Memory invisible to user code

$2^{48} - 1$

User stack
(created at runtime)

`%rsp` (stack pointer)

Memory-mapped region for shared libraries

`brk`

Run-time heap
(created by `malloc`)

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

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

Loaded from the executable file

`0x400000`

Unused

0

1. shell process generate a child process
2. child process called loader with execve()
3. loader removes the virtual memory segment
4. New stack and heap are initialized 0
5. New data and code segment are initialized
6. Jump to the _start address

Lazy data policy

> CPUs do not load data from disk to memory until the data is actually accessed

> malloc - allocate memory at first touch

Packaging Commonly Used Functions

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

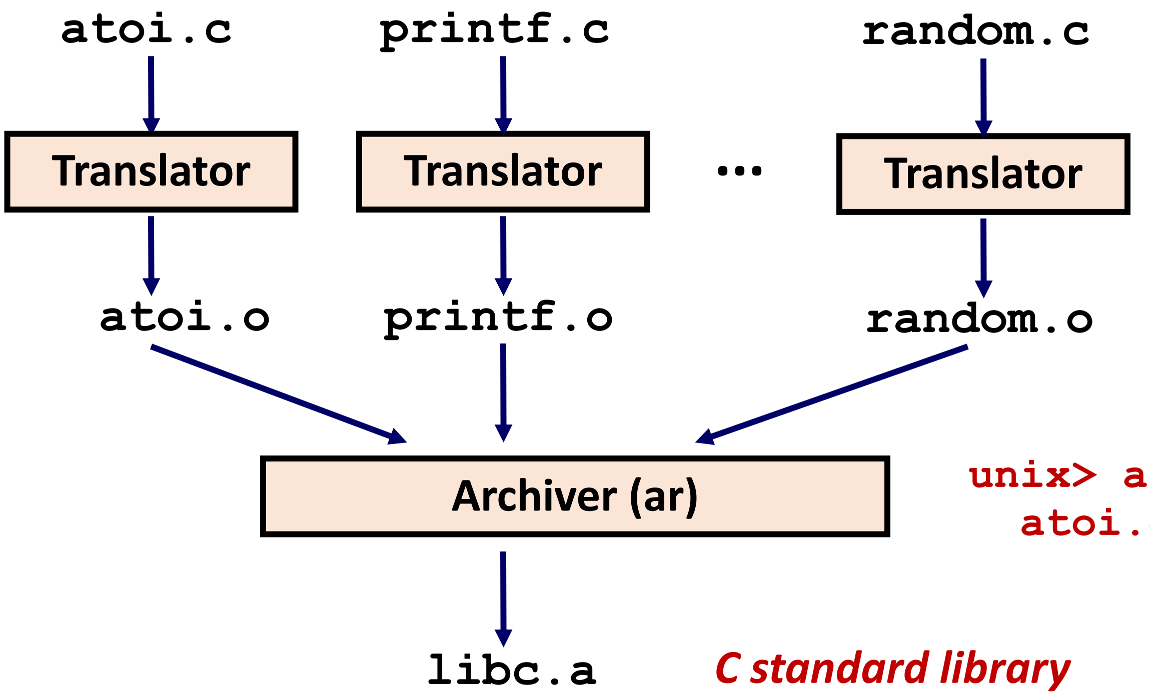
- **Awkward, given the linker framework so far:**
  - **Option 1:** Put all functions into a single source file
    - Programmers link big object file into their programs
    - Space and time inefficient

  - **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



`atoi.c` `printf.c` … `random.c`

Translator Translator Translator

`atoi.o` `printf.o` `random.o`

Archiver (ar)

`libc.a`

C standard library

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

- 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.
- 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.
- 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`

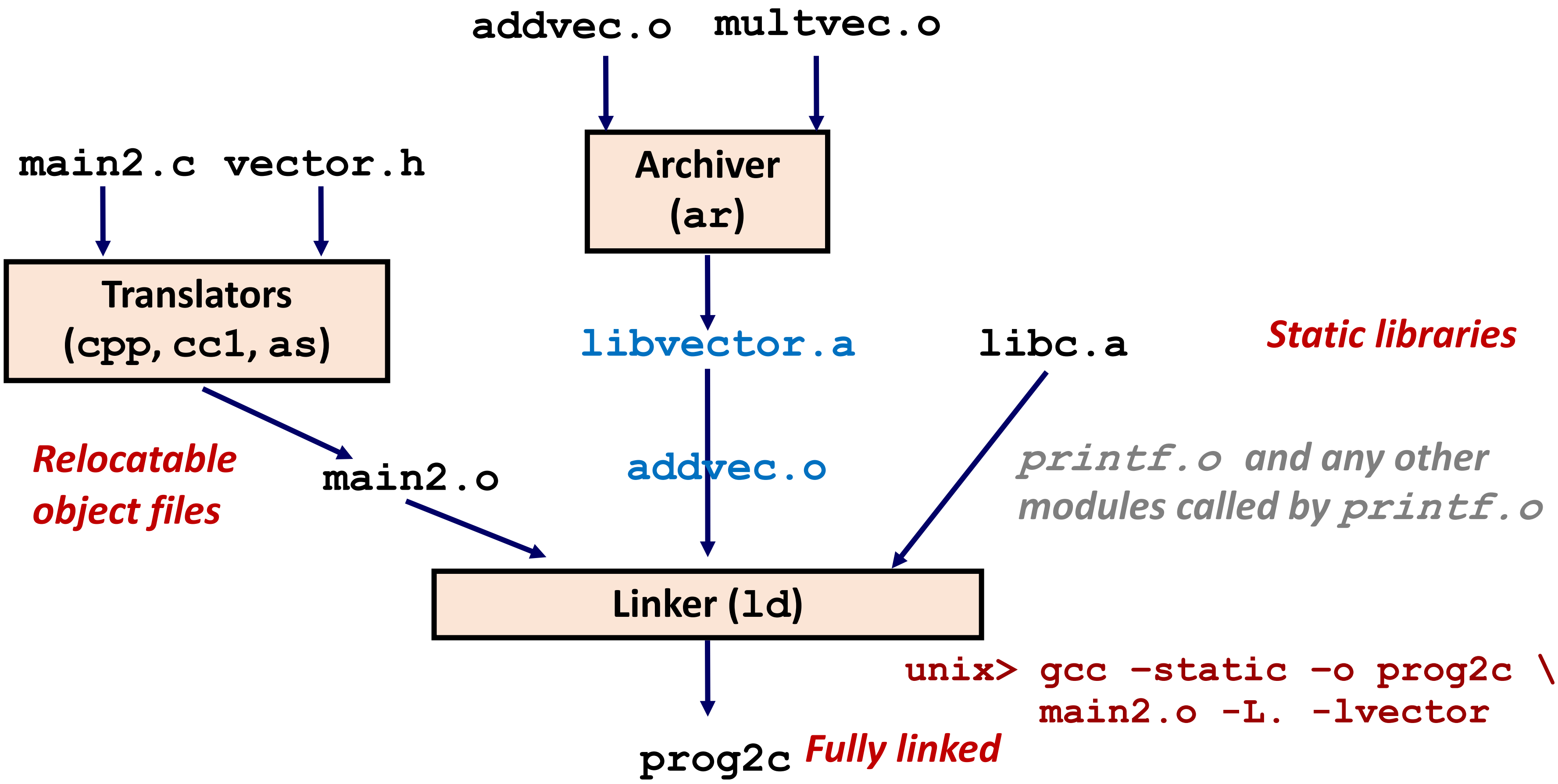
```
void addvec(int *x, int *y,
            int *z, int n) {
    int i;

    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`

`main2.c` `vector.h`

Archiver (`ar`)

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*
(892,607 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
```

Excersize

- **P478 Chinese Version**
  - Excersize 7.3

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 updates - Windows
    - High-performance web servers - generate dynamic content without CGI
    - Runtime library interpositioning.

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

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`**

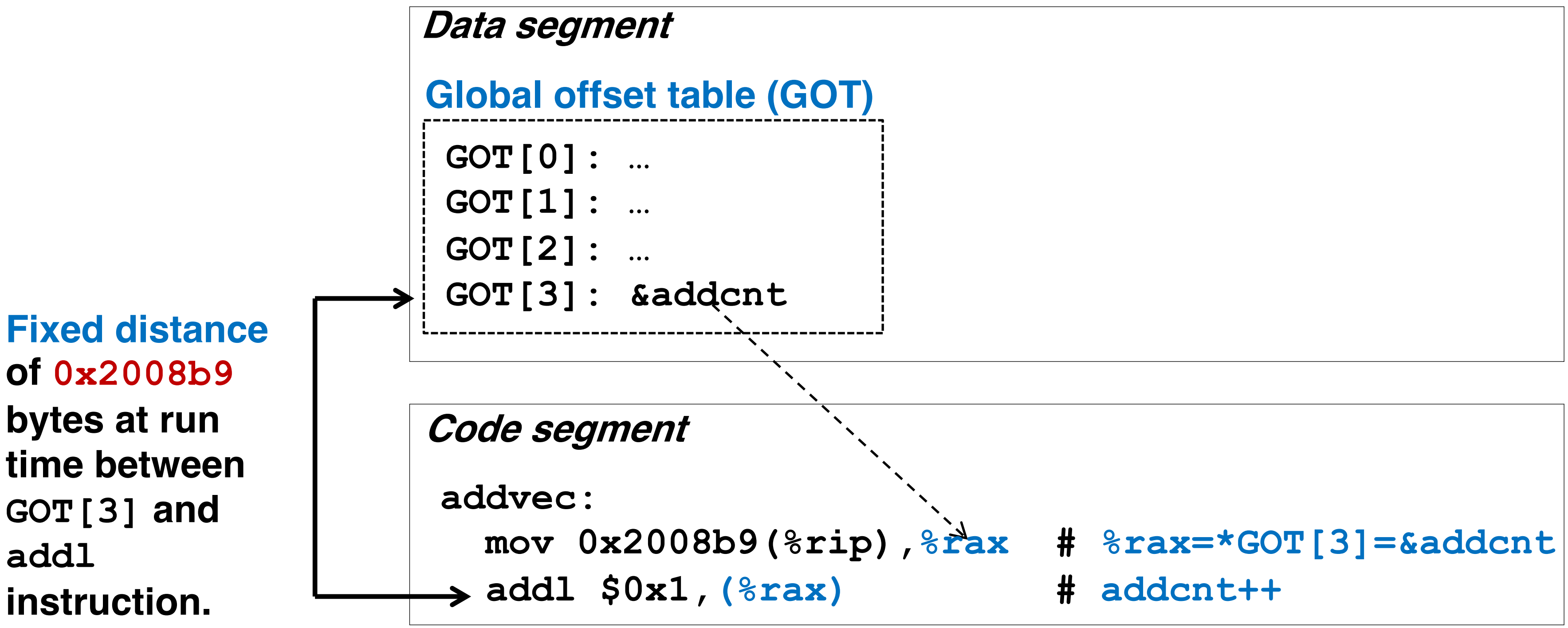
```
(NEEDED)                Shared library: [libm.so.6]
```

- **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)
```

Position Independent Code

- **1) Data reference** in PIC
  - Global Offset Table (GOT) at the start of data segment
  - Relative addressing
  - Use fixed distance between data segment and code segment



Data segment

Global offset table (GOT)

```
GOT[0]: …
GOT[1]: …
GOT[2]: …
GOT[3]: &addcnt
```

Code segment

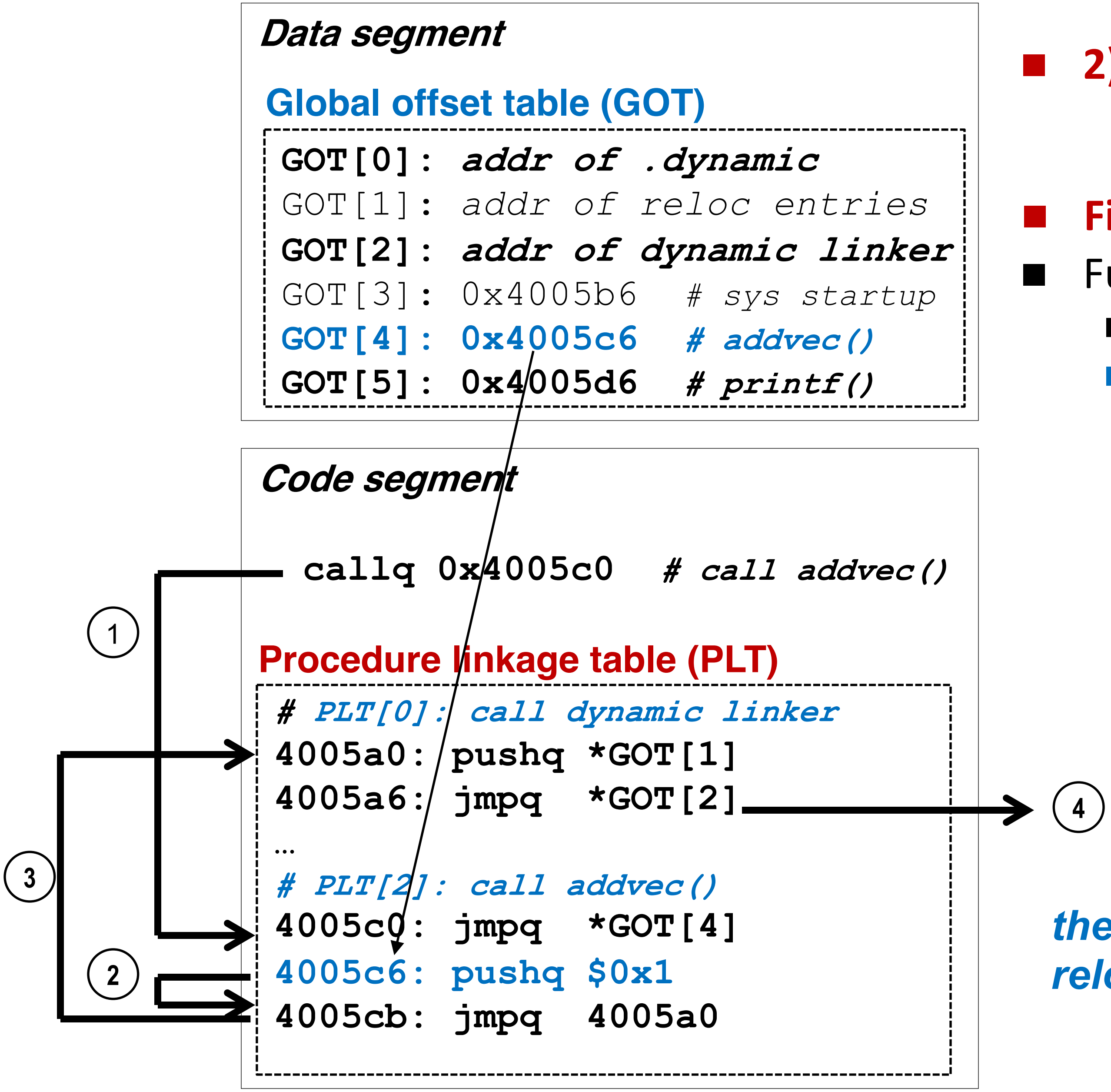
```
addvec:
   mov 0x2008b9(%rip),%rax   # %rax=*GOT[3]=&addcnt
   addl $0x1,(%rax)          # addcnt++
```

Fixed distance of `0x2008b9` bytes at run time between `GOT[3]` and `addl` instruction.

Position Independent Code

- **2) Function reference**

- **First** call addvec
- Function call in IPC
  - PLT in code segment
  - Each library function has an item in PLT



Data segment

Global offset table (GOT)

```
GOT[0]: addr of .dynamic
GOT[1]: addr of reloc entries
GOT[2]: addr of dynamic linker
GOT[3]: 0x4005b6   # sys startup
GOT[4]: 0x4005c6   # addvec()
GOT[5]: 0x4005d6   # printf()
```

Code segment

```
callq 0x4005c0   # call addvec()
```

Procedure linkage table (PLT)

```
# PLT[0]: call dynamic linker
4005a0: pushq *GOT[1]
4005a6: jmpq  *GOT[2]
…
# PLT[2]: call addvec()
4005c0: jmpq  *GOT[4]
4005c6: pushq $0x1
4005cb: jmpq  4005a0
```

use two stack items 0x1 and GOT[1] to locate the addvec in reloc entries

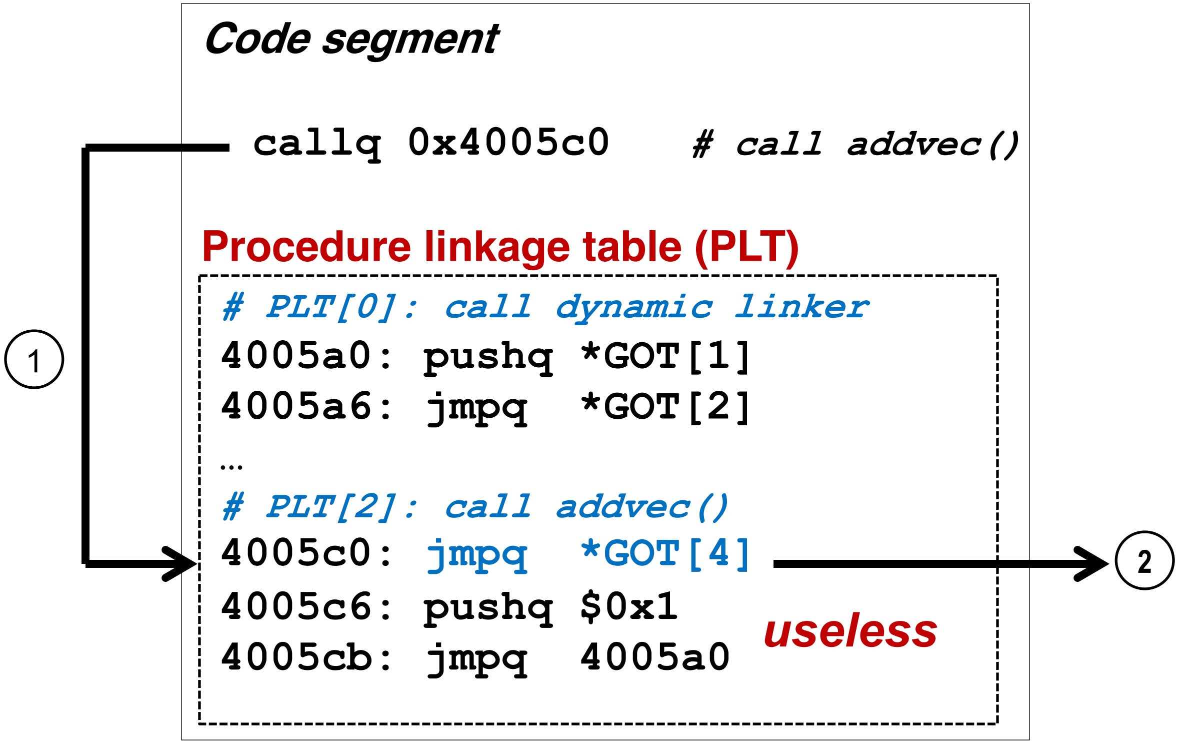
the ID of addvec is 0x1 in the reloc entries (a table)

Position Independent Code

Data segment

Global offset table (GOT)

```
GOT[0]: addr of .dynamic
GOT[1]: addr of reloc entries
GOT[2]: addr of dynamic linker
GOT[3]: 0x4005b6   # sys startup
GOT[4]: &addvec()
GOT[5]: 0x4005d6   # printf()
```



Code segment

```
callq 0x4005c0    # call addvec()
```

Procedure linkage table (PLT)

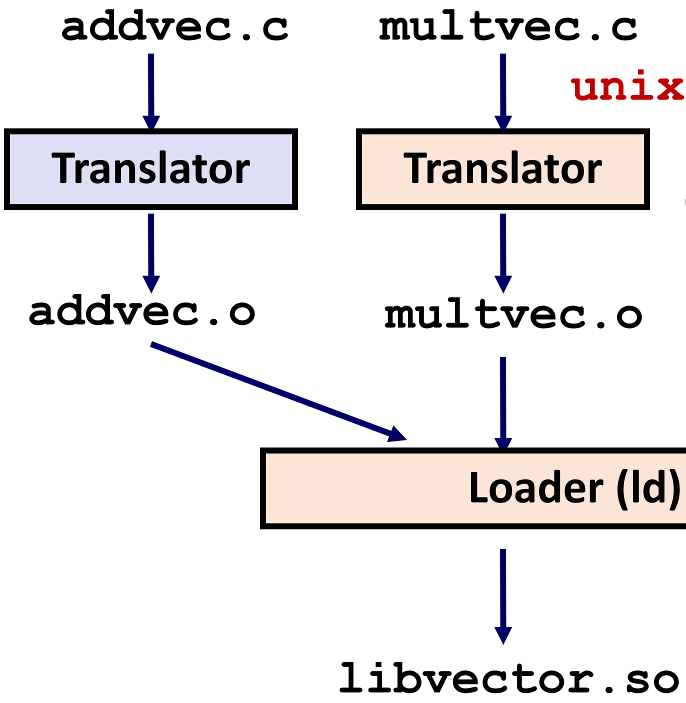
```
# PLT[0]: call dynamic linker
4005a0: pushq *GOT[1]
4005a6: jmpq  *GOT[2]
…
# PLT[2]: call addvec()
4005c0: jmpq  *GOT[4]
4005c6: pushq $0x1
4005cb: jmpq  4005a0
```

useless

- **Update** GOT[4] with the absolute address of addvec
- Call addvec directly in the following

Generate Dynamic Library

-fpic: tell the compiler to produce Position-Independent Code



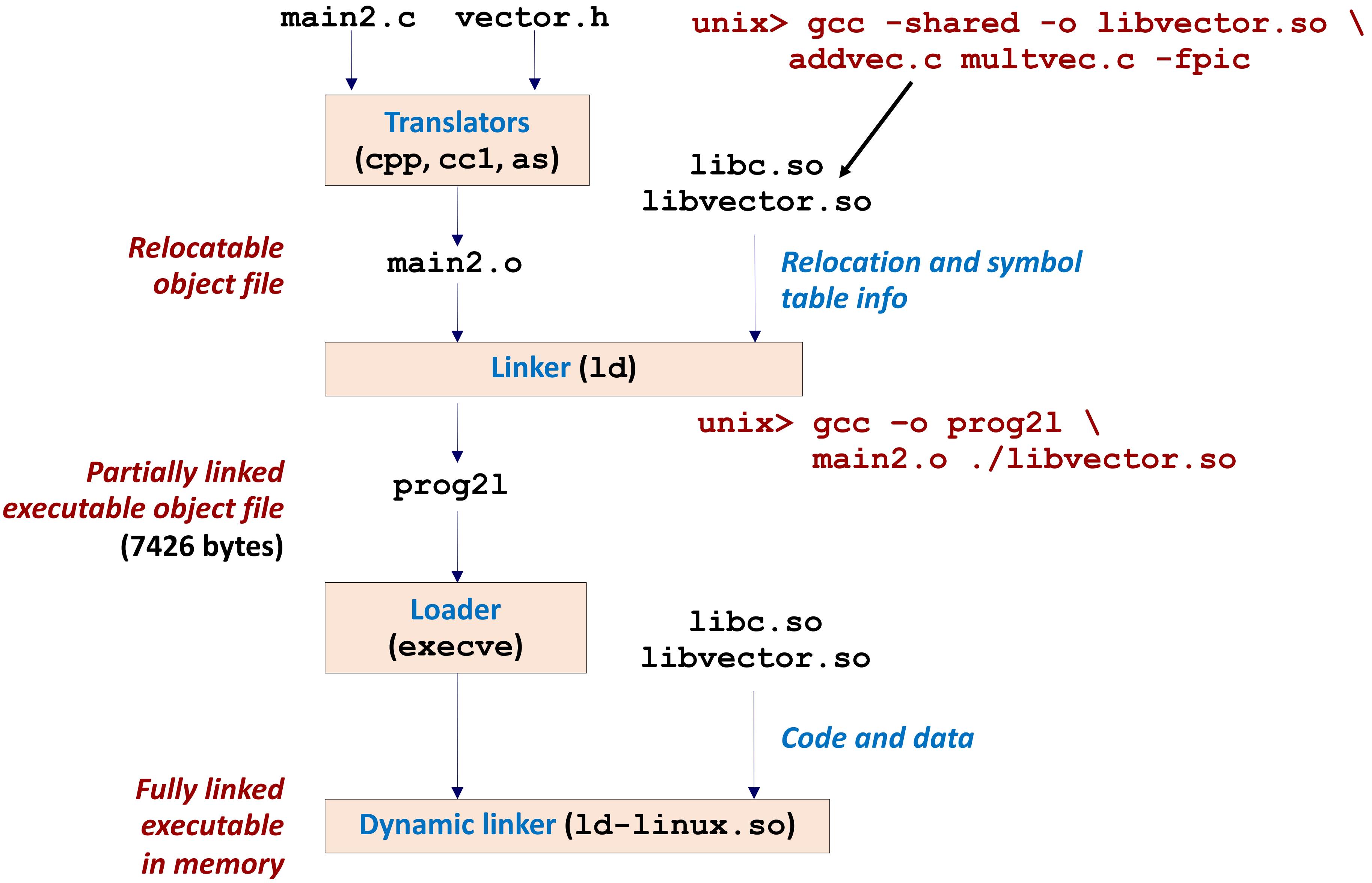
```
unix> gcc –Og –c addvec.c multvec.c -fpic
```

Og - Debug with reasonable optimization

```
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 (7426 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

```c
#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);
    }
  . . .
```

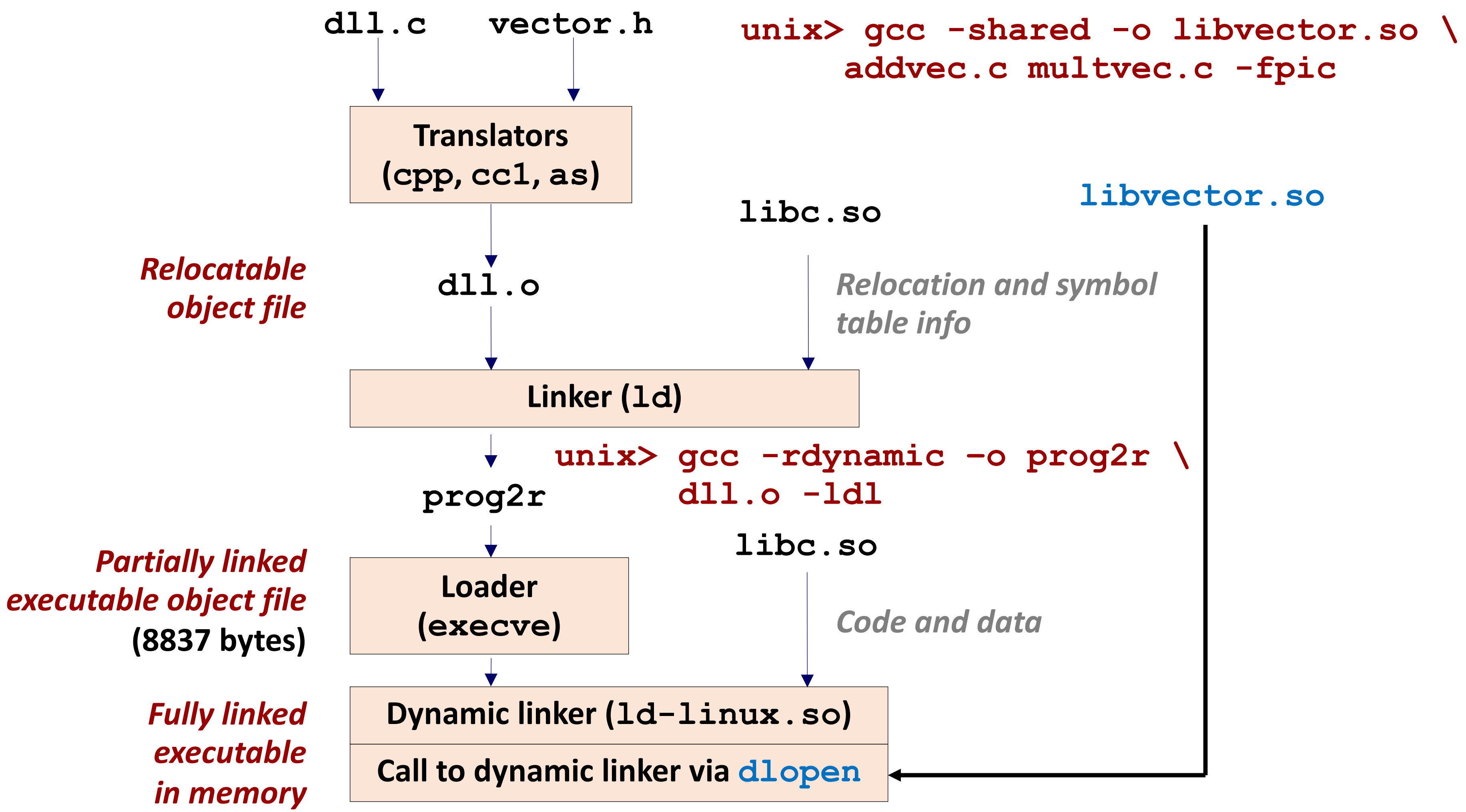
dll.c

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



`dll.c` `vector.h`

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

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

Relocatable object file `dll.o`

`libc.so`

Relocation and symbol table info

`libvector.so`

Linker (`ld`)

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

Partially linked executable object file (8837 bytes) `prog2r`

`libc.so`

Code and data

Loader
(`execve`)

Fully linked executable in memory

Dynamic linker (`ld-linux.so`)

Call to dynamic linker via `dlopen`

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.**

Linking

- Linking
- **Case study: Library interpositioning**

Case Study: Library Interpositioning

- **Documented in Section 7.13 of book**
- **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) - detect malicious behaviors in untrusted code
    - write/read files in unallowed directories
  - 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 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

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

```
#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

```c
#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

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

```
#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

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:

```
(setenv 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

```
(setenv 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

Interposition - Virtual Machine

- **All guest actions go through monitor**
- **Monitor can inspect, modify, deny operations**
- **Ex**
  - Compression
  - Encryption
  - Profiling
  - Translation

- **A windows application can run on a Linux system**
- **A iOS application can run on android**
- **A application compiled for x86 architecture can run on MIPS**