计算机系统基础10

Linking

Today

- **Linking**
  - Motivation
  - What it does
  - How it works
  - Dynamic linking
- **Lazy Binding**

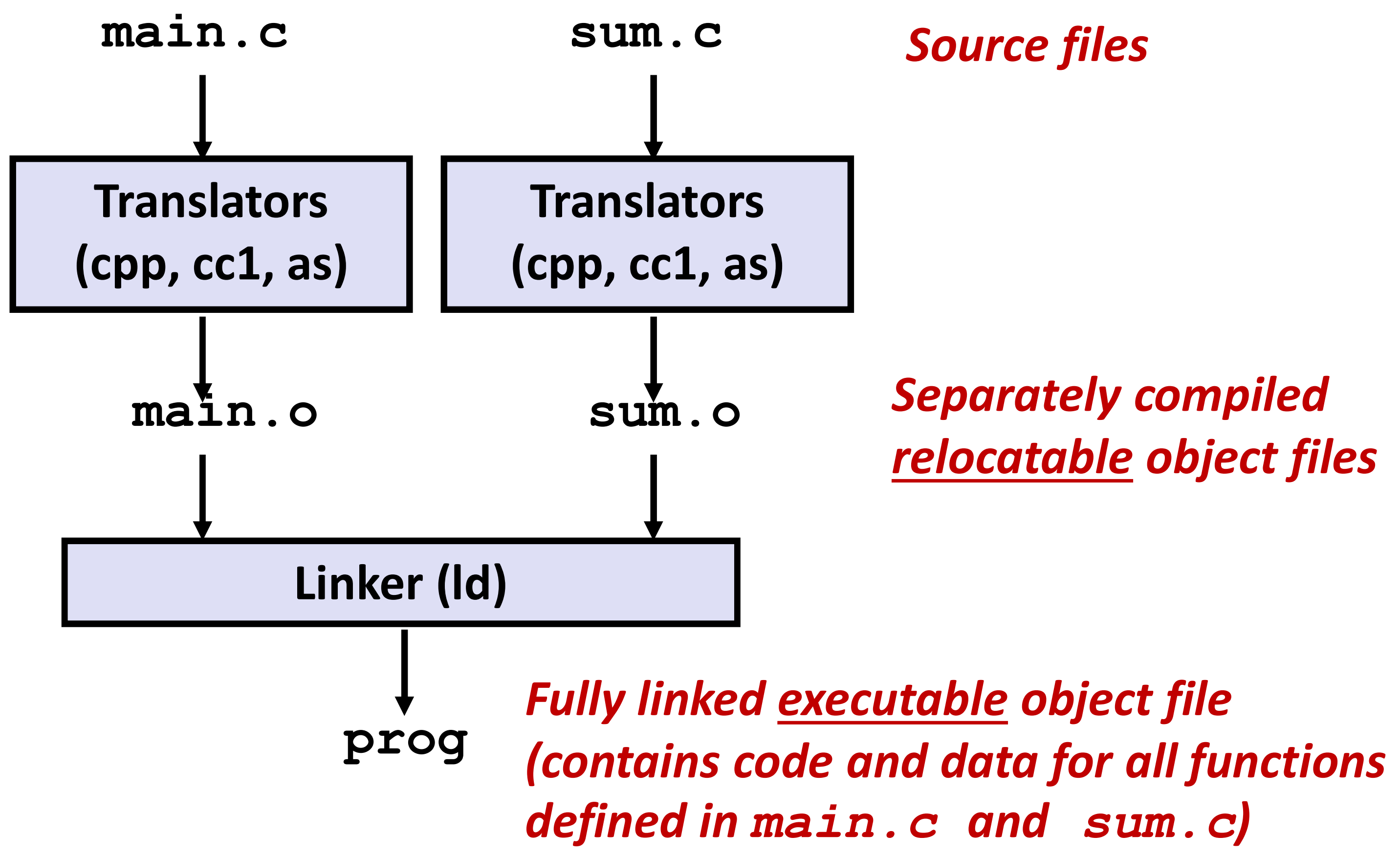
Example C Program

```
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`


main.c
sum.c
Source files
Translators (cpp, cc1, as)
Translators (cpp, cc1, as)
main.o
sum.o
Separately compiled relocatable object files
Linker (ld)
prog
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

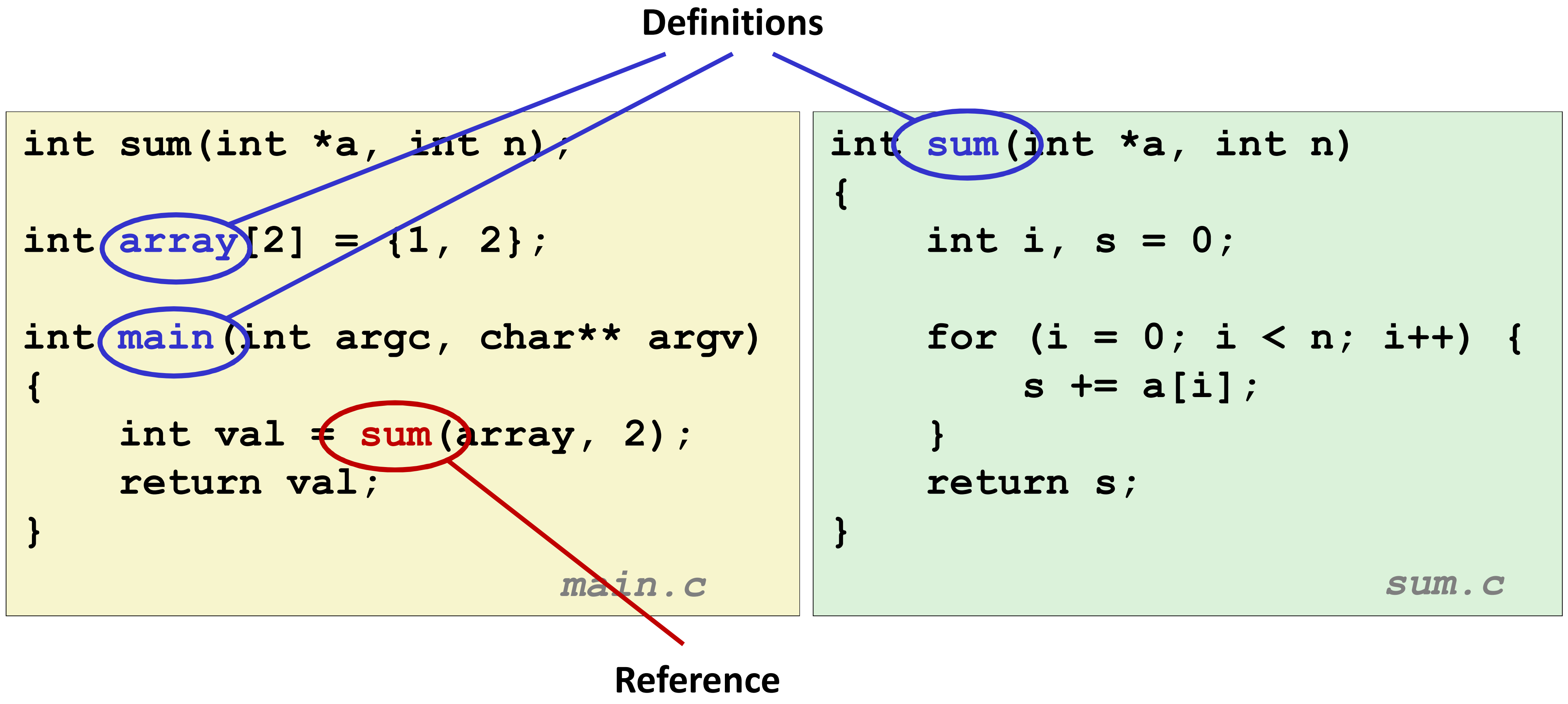
Why Linkers? (cont)

- **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



```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

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.

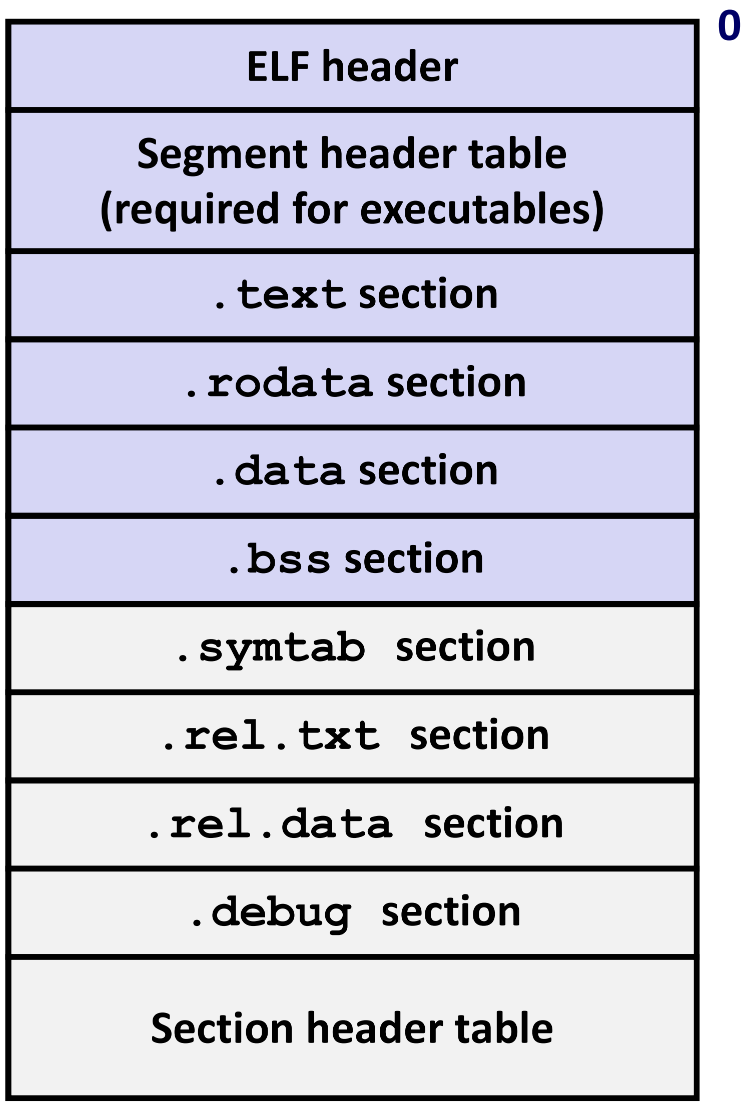
- **Shared object file (`.so` file)**
  - Special type of relocatable object file that can be loaded into memory and linked dynamically, at either load time or run-time.
  - Called *Dynamic Link Libraries* (DLLs) by Windows

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

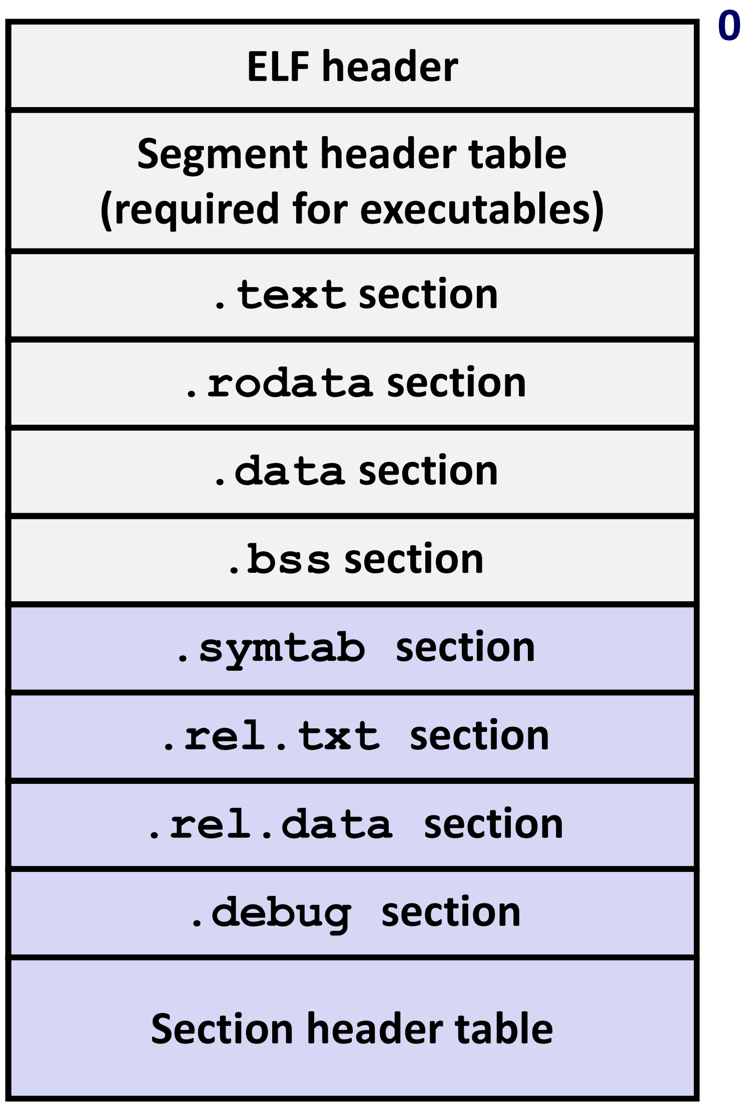
ELF Object File Format

- **ELF header**
  - Word size, byte ordering, file type (.o, exec, .so), machine type, etc.
- **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 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



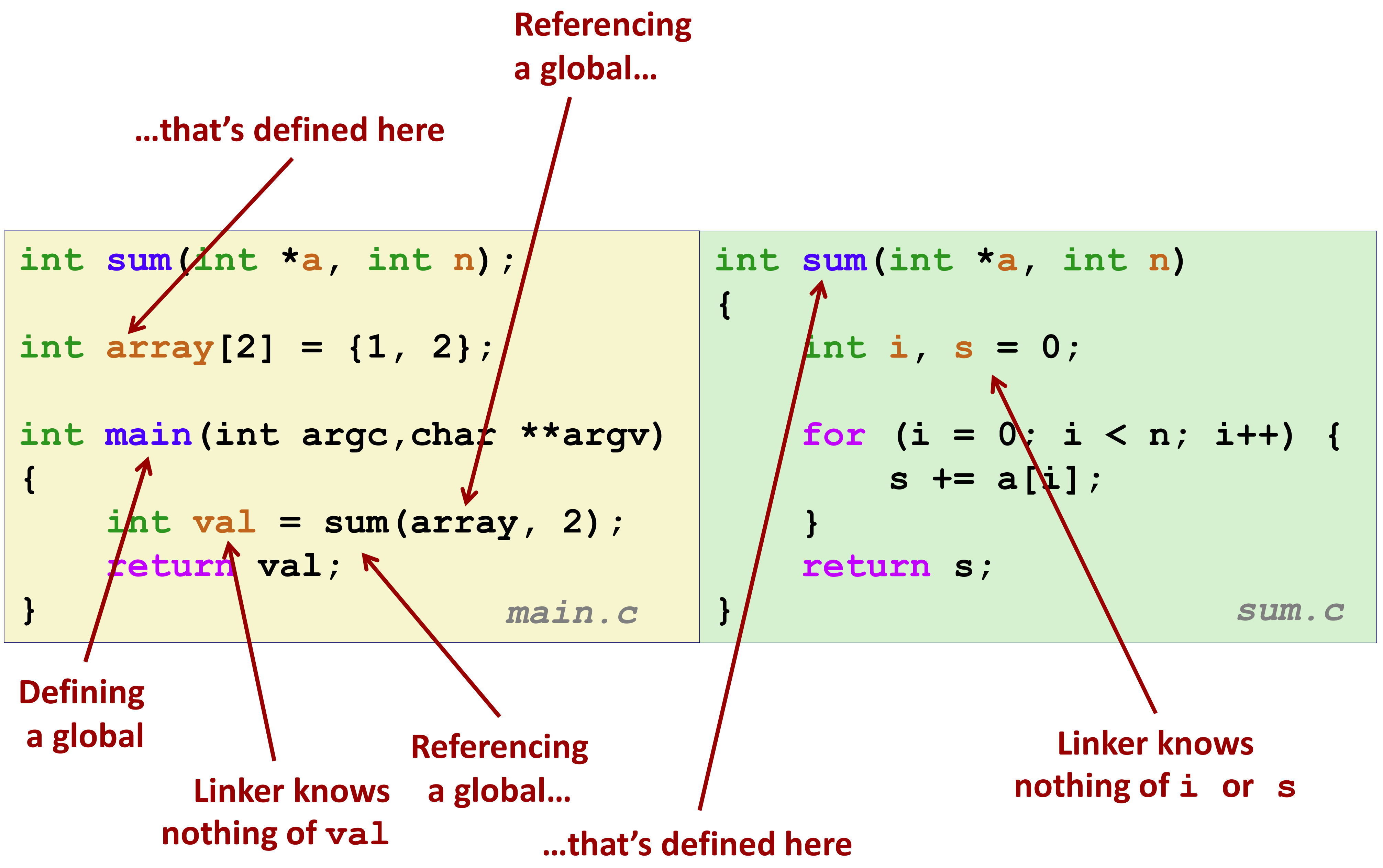
Linker Symbols

- **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

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"`

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;
}
```

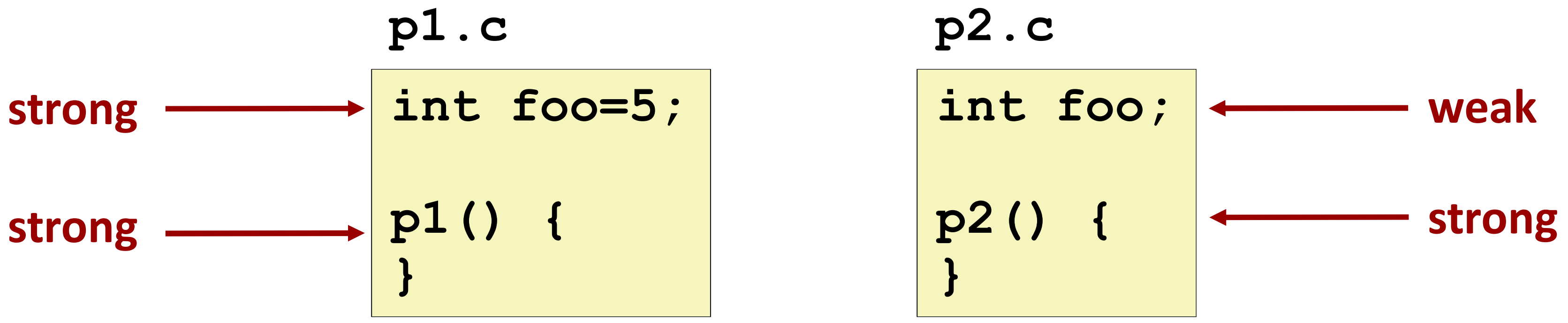
static-local.c

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 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() {
}
```

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`** will 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

```
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?**

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

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)

`global.h`

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

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

`c1.c`

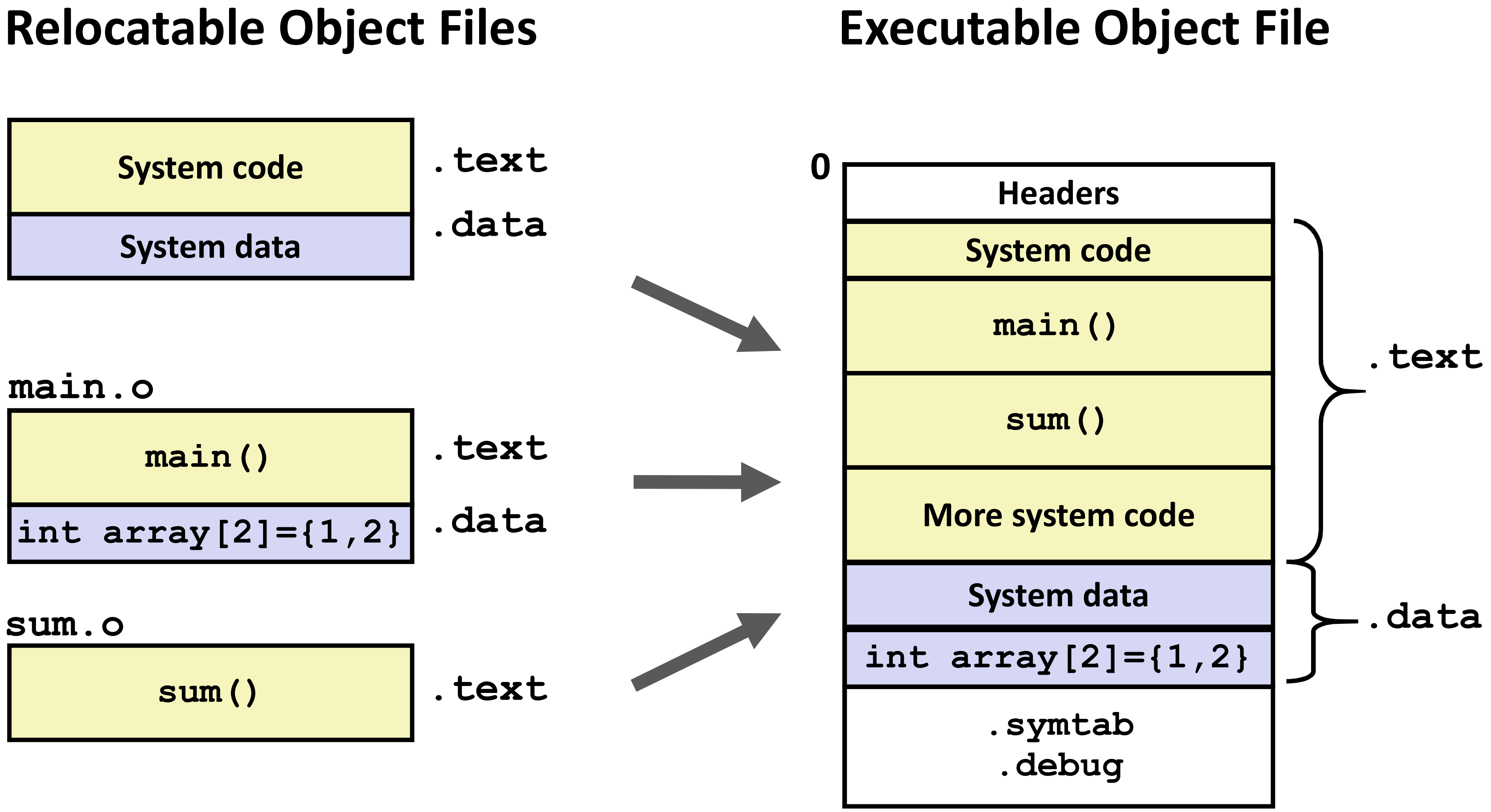
```
~~#include "global.h"~~

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

`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



Relocation Entries

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

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

```
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()
                        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

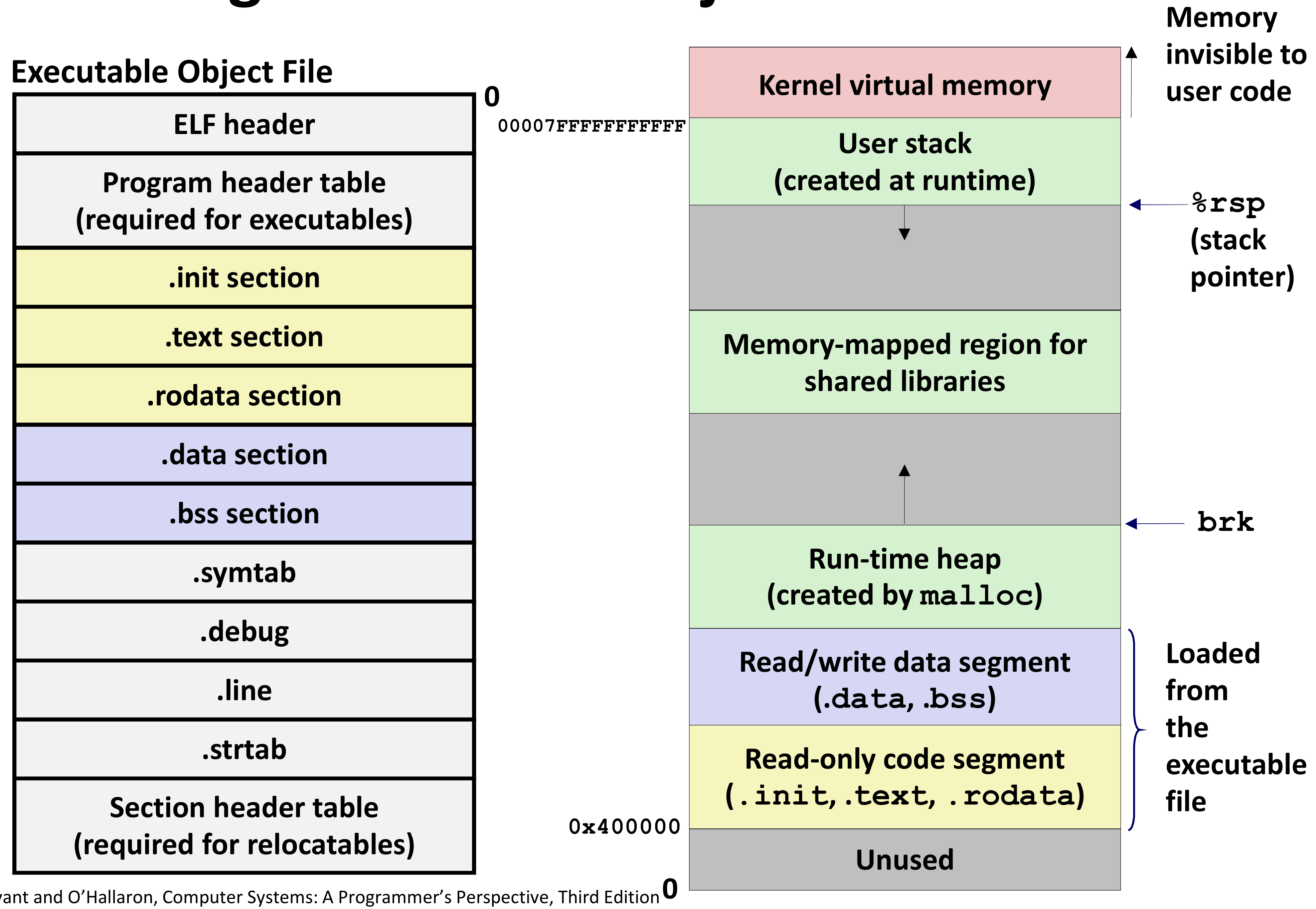
```
00000000004004d0 <main>:
  4004d0:       48 83 ec 08          sub    $0x8,%rsp
  4004d4:       be 02 00 00 00       mov    $0x2,%esi
  4004d9:       bf 18 10 60 00       mov    $0x601018,%edi  # %edi = &array
  4004de:       e8 05 00 00 00       callq  4004e8 <sum>    # sum()
  4004e3:       48 83 c4 08          add    $0x8,%rsp
  4004e7:       c3                   retq

00000000004004e8 <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`

Loading Executable Object Files



Packaging Commonly Used Functions

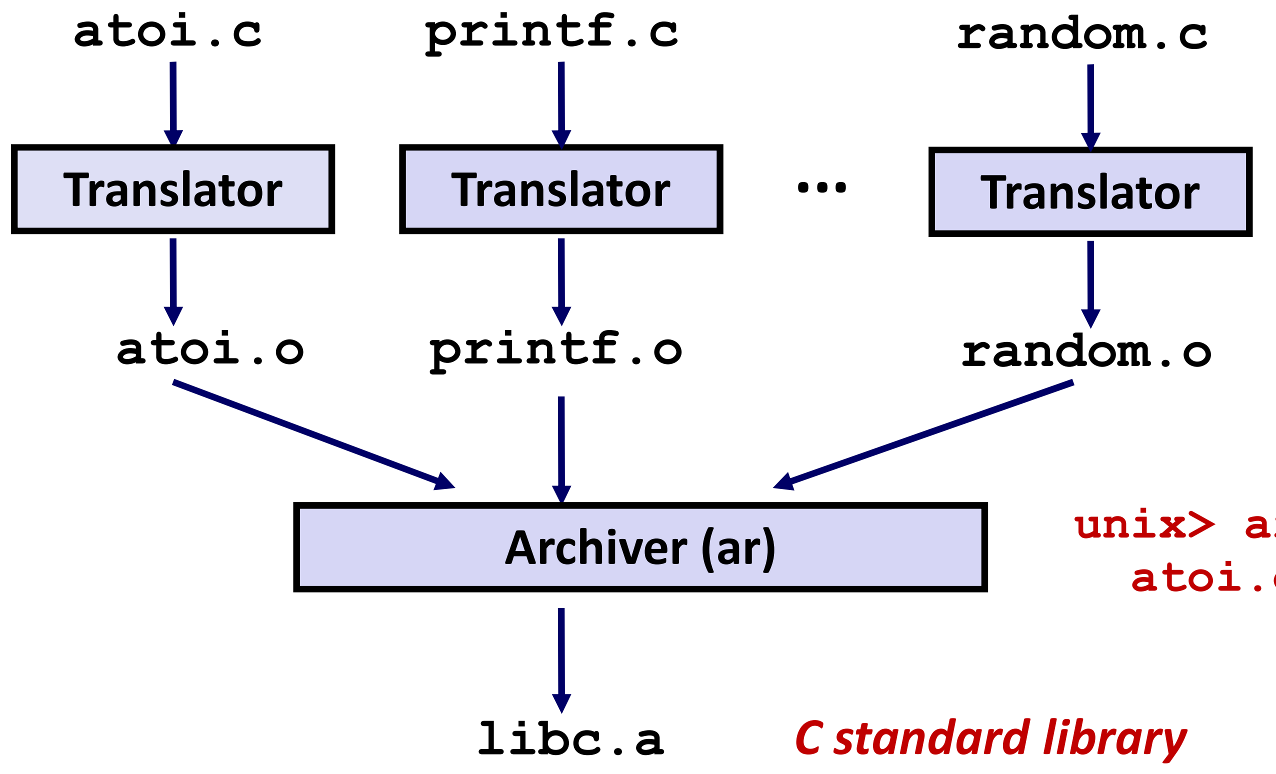
- **How to package functions commonly used by programmers?**
  - Math, I/O, memory management, string manipulation, etc.

- **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



```
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.
- 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

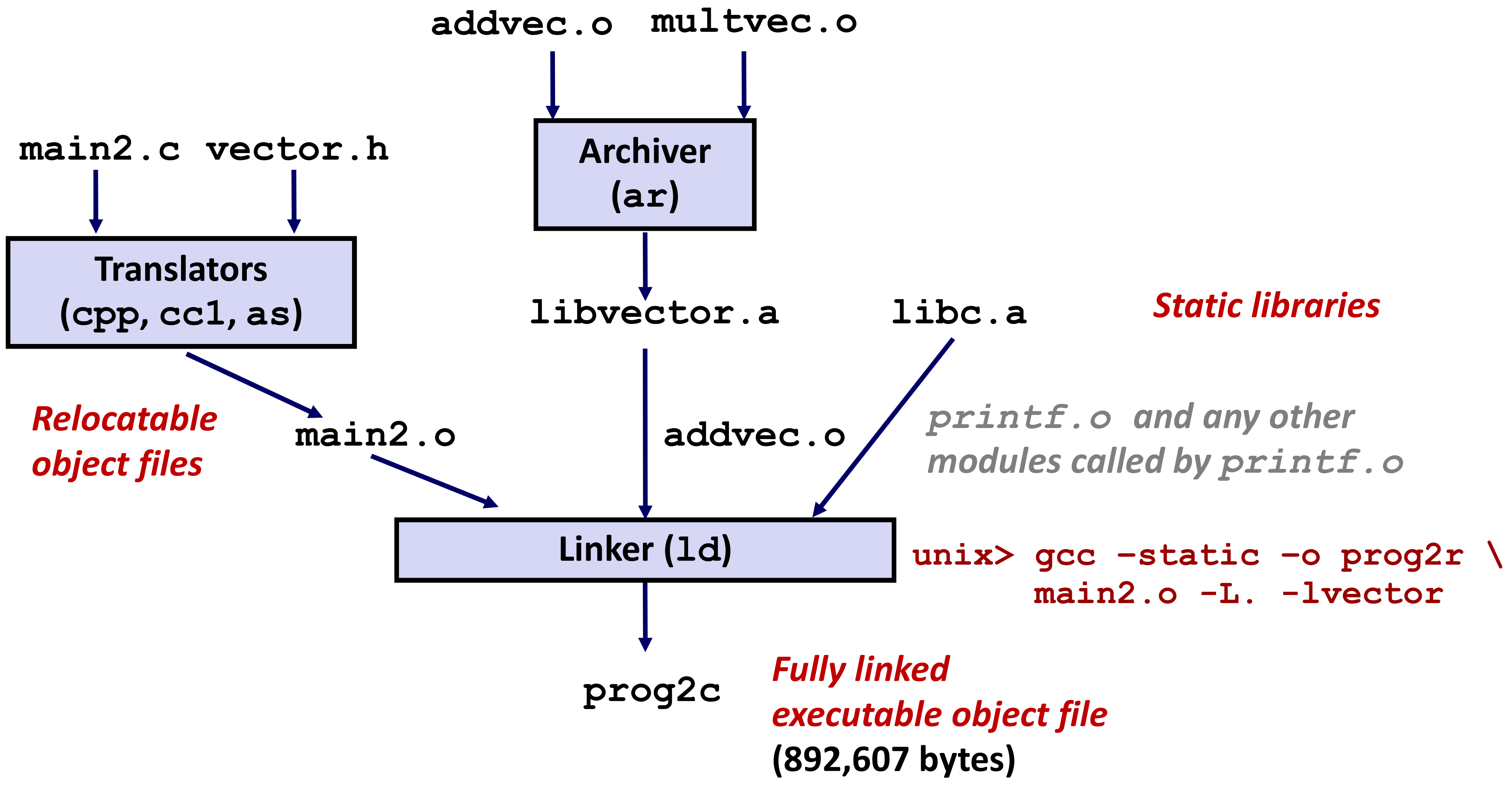
```
void addvec(int *x, int *y,
            int *z, int n) {
    int i;

    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



```
unix> gcc -static -o prog2r \
      main2.o -L. -lvector
```

"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 -L. libtest.o -lmine
unix> gcc -L. -lmine libtest.o
libtest.o: In function 'main':
libtest.o(.text+0x4): undefined reference to 'libfun'
```

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

What dynamic libraries are required?

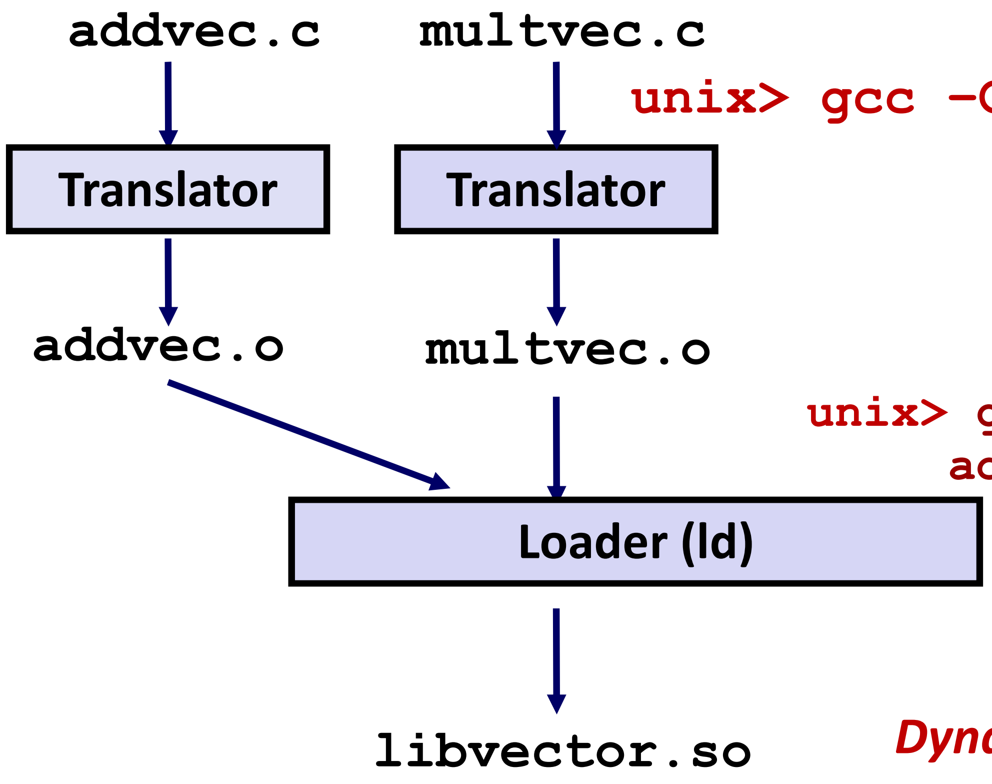
- **.interp section**
  - Specifies the dynamic linker to use (i.e., **`ld-linux.so`**)
- **.dynamic section**
  - Specifies the names, etc of the dynamic libraries to use
  - Follow an example of **`prog`**

```
(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)
```

Dynamic Library Example

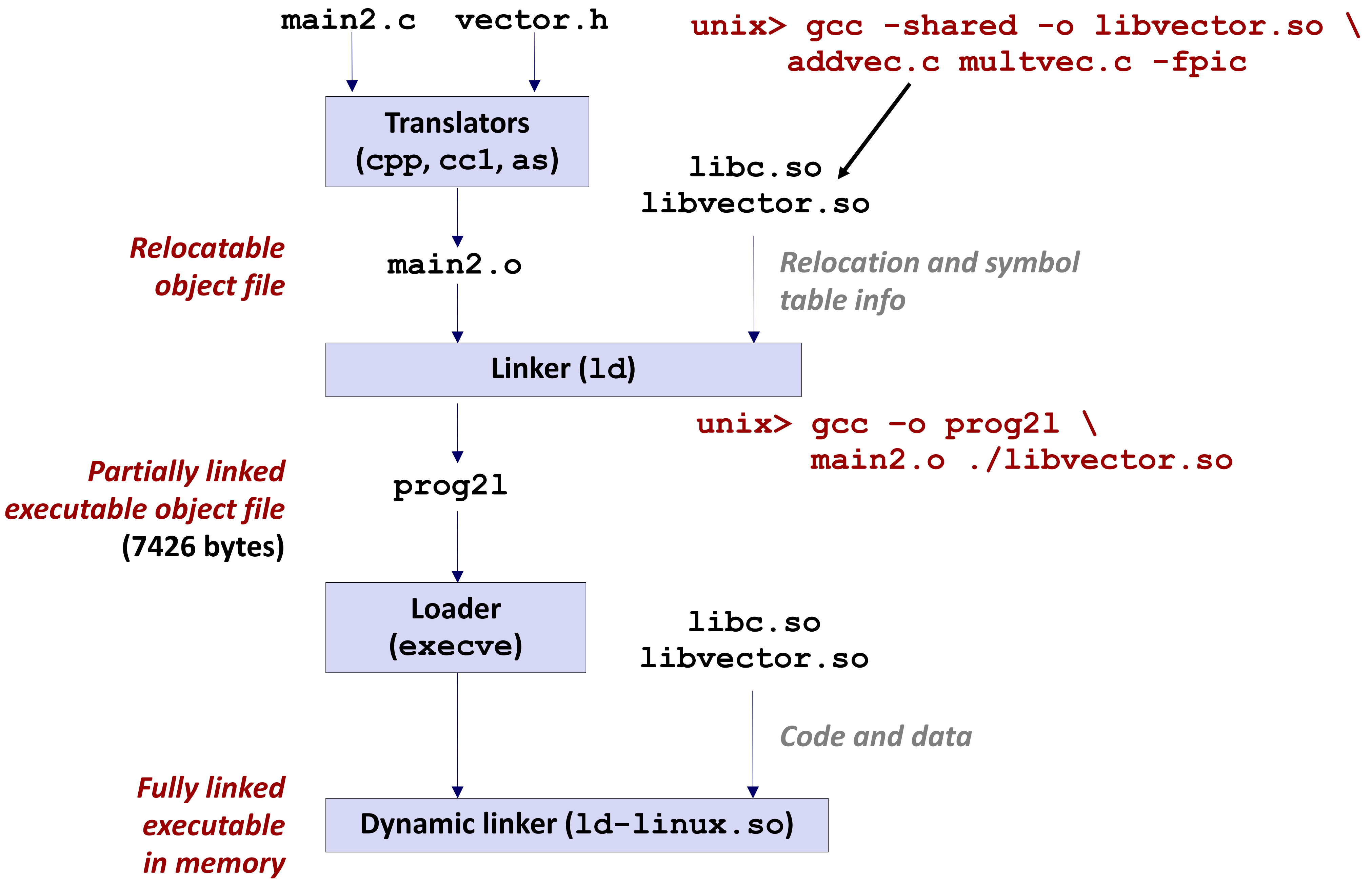


```
unix> gcc -Og -c addvec.c multvec.c -fpic
```

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

Dynamic vector library

Dynamic Linking at Load-time


main2.c
vector.h
Translators (cpp, cc1, as)
libc.so
libvector.so
Relocatable object file
main2.o
Relocation and symbol table info
Linker (ld)
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)

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

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

Dynamic Linking at Run-time

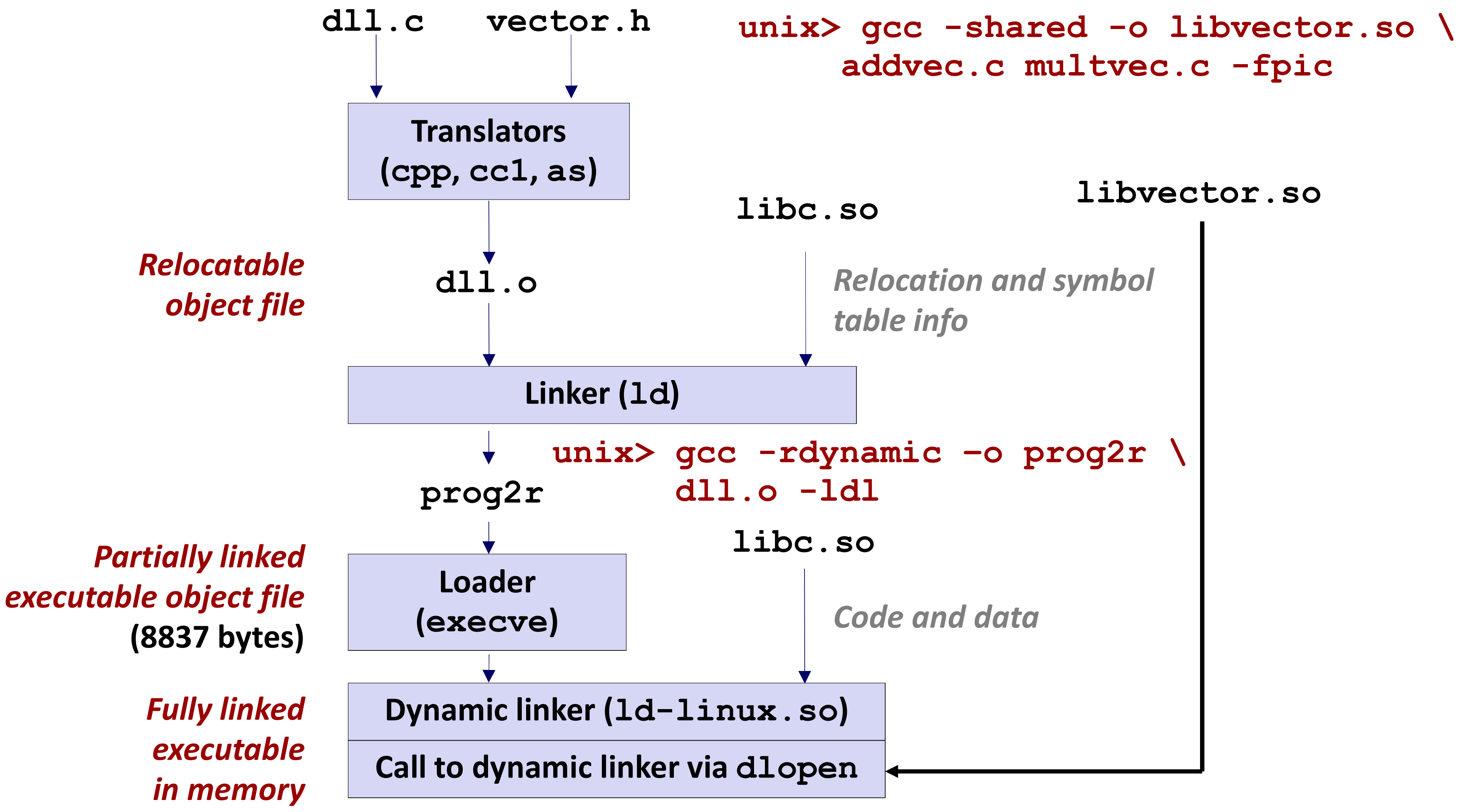
```
#include <stdio.h>
#include <stdlib.h>
#include <dlfcn.h>

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


dll.c
vector.h
Translators (cpp, cc1, as)
Relocatable object file
dll.o
libc.so
libvector.so
Relocation and symbol table info
Linker (ld)
prog2r
Partially linked executable object file
(8837 bytes)
Loader (execve)
libc.so
Code and data
Fully linked executable in memory
Dynamic linker (ld-linux.so)
Call to dynamic linker via dlopen

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

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

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.**

Today

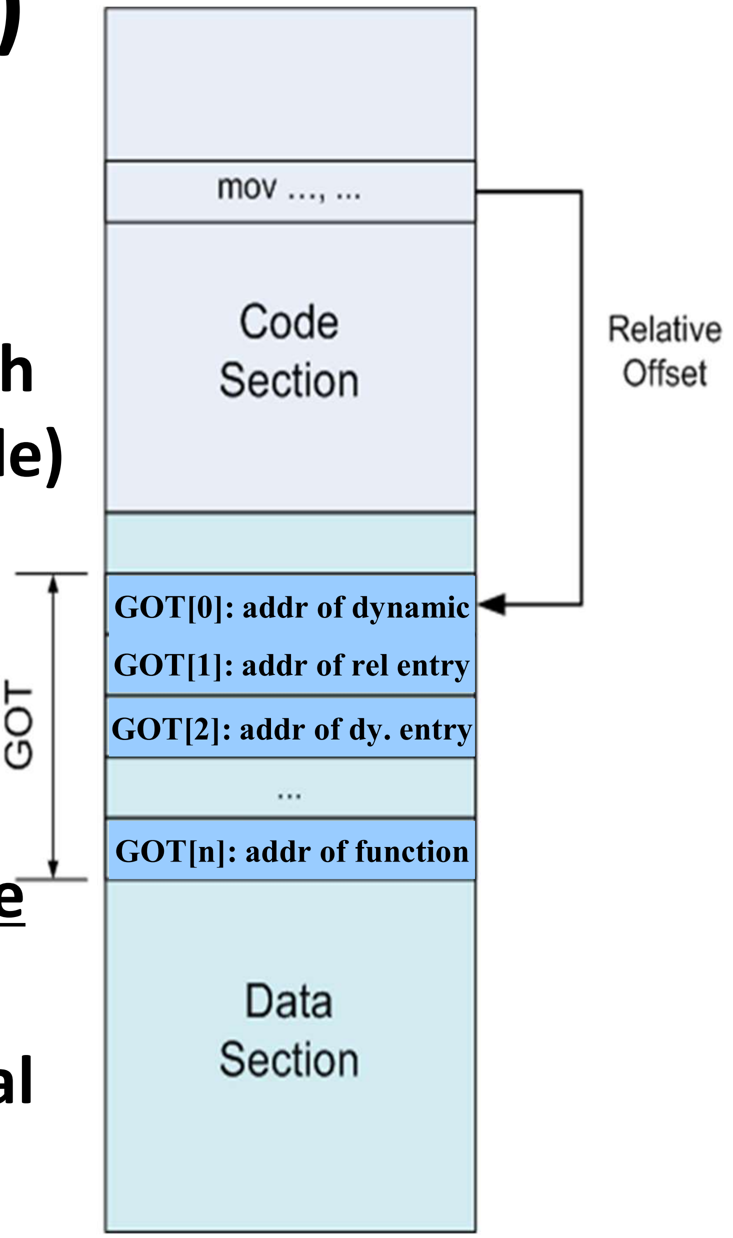
- Linking
- **Lazy Binding**

Lazy Binding

- Lazy binding, or dynamic binding, defers the binding of each procedure address until the <u>first time</u> the procedure is called.
- The motivation for lazy binding is that a typical application program will call only a handful of the hundreds or thousands of functions exported by a shared library such as libc.so.
- By deferring the resolution of a function's address until it is actually called, the dynamic linker can avoid hundreds or thousands of unnecessary relocations at load time.
- There is a nontrivial run-time overhead the first time the function is called, but each call thereafter takes only little time
- Lazy binding is implemented with a compact yet somewhat complex interaction between two data structures: the GOT and the PLT.

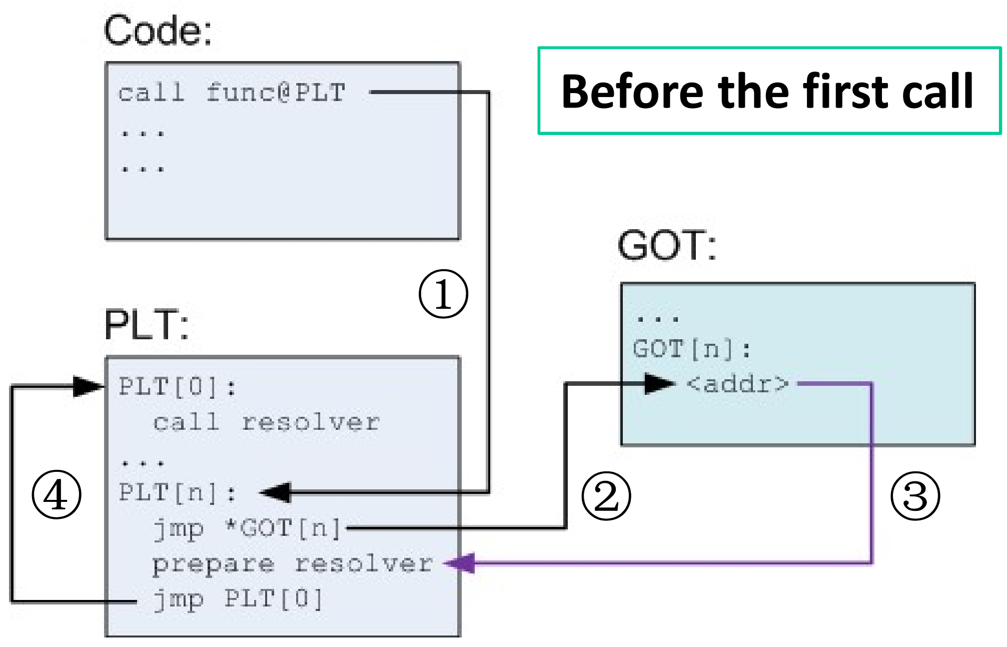
The Global Offset Table (GOT)

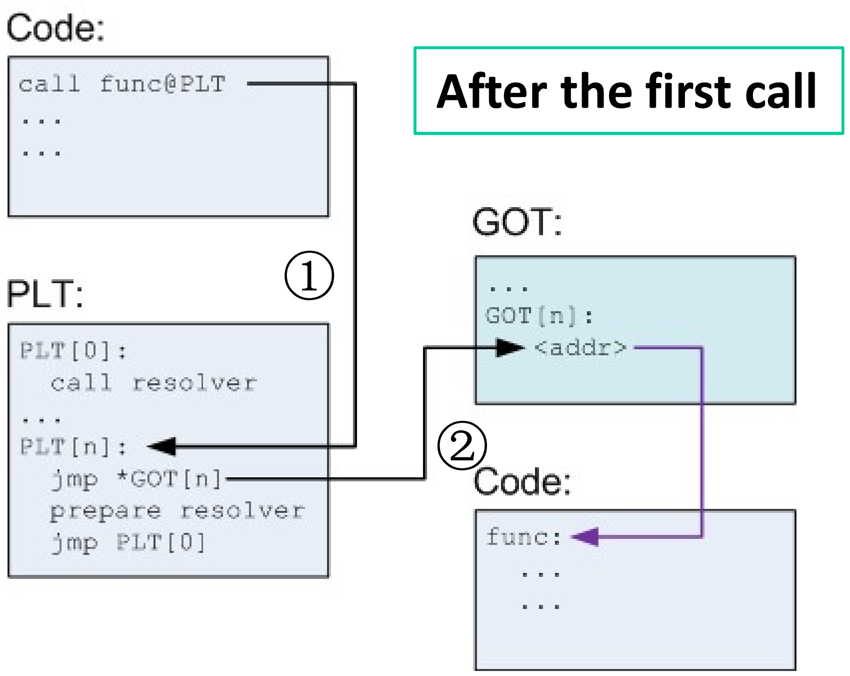
- A GOT is simply a table of addresses, residing in the data section
- The GOT contains an 8-byte entry for each global object (procedure or global variable) that is referenced by the object module
- The compiler also generates a relocation record for each entry in the GOT. At load time, the dynamic linker relocates each GOT entry so that it contains the <u>absolute address</u> of the object.
- Each object module that references global objects has its own GOT.



The Procedure Linkage Table (PLT)

- Each PLT entry is 16 bytes of executable code. Instead of calling the function directly, the code calls an entry in the PLT, which then takes care to call the actual function
- Each PLT entry also has a corresponding entry in the GOT which contains the actual offset to the function, but only when the dynamic linker resolves it





Example program

```
/* fopen.c
   Open a file, write "Hello World!" to it */

#include <stdio.h>
int main() {
    FILE *out;
    char buf[16] = "Hello World!\n";

    out = fopen("hello.txt", "w+");
    fprintf(out, "%s", buf);
    fclose(out);
    return 0;
}
```

PLT

```
/* section .plt */
# PLT[0] <fclose@plt-0x10>: call dynamic linker
  400410:  pushq  0x200552(%rip)         # GOT[1]
  400416:  jmpq   *0x200554(%rip)        # GOT[2]
  40041c:  nopl   0x0(%rax)
# PLT[1] <fclose@plt>:
  400420:  jmpq   *0x200552(%rip)        # GOT[3]
  400426:  pushq  $0x0
  40042b:  jmpq   400410 <_init+0x10>
# PLT[2] <fputs@plt>:
  400430:  jmpq   *0x20054a(%rip)        # GOT[4]
  400436:  pushq  $0x1
  40043b:  jmpq   400410 <_init+0x10>
# PLT[3] <__libc_start_main@plt>:
  400440:  jmpq   *0x200542(%rip)        # GOT[5]
  400446:  pushq  $0x2
  40044b:  jmpq   400410 <_init+0x10>
# PLT[4] <fopen@plt>:
  400450:  jmpq   *0x20053a(%rip)        # GOT[6]
  400456:  pushq  $0x3
  40045b:  jmpq   400410 <_init+0x10>
```

GOT

Before the first call

```
/* (gdb) x /8xg 0x600960
   <_GLOBAL_OFFSET_TABLE_> */
0x600960 0x0000000000600788  # GOT[0] addr of .dynamic
0x600968 0x0000003852e22190  # GOT[1] addr of reloc entries
0x600970 0x0000003852c14c20  # GOT[2] addr of dynamic linker
0x600978 0x0000000000400426  # GOT[3] fclose()
0x600980 0x0000000000400436  # GOT[4] fputs()
0x600988 0x000000385301ec20  # GOT[5] sys startup
0x600990 0x0000000000400456  # GOT[6] fopen()
0x600998 0x0000000000000000
```

After the first call

```
/* (gdb) x /8xg 0x600960
   <_GLOBAL_OFFSET_TABLE_> */
0x600960 0x0000000000600788  # GOT[0] addr of .dynamic
0x600968 0x0000003852e22190  # GOT[1] addr of reloc entries
0x600970 0x0000003852c14c20  # GOT[2] addr of dynamic linker
0x600978 0x0000003853066260  # GOT[3] fclose()
0x600980 0x0000003853067100  # GOT[4] fputs()
0x600988 0x000000385301ec20  # GOT[5] sys startup
0x600990 0x0000003853066e60  # GOT[6] fopen()
0x600998 0x0000000000000000
```

教材阅读

- **第7章 7.1-7.5、7.6.1-7.6.2、7.7、7.8、7.9、7.10、7.11、7.12**