Introduction to Computer Systems
Lecture 13 – Linking

2022 Spring, CSE3030

Sogang University

Today

- Linking
- Case study: Library interpositioning

Example C Program

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

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

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

`main.c`

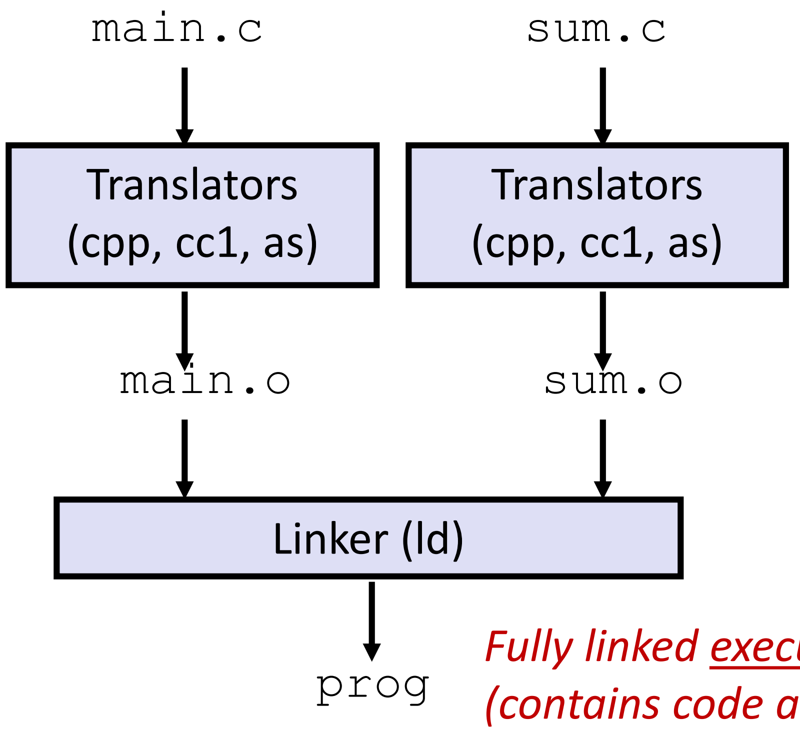
```c
int sum(int *a, int n)
{
    int i, s = 0;

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

`sum.c`

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 <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.

  - Space: Libraries
    - Common functions can be aggregated into a single file...
    - Yet executable files and running memory images contain only code for the functions they a ctually use.

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 `structs`
    - Each entry includes name, size, and location of symbol.

  - **During symbol resolution step, the linker associates each symbol referen ce with exactly one symbol definition.**

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)

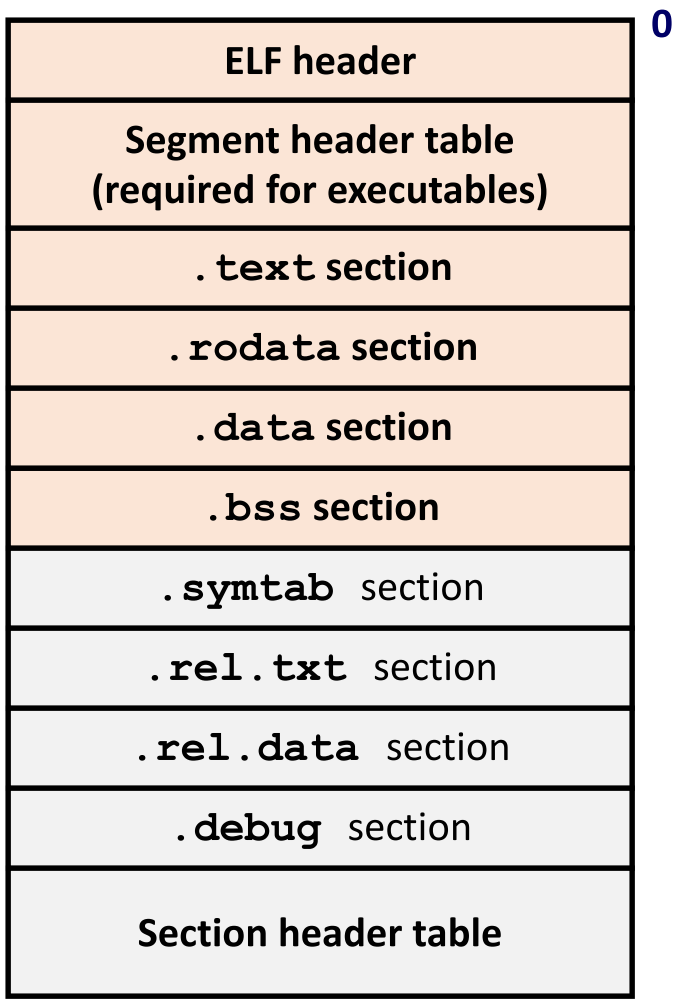
- Standard binary format for object files

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

- Generic name: ELF binaries

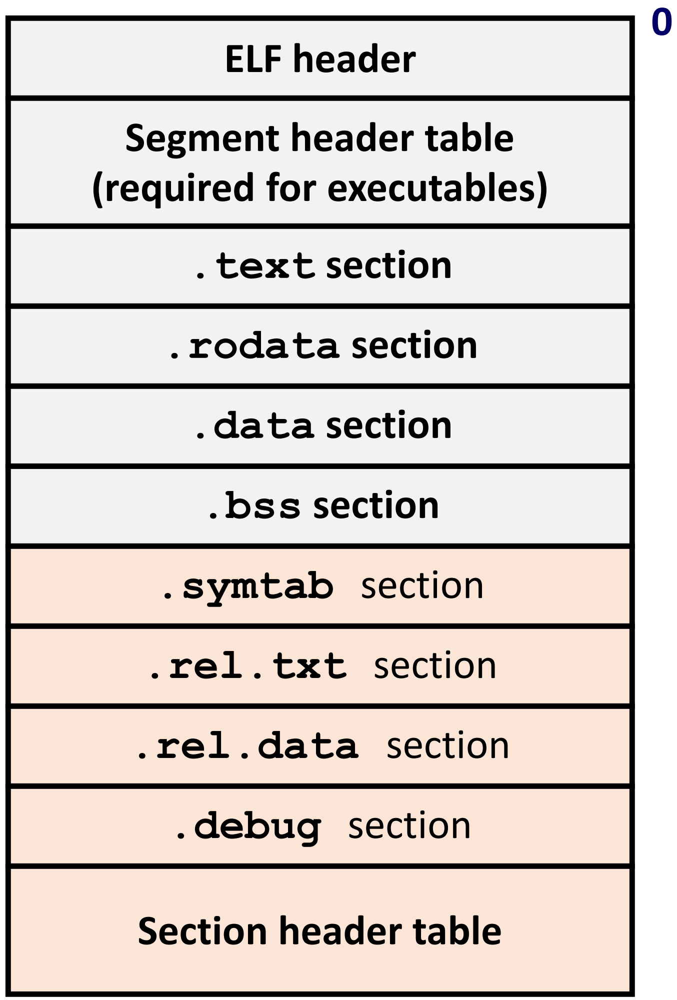
ELF Object File Format

- 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, ...
- `.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**

https://www.bogotobogo.com/cplusplus/statics.php#:~:text=A%20variable%20declared%20static%20within%20a%20module%20(but%20outside%20the,each%20object%20of%20the%20class.

Step 1: Symbol Resolution

Referencing a global…

…that's defined here

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

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

int main()
{
    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

Defining a global

Linker knows nothing of `val`

Referencing a global…

…that's defined here

Linker knows nothing of `i` or `s`

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`

```
int f()
{
    static int x = 0;
    return x;
}

int g()
{
    static int x = 1;
    return x;
}
```

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

Creates local symbols in the symbol tabl e with unique names, e.g., `x.1` and `x.2`.

How Linker Resolves Duplicate Symbol Definitions

- Program symbols are either *strong* or *weak*
  - ***Strong***: procedures and initialized globals
  - ***Weak***: uninitialized globals

p1.c

strong → `int foo=5;`

strong → `p1() {`

```
int foo=5;

p1() {
}
```

p2.c

`int foo;` ← weak

`p2() {` ← strong

```
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`**

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.

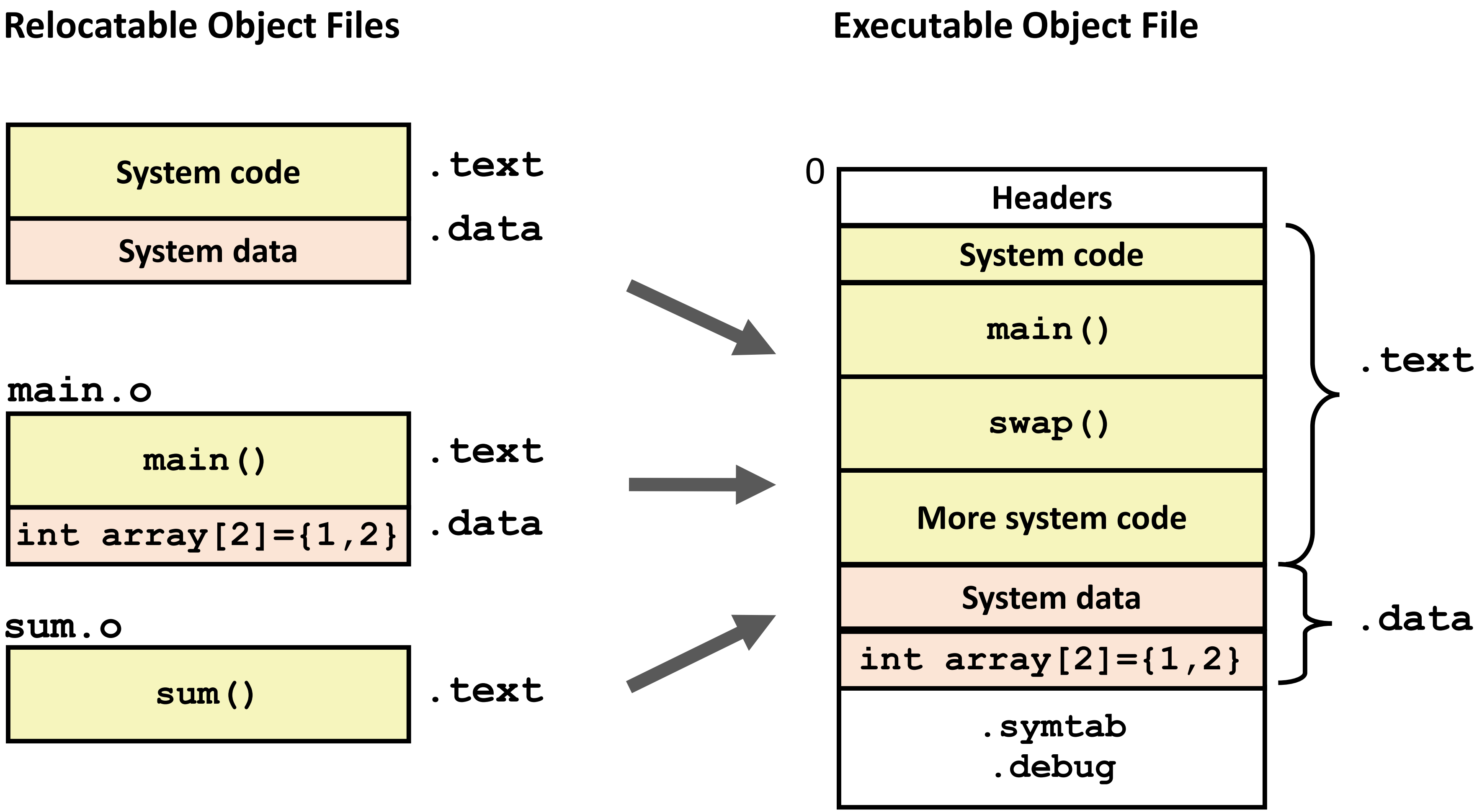
Nightmare scenario: two identical weak structs, compiled by different compilers with different alignment rules.

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

Step 2: Relocation



Relocation Entries

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

int main()
{
    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

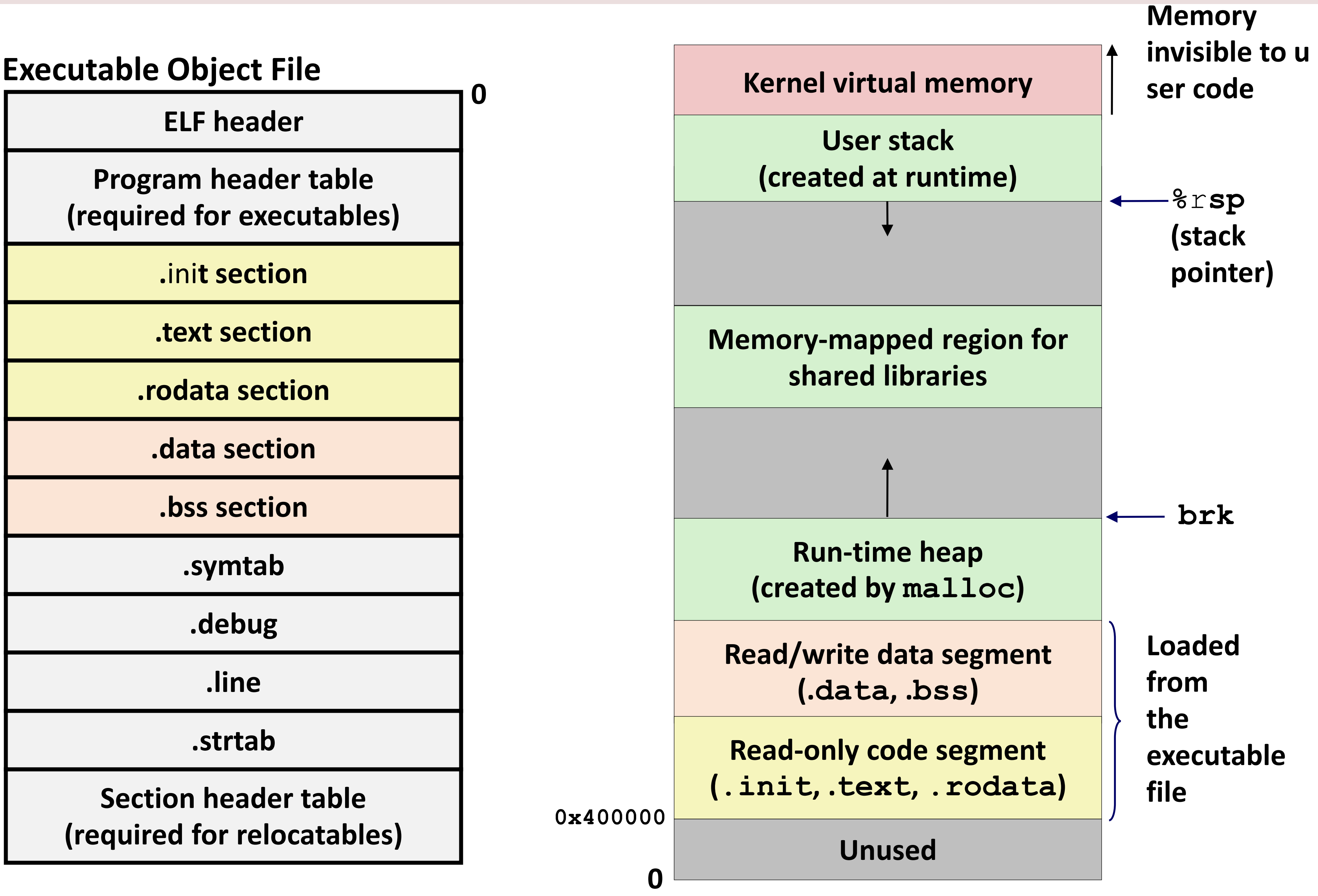
```
00000000004004d0 <main>:
  4004d0:    48 83 ec 08       sub    $0x8,%rsp
  4004d4:    be 02 00 00 00    mov    $0x2,%esi
  4004d9:    bf 18 10 60 00    mov    $0x601018,%edi  # %edi = &array
  4004de:    e8 05 00 00 00    callq  4004e8 <sum>    # sum()
  4004e3:    48 83 c4 08       add    $0x8,%rsp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

Using PC-relative addressing for sum(): 0x4004e8 = 0x4004e3 + 0x5

Source: `objdump -dx prog`

Loading Executable Object Files



Packaging Commonly Used Functions

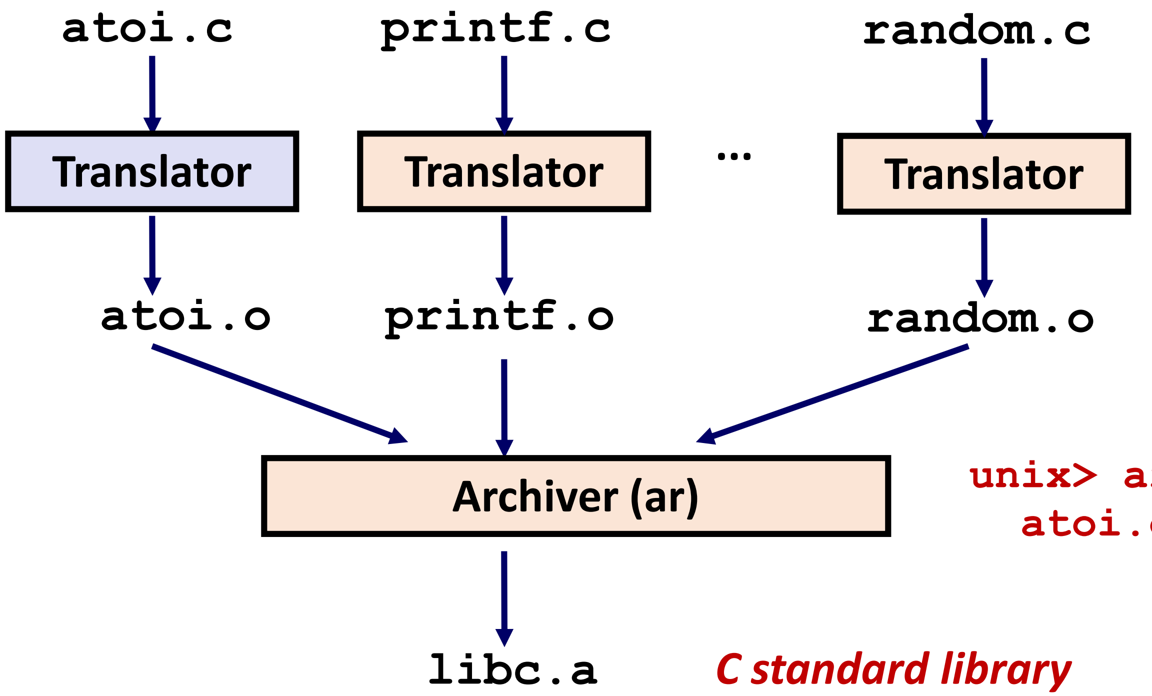
- How to package functions commonly used by programmers?
  - Math, I/O, memory management, string manipulation, etc.

- 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 (call ed an *archive*).
  - Enhance linker so that it tries to resolve unresolved external references by loo king 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
```

- 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 libc.a | sort
…
fork.o
…
fprintf.o
fpu_control.o
fputc.o
freopen.o
fscanf.o
fseek.o
fstab.o
…
```

```
% ar -t 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

libvector.a

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

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

int main()
{
    addvec(x, y, z, 2);
    printf("z = [%d %d]₩n",
           z[0], z[1]);
    return 0;
}
```

main2.c

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

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

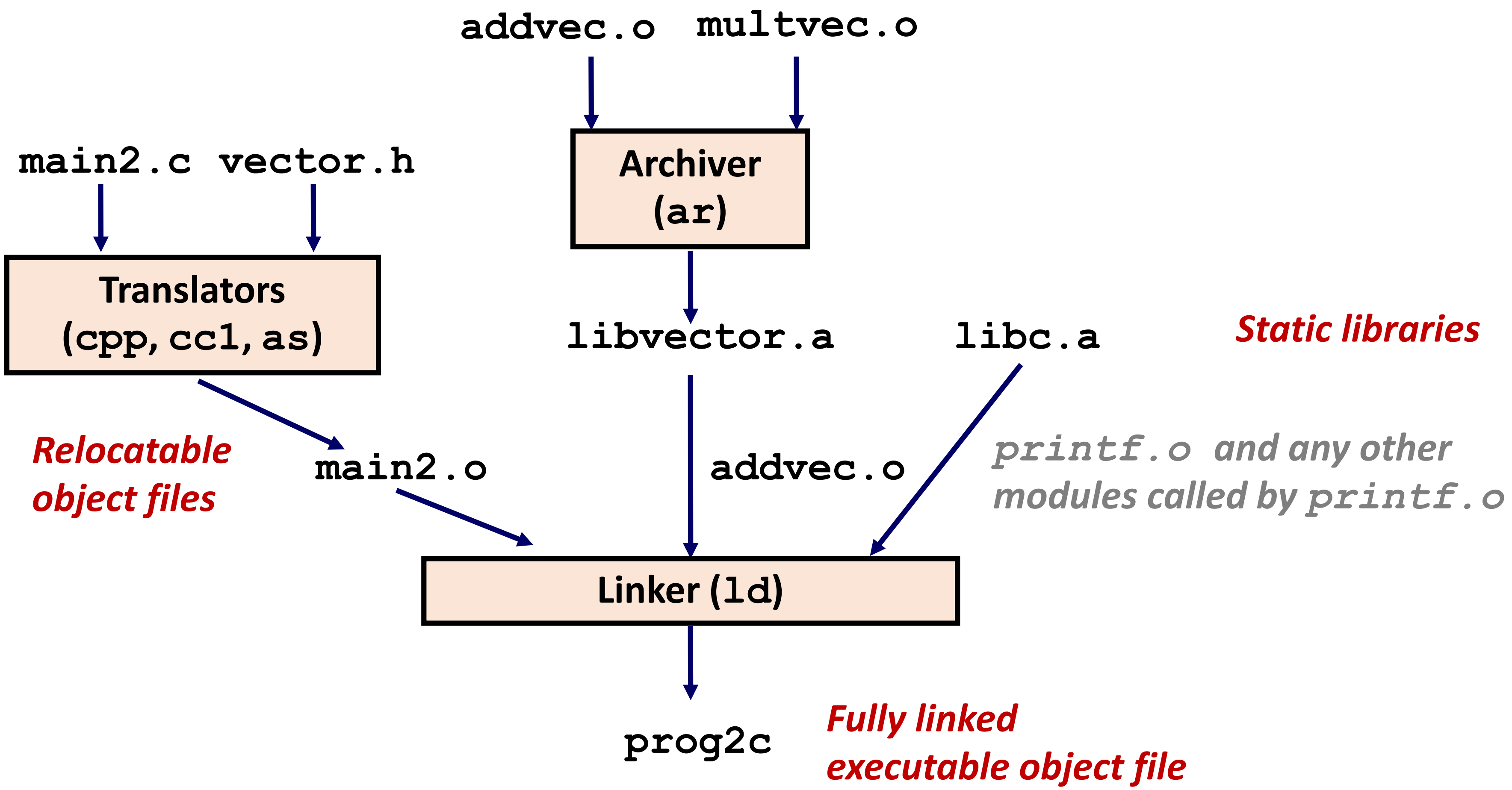
addvec.c

```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



"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

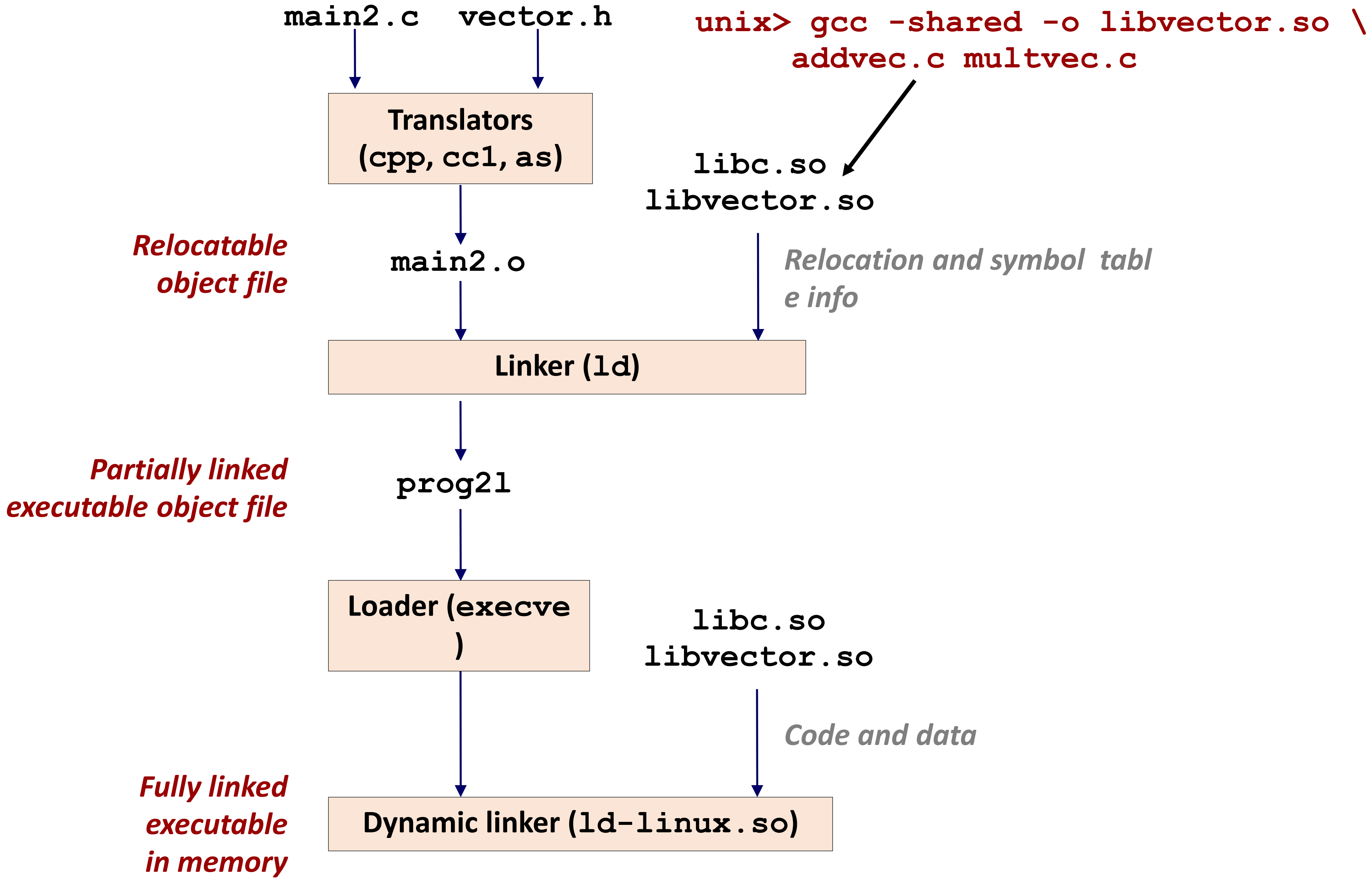
- Static libraries have the following disadvantages:
  - Duplication in the stored executables (every function needs libc)
  - Duplication in the running executables
  - Minor bug fixes of system libraries require each application to explicitly relink

- Modern solution: Shared Libraries
  - Object files that contain code and data that are loaded and linked into an appli cation *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

Dynamic Linking at Load-time



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()
{
    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

```
    ...

    /* 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

Linking Summary

- Linking is a technique that allows programs to be constructed from mu ltiple 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.