

Linking

15-213/15-503: Introduction to Computer Systems
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Disclaimer

- **Linkers continue to improve their functionality to help avoid programmer mistakes**
 - This lecture follows the textbook, although some examples may be out of date with linker defaults / terminology

Today

■ Linking

- Motivation
- What it does
- How it works

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;

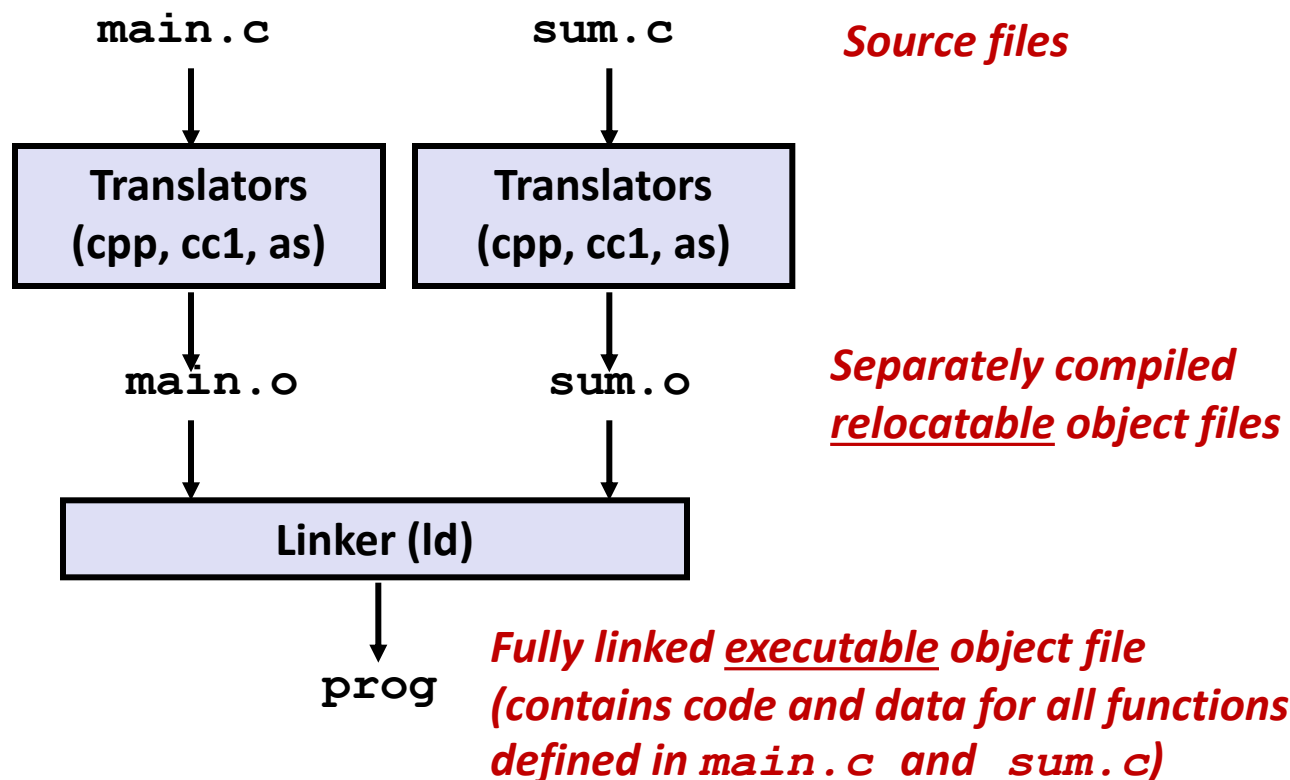
    for (i = 0; i < n; i++) {
        s += a[i];
    }
    return s;
}
```

sum.c

Linking

■ Programs are translated and linked using a *compiler driver*:

- `linux> gcc -Og -o prog main.c sum.c`
- `linux> ./prog`



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
 - e.g., Math library, standard C library
 - Header files in C declare types that are defined in libraries

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

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

main.c

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

sum.c

Reference

What Do Linkers Do? (cont'd)

■ 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 address memory segments (sections), segment sizes.

■ .text section

- Code

■ .rodata section

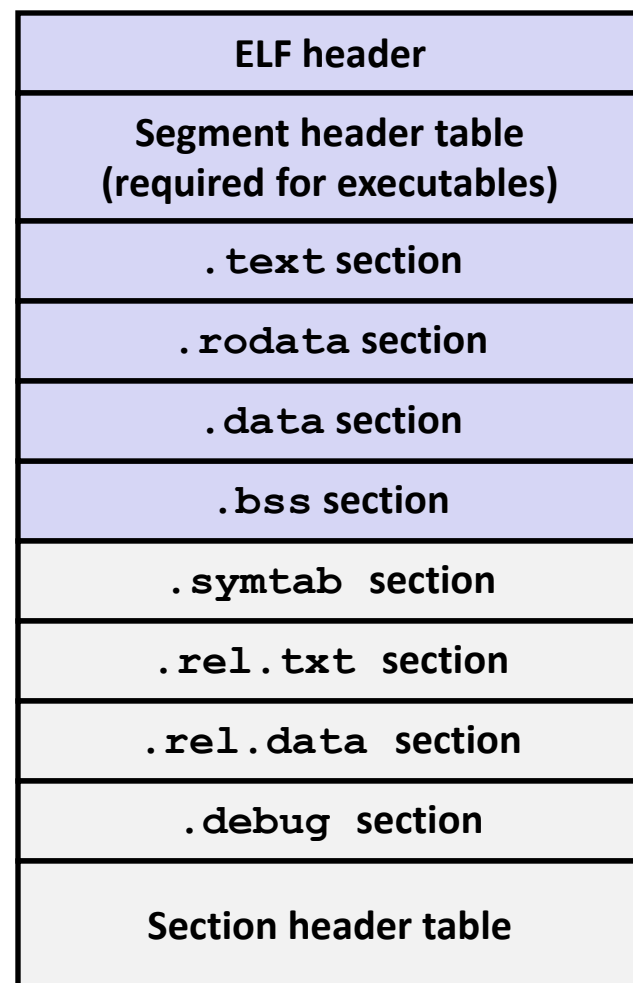
- Read only data: jump tables, string constants, ...

■ .data section

- Initialized global variables

■ .bss section

- Uninitialized global variables
- “Block Started by Symbol”
- “Better Save Space”
- Has section header but occupies no space



ELF Object File Format (cont.)

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

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

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

...that's defined here

Referencing
a global...

```
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

Defining
a global

Linker knows
nothing of val

Referencing
a global...

...that's defined here

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

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

    return s;
}
```

sum.c

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`:

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

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

Names:

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

Can find this with `readelf`:

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

Local Symbols

■ Local non-static C variables vs. local static C variables

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

```
static int x = 15;

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

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

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

static-local.c

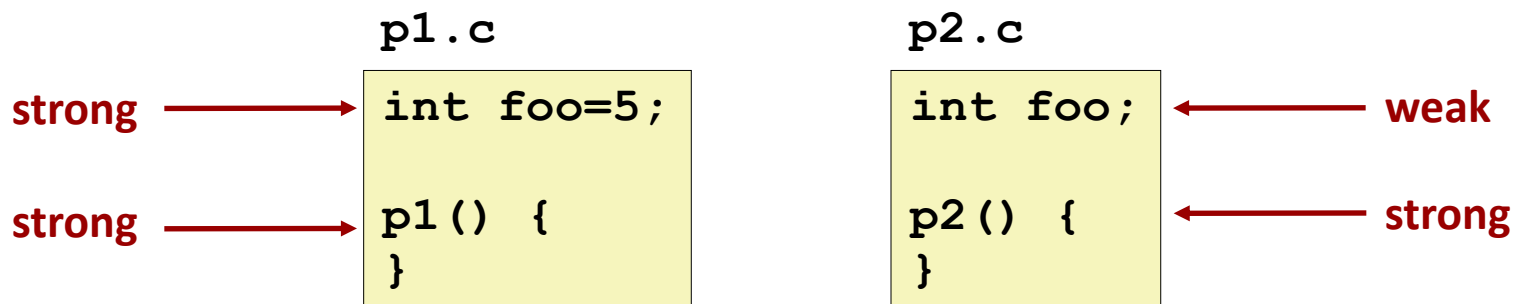
Compiler allocates space in `.data` for each definition of `x`

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

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**



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 **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?

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

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;
}
```


Linking Example

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

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

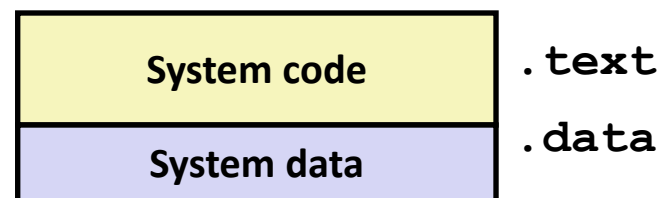
int main(int argc, char **argv)
{
    int val = sum(array, 2);
    return val;
}                                     main.c
```

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

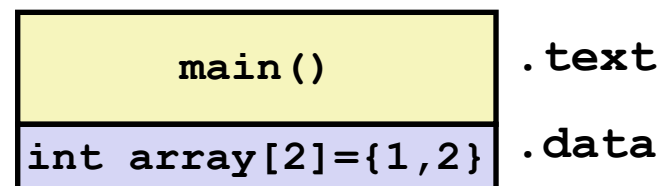
    for (i = 0; i < n; i++) {
        s += a[i];
    }
    return s;
}                                     sum.c
```

Step 2: Relocation

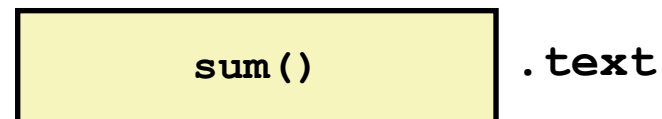
Relocatable Object Files



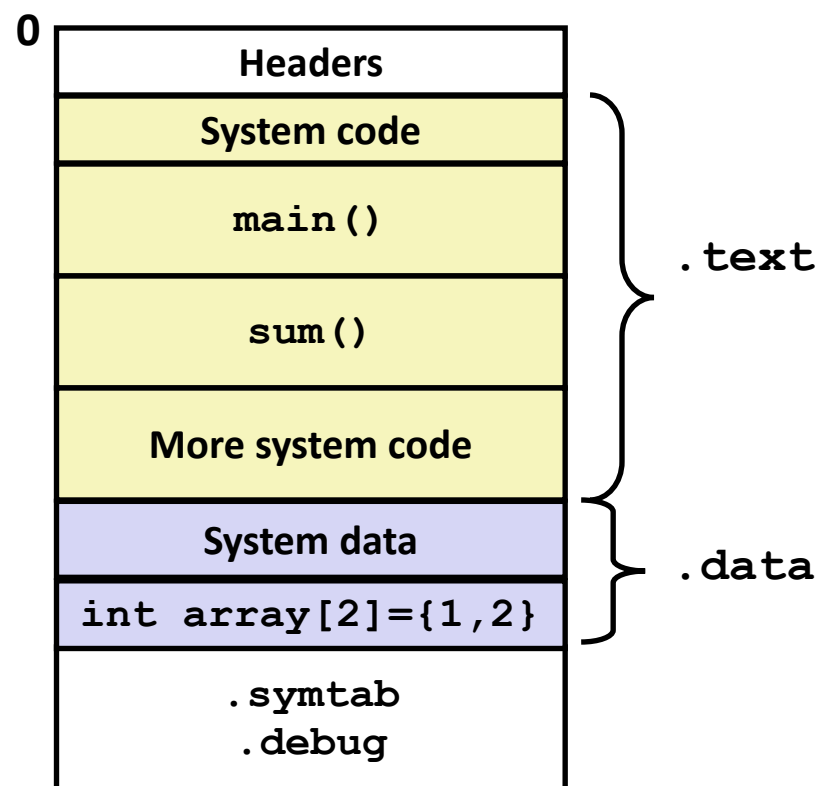
main.o



sum.o



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
```

00000000000000000 <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
				# Relocation entry
		a: R_X86_64_32	array	
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

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	j1	4004f4 <sum+0xc>
400501:	f3 c3	repz retq	

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

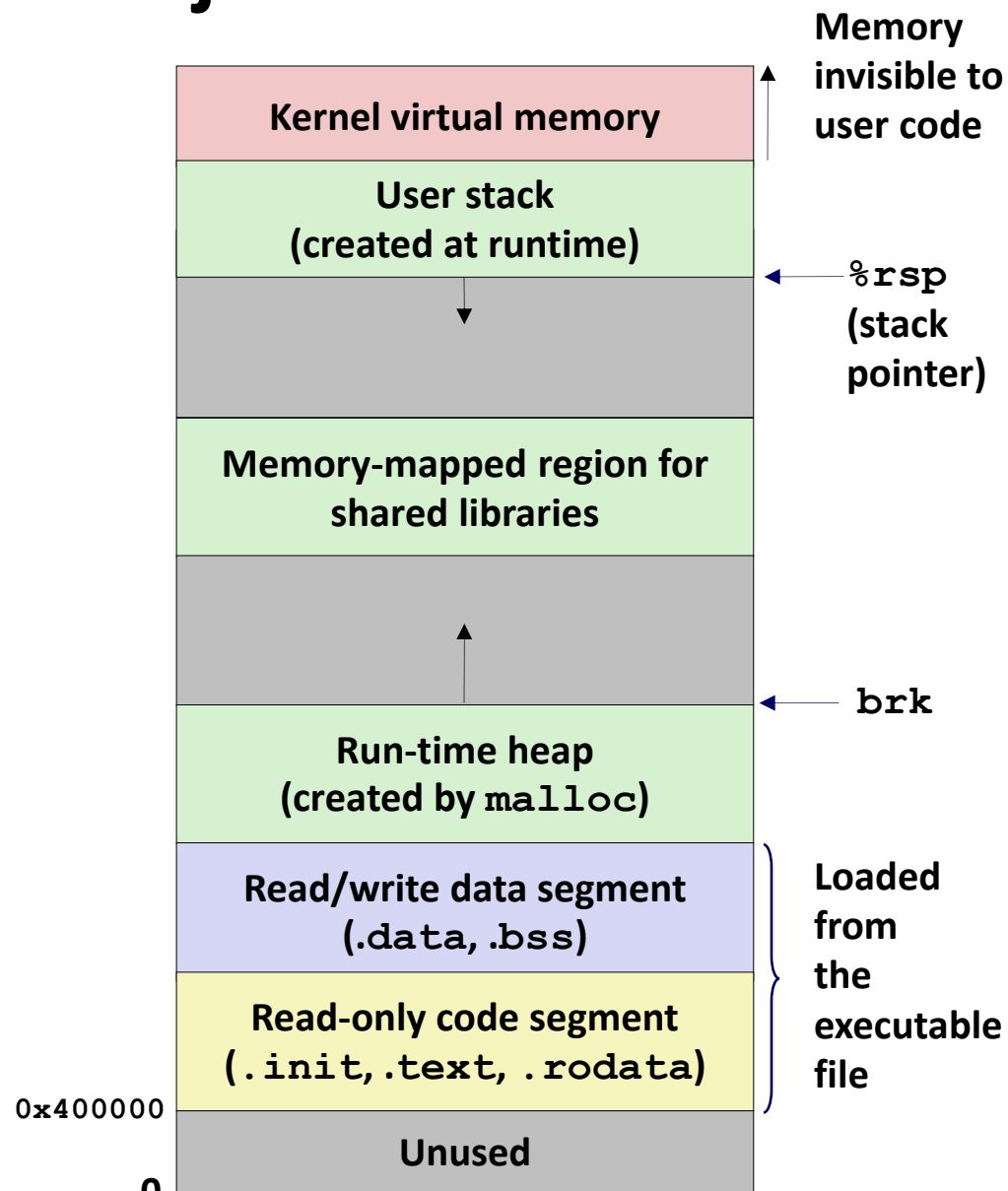
$$0x4004e8 = 0x4004e3 + 0x5$$

Source: `objdump -d prog`

Loading Executable Object Files

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)



Quiz

<https://canvas.cmu.edu/courses/47415/quizzes/143244>

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:

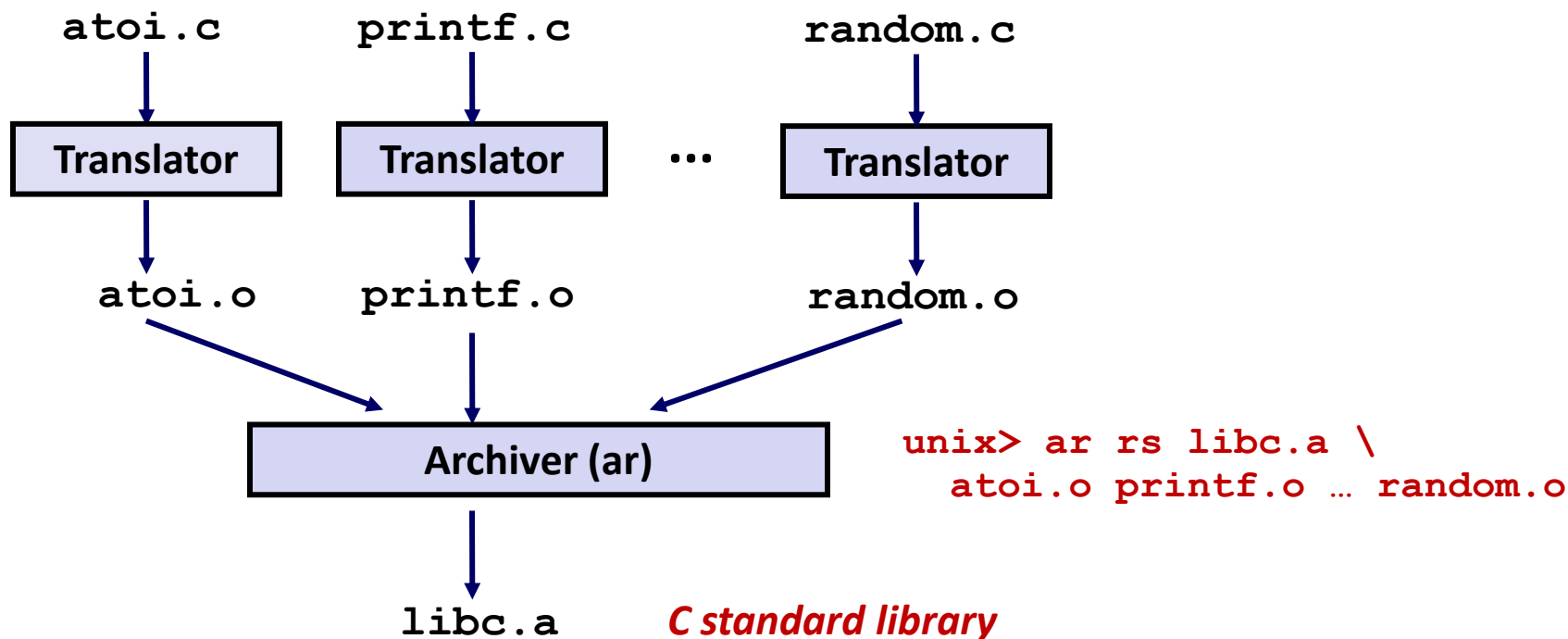
- **Option 1:** Put all functions into a single source file
 - Programmers link big object file into their programs
 - Space and time inefficient
- **Option 2:** Put each function in a separate source file
 - Programmers explicitly link appropriate binaries into their programs
 - More efficient, but 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



- 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

```
#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



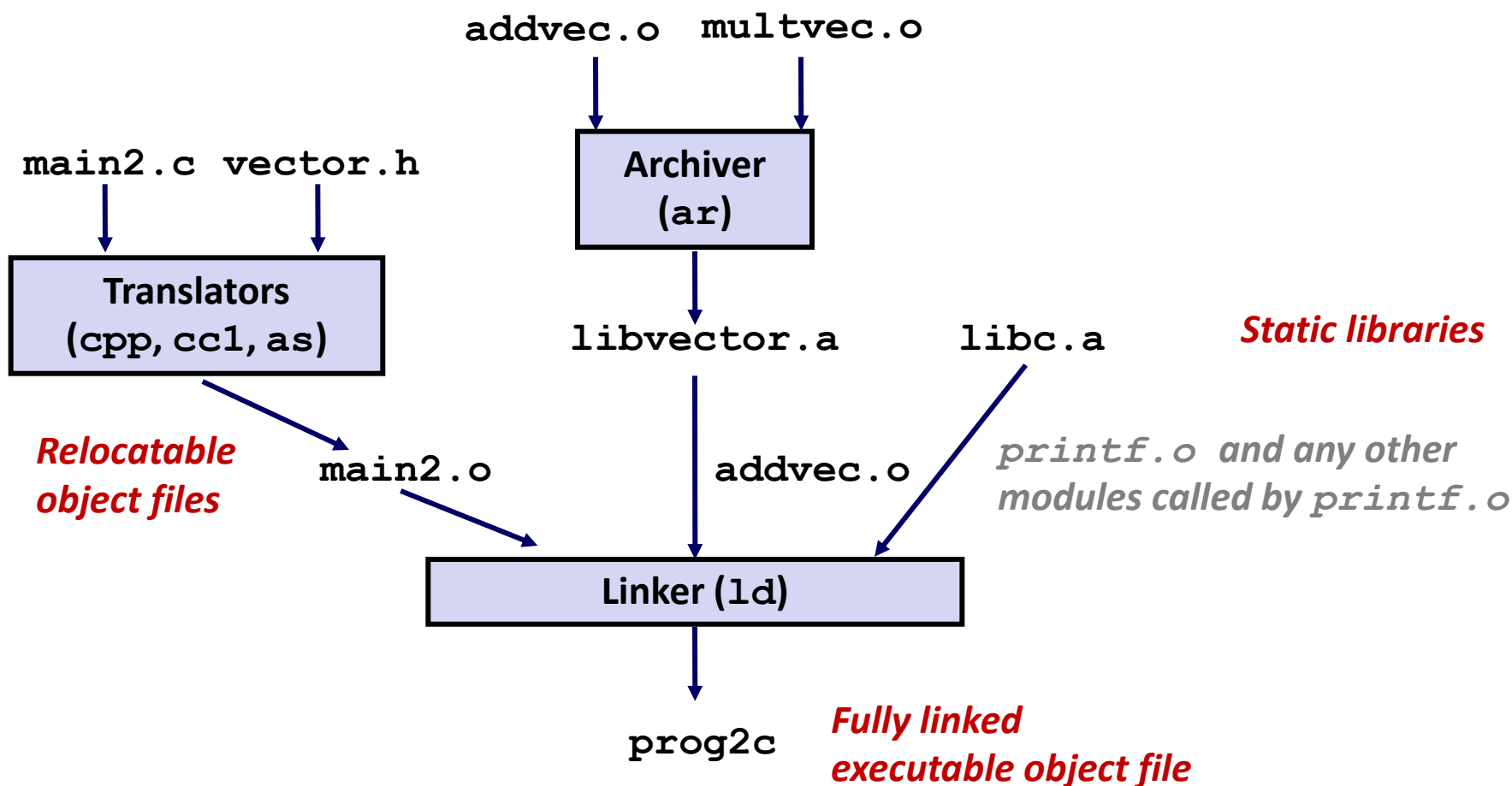
```
void addvec(int *x, int *y,
            int *z, int n) {
    int i;

    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



"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 `csim-ref` from `cachelab`

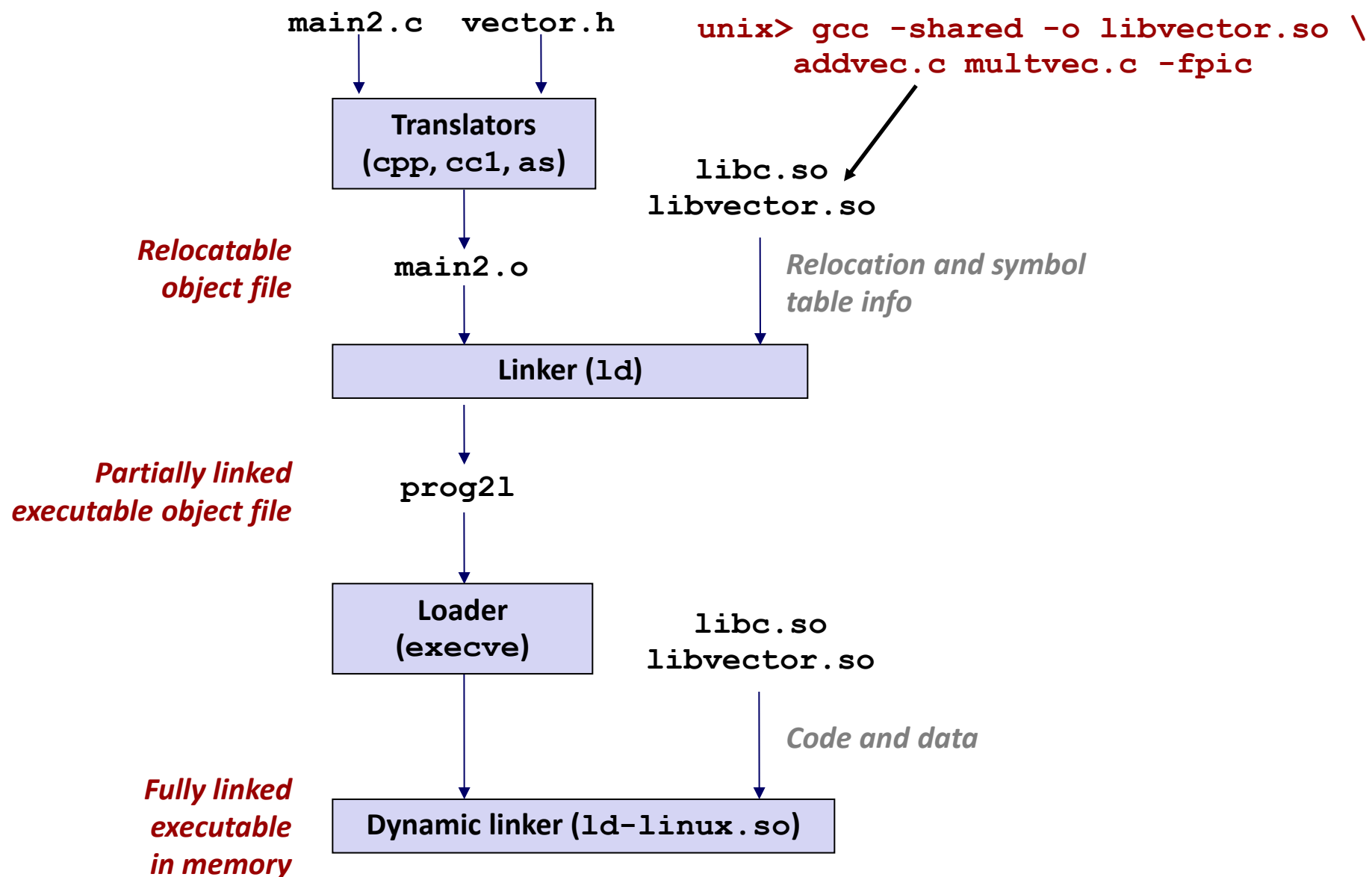
(NEEDED) Shared library: [libm.so.6]

■ Where are the libraries found?

- Use “`ldd`” to find out:

```
unix> ldd csim-ref
linux-vdso.so.1 => (0x00007ffc195f5000)
libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007f345eda6000)
/lib64/ld-linux-x86-64.so.2 (0x00007f345f181000)
```


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(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);
    }
    . . .
```

d11.c

Dynamic Linking at Run-time (cont)

```
...

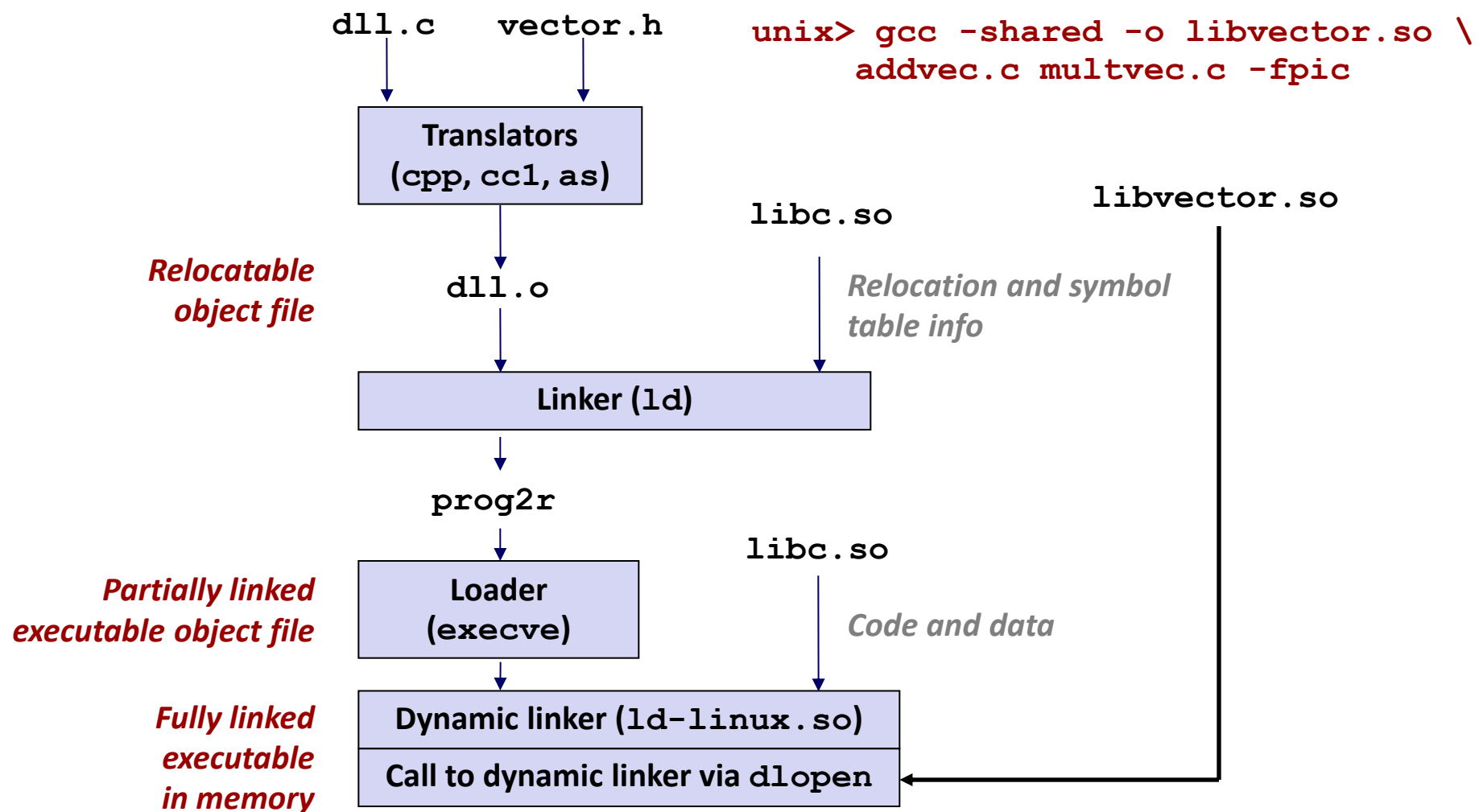
/* Get a pointer to the addvec() function we just loaded */
addvec = dlsym(handle, "addvec");
if ((error = dlerror()) != NULL) {
    fprintf(stderr, "%s\n", error);
    exit(1);
}

/* 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



Linking Recap

- Usually: Just happens, no big deal
- Sometimes: Strange errors

Supplemental

- Dynamic linking can also be