

# COMP201

## Computer Systems & Programming

### Lecture #24 – Linking

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**KOÇ  
UNIVERSITY**

Aykut Erdem // Koç University // Fall 2024

# Recap

- Writing cache-friendly code
- Optimization

# Plan for Today

- Linking

**Disclaimer:** Slides for this lecture were borrowed from  
—Randal E. Bryant and David R. O'Hallaron's CMU 15-213 class

# Learning Goals

- Describe the steps of linking and learn about the notions like relocatable and executable object files, symbol resolution
- Learn about the differences between static and dynamic linking, and static and shared object libraries
- Identify ways to solve confusing linking errors that might happen during the compilation process

# Example C Program

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

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

int main()
{
    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;
}
```

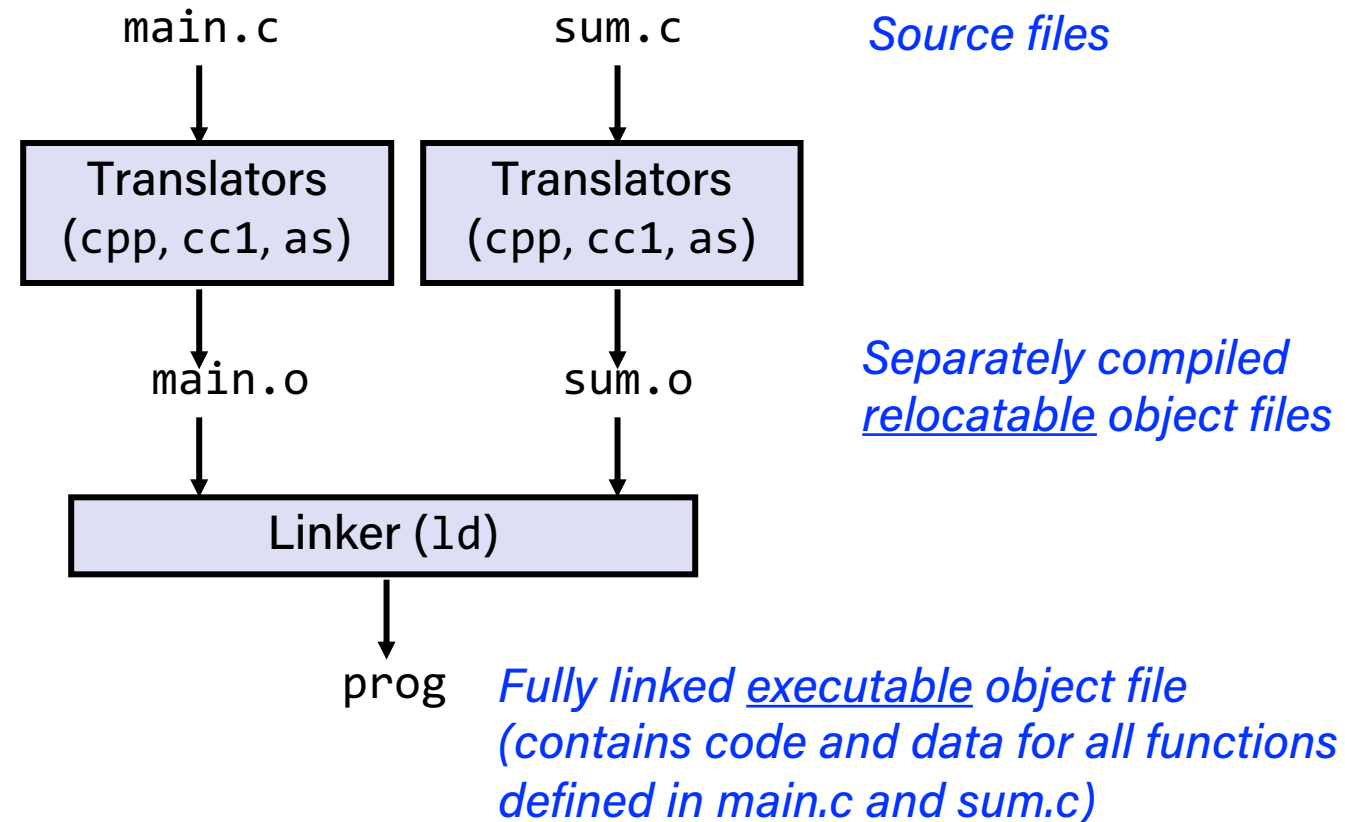
*sum.c*

# Static 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 (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 actually 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 reference 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)**

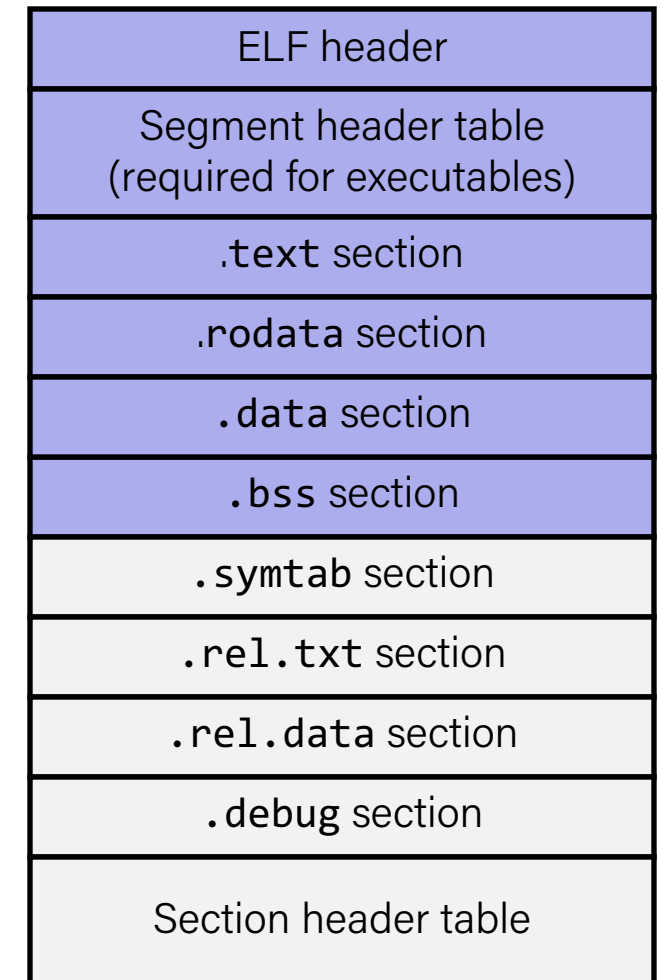
- Special type of relocatable object file that can be loaded into memory and linked dynamically, at either load time or run-time.
- Called *Dynamic Link Libraries* (DLLs) by Windows

# 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

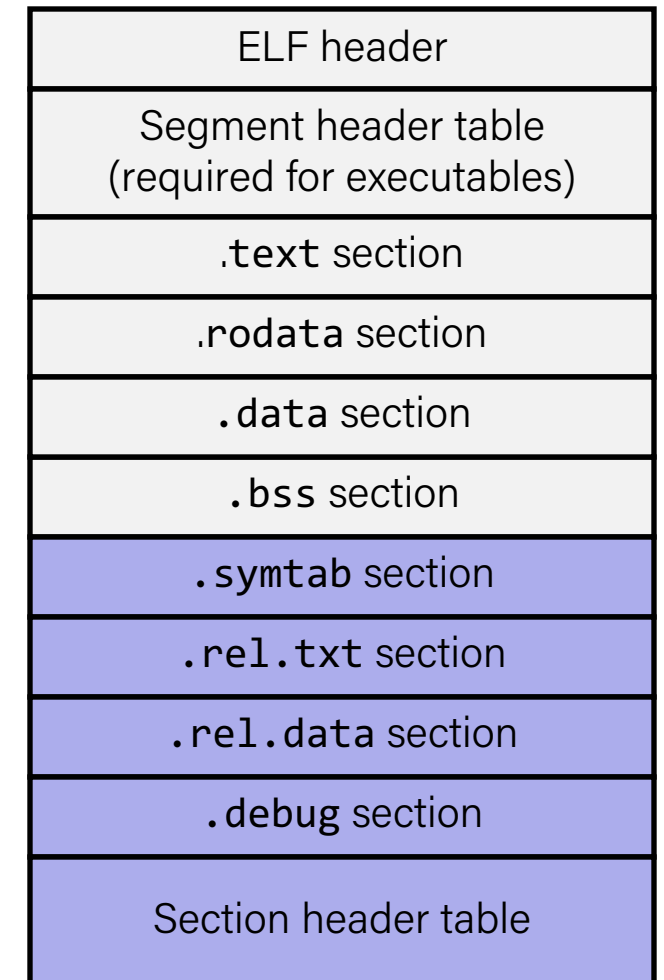
# ELF Object File Format

- **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

# 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 val = sum(array, 2);  
    return val;  
}
```

*main.c*

Defining  
a global

Linker knows  
nothing of `val`

Referencing  
a global...

```
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`

...that's defined here



# 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`

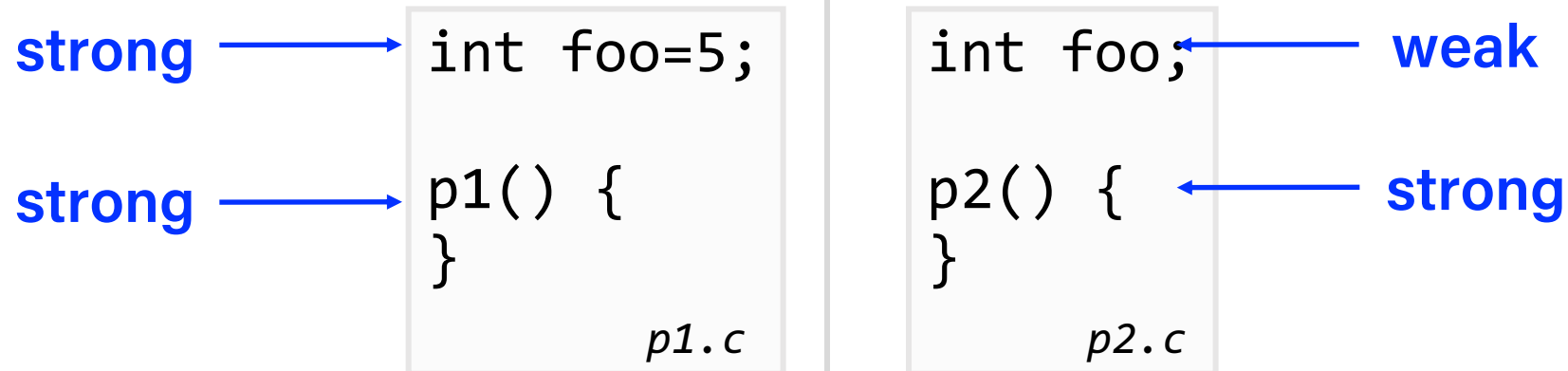
```
int f()
{
    static int x = 0;
    return x;
}

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

- Compiler allocates space in `.data` for each definition of `x`
- Creates local symbols in the symbol table 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



# 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 1

```
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.**

# Linker Puzzles 2

- Which definitions do the references `main` or `x` refer to?

```
int main()  
{}
```

```
int main;  
int p2() {}
```

REF(main.1) → DEF(main.1)

REF(main.2) → DEF(main.1)

```
void main()  
{}
```

```
int main = 1;  
p2() {}
```

Error! Each module defines a strong symbol `main`

```
int x;  
void main()  
{}
```

```
double x=1.0;  
int p2()  
{}
```

REF(x.1) → DEF(x.2)

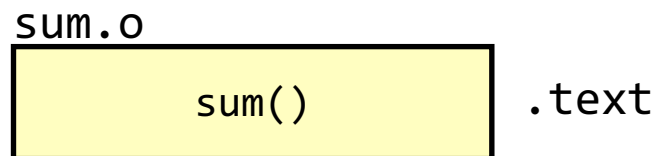
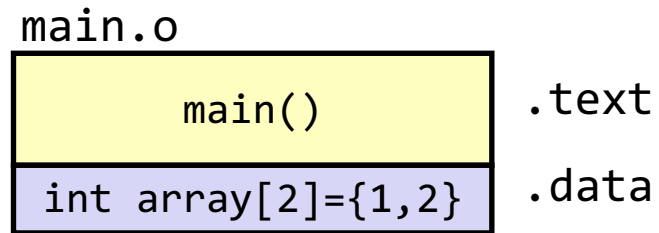
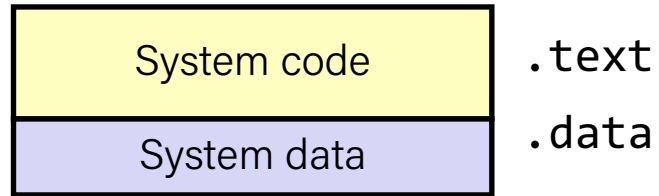
REF(x.2) → DEF(x.2)

# Global Variables

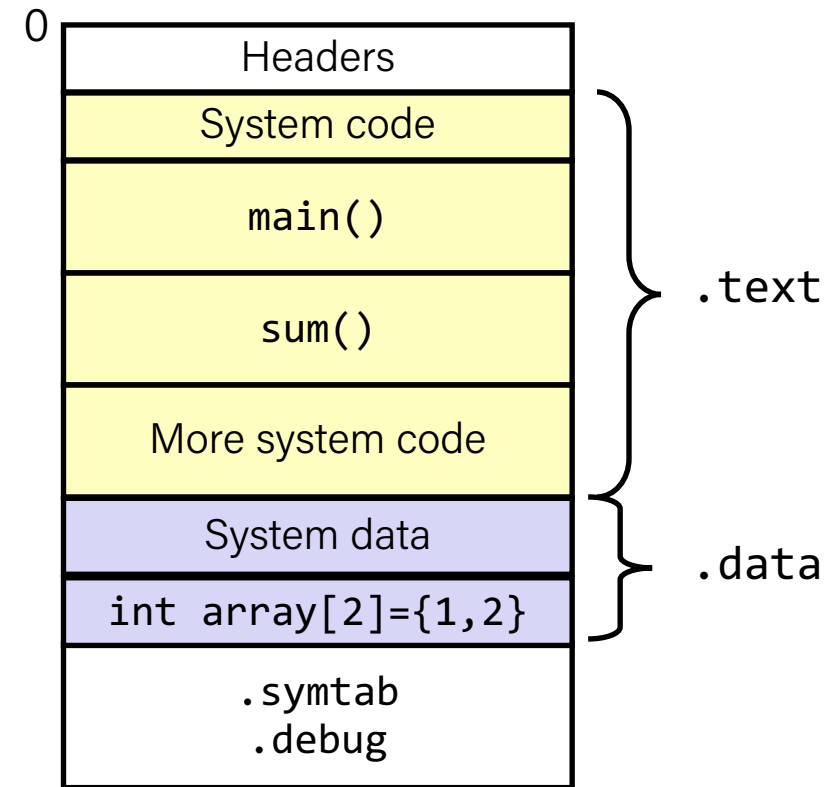
- Avoid if you can
- Otherwise
  - Use `static` if you can
  - Initialize if you define a global variable
  - Use `extern` if you reference an external global variable

# Step 2: Relocation

## Relocatable Object Files



## Executable Object File



# Relocation Entries

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

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

objdump -r -d main.o

```
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
                             # Relocation entry
                             a: R_X86_64_32 array

 e:  e8 00 00 00 00            callq  13 <main+0x13>      # sum()
                             # Relocation entry
                             f: R_X86_64_PC32 sum-0x4

13:  48 83 c4 08                add    $0x8,%rsp
17:  c3                        retq                                     main.o
```



# Relocated .text section

objdump -dx prog

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	

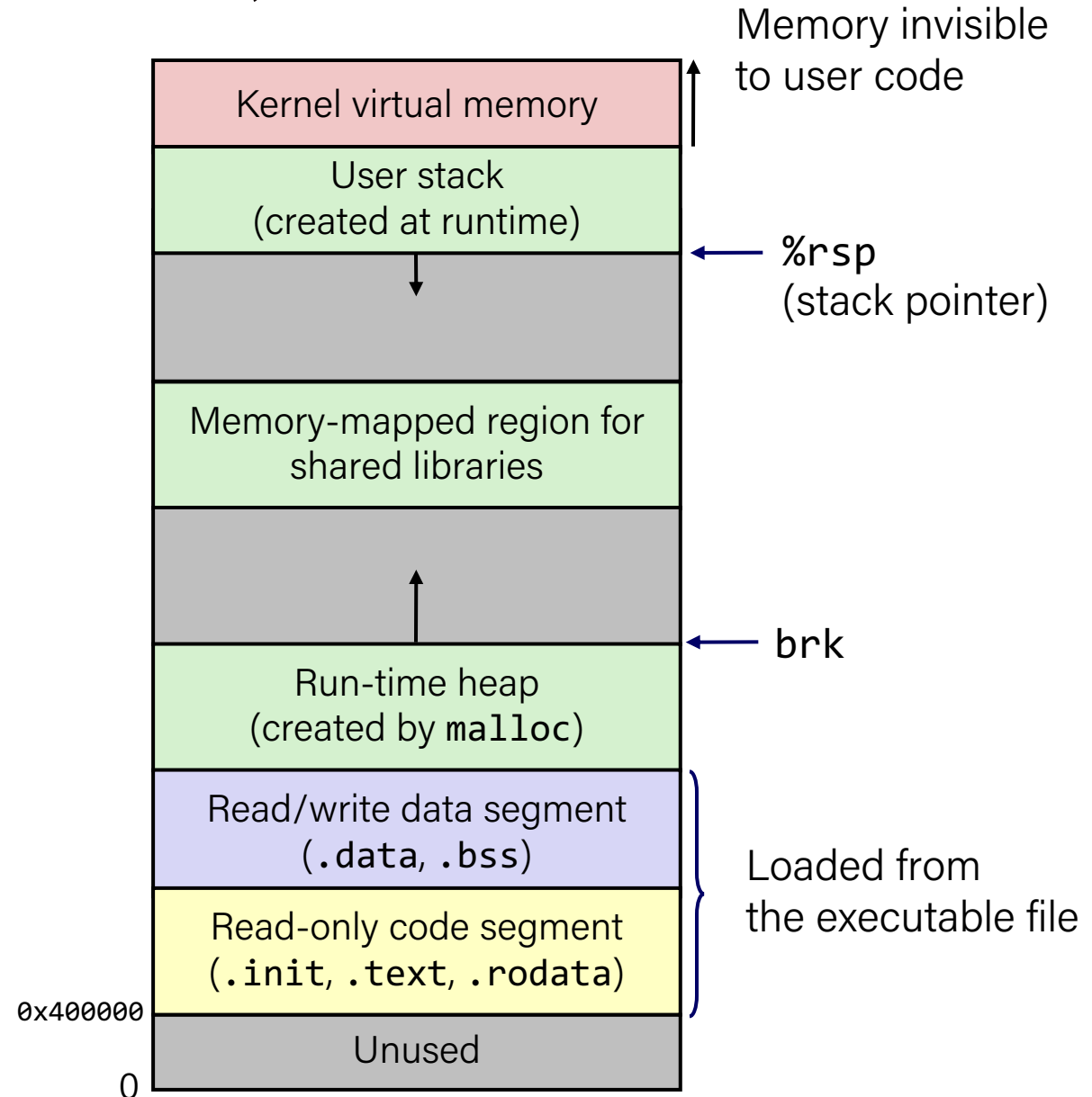
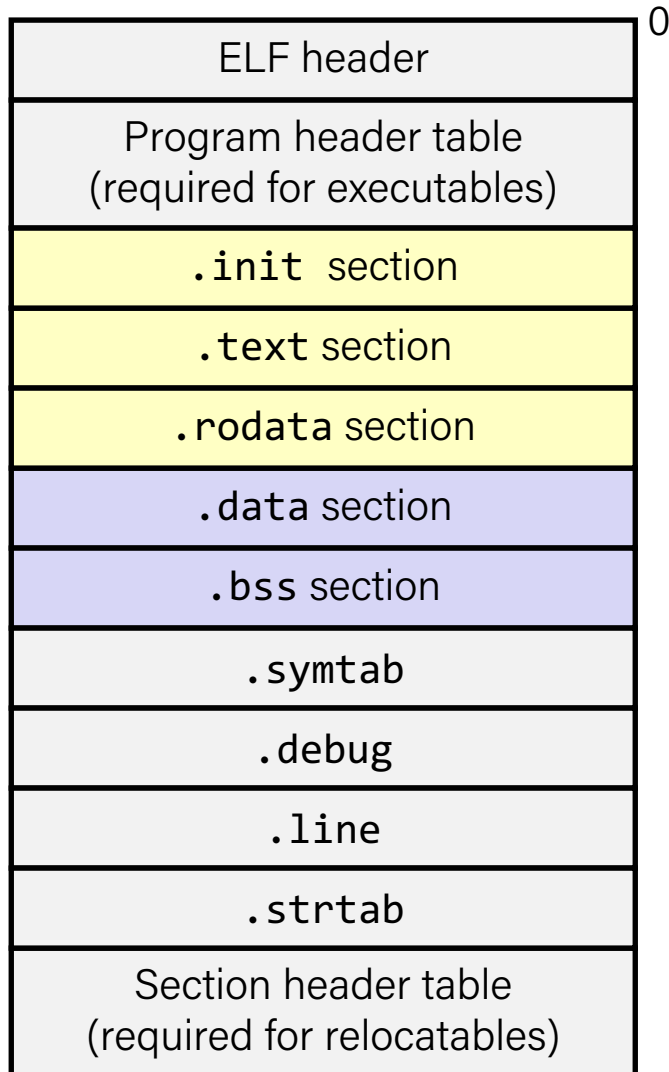
00000000004004e8 <sum>:

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	

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

# Loading Executable Object Files

## Executable Object File



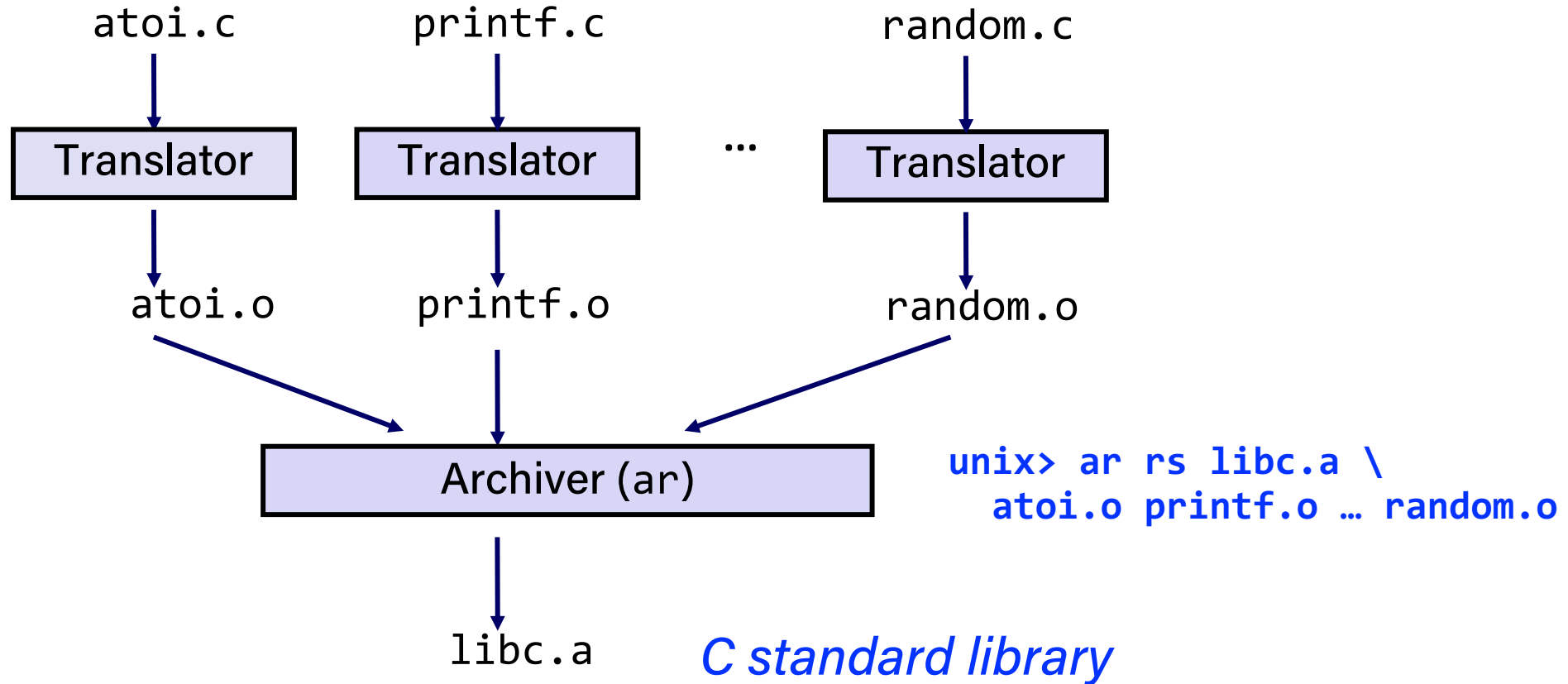
# Packaging Commonly Used Functions

- 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()
{
    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];
}
```

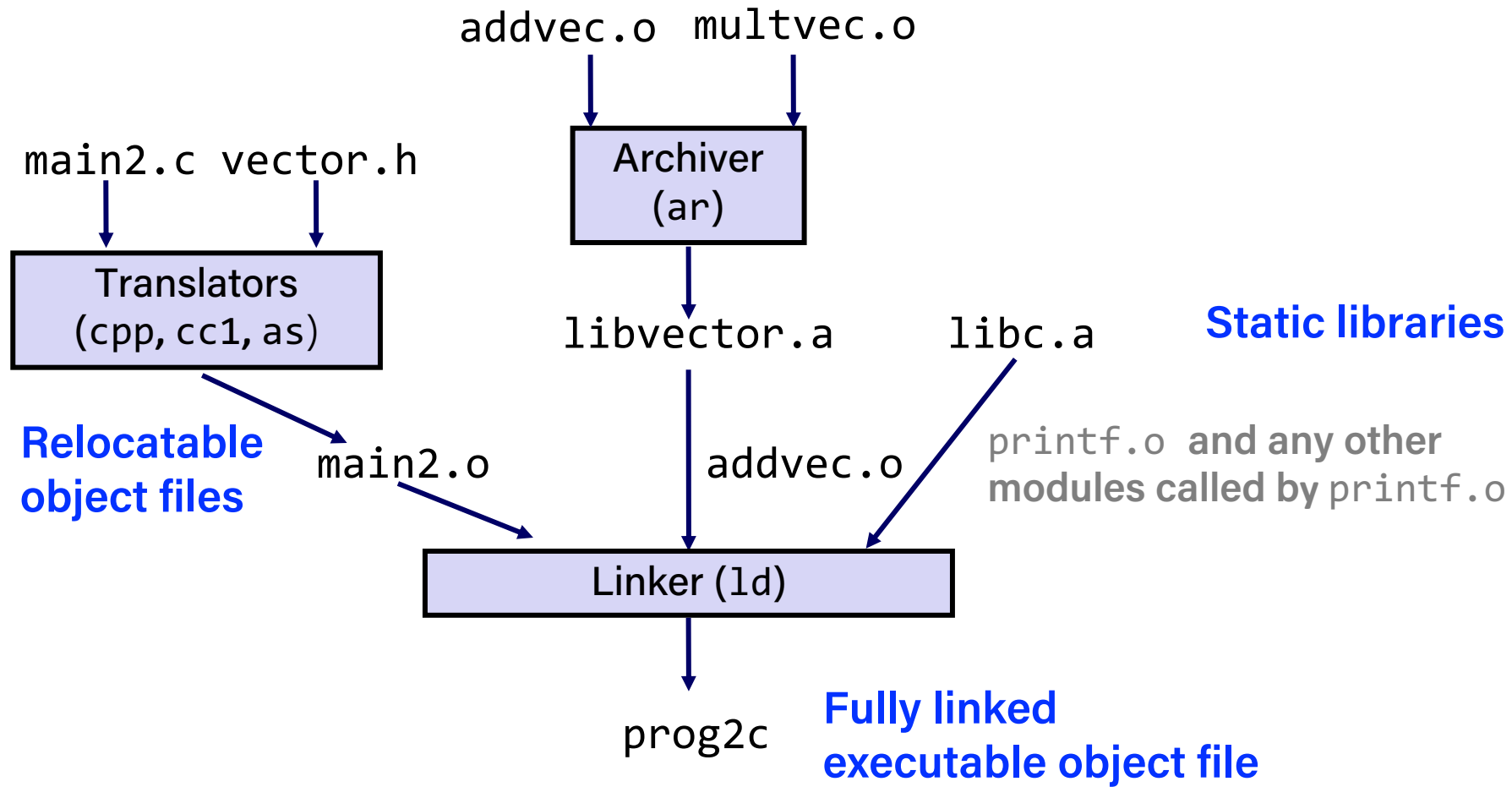
*addvec.c*

```
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'
```

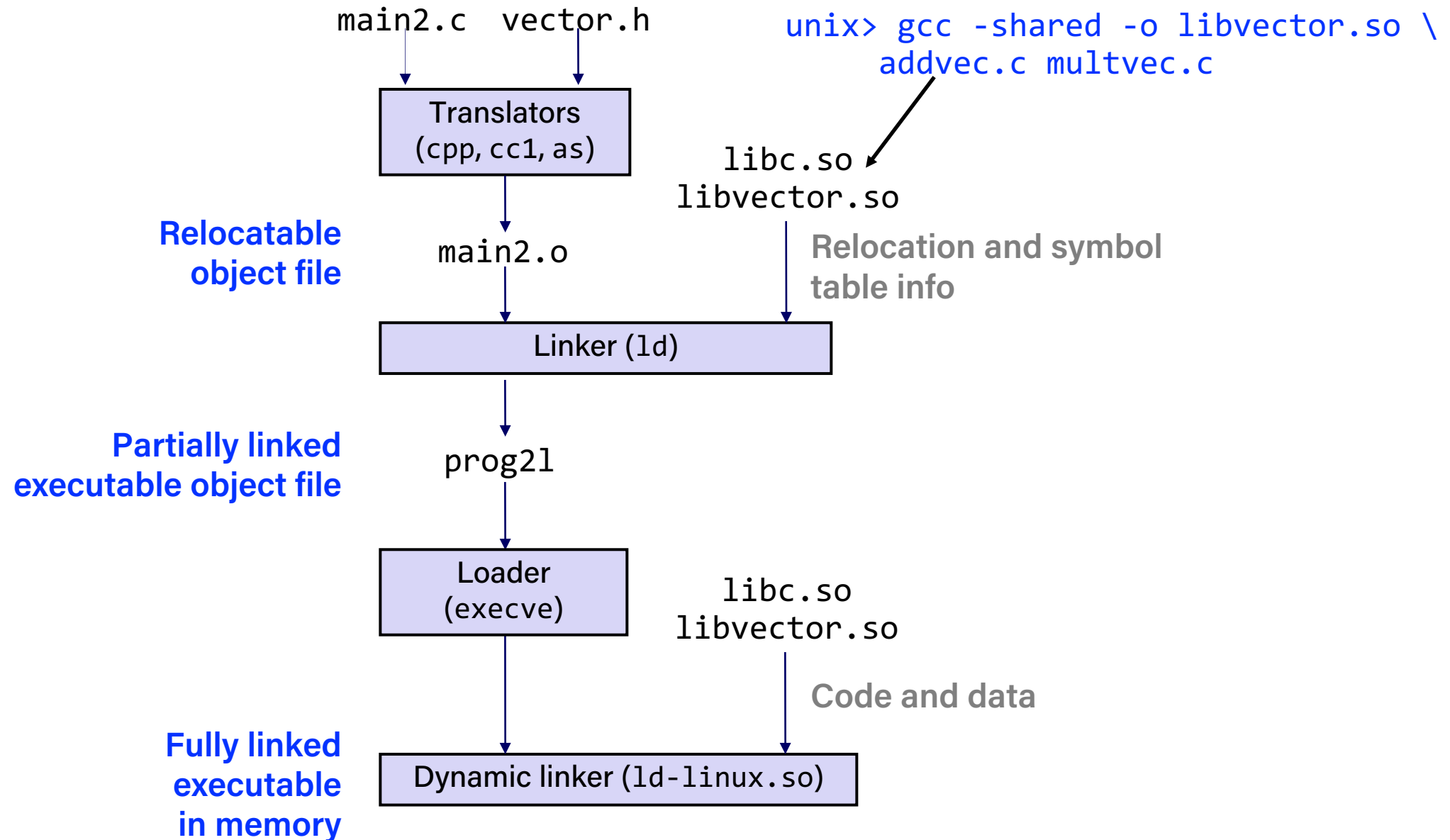
# Modern Solution: Shared Libraries

- **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
- **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 you 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 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.

# Recap

- Static linking
- Dynamic linking

- **Next time:** *Wrapping up*