



# Linking

15-213/18-213/14-513/15-513/18-613:  
Introduction to Computer Systems  
14<sup>th</sup> Lecture, October 10th, 2019

# Today

## ■ **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;

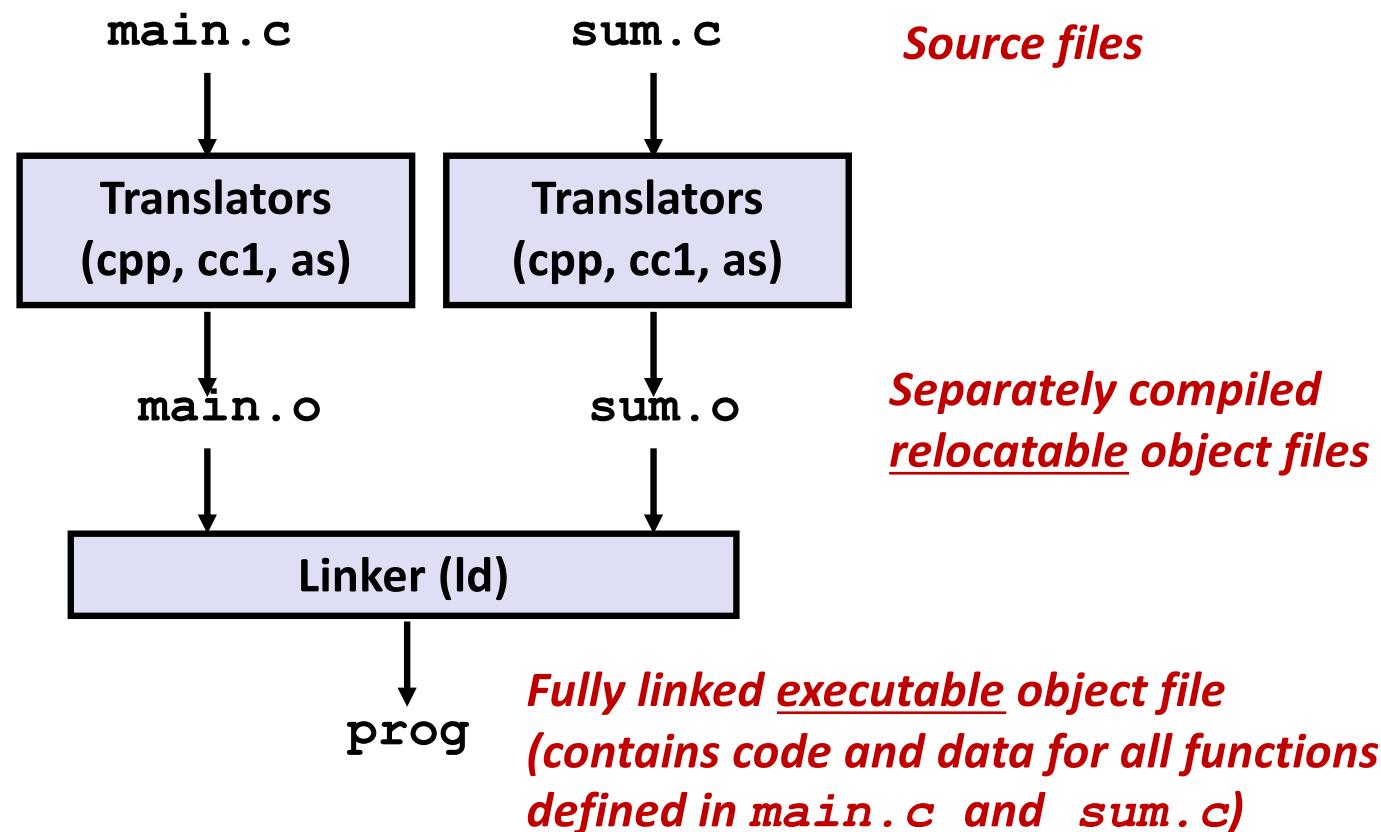
    for (i = 0; i < n; i++) {
        s += a[i];
    }
    return s;
}

sum.c
```

# Linking

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

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



# 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

```
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)

## ■ 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, ...

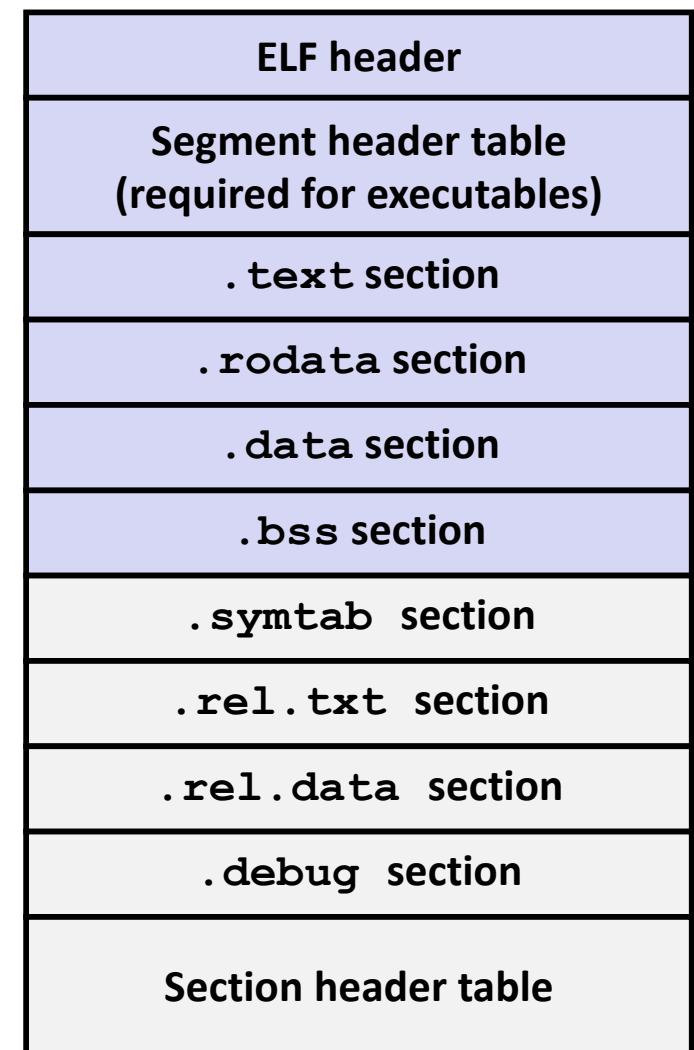
## .data section

- 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

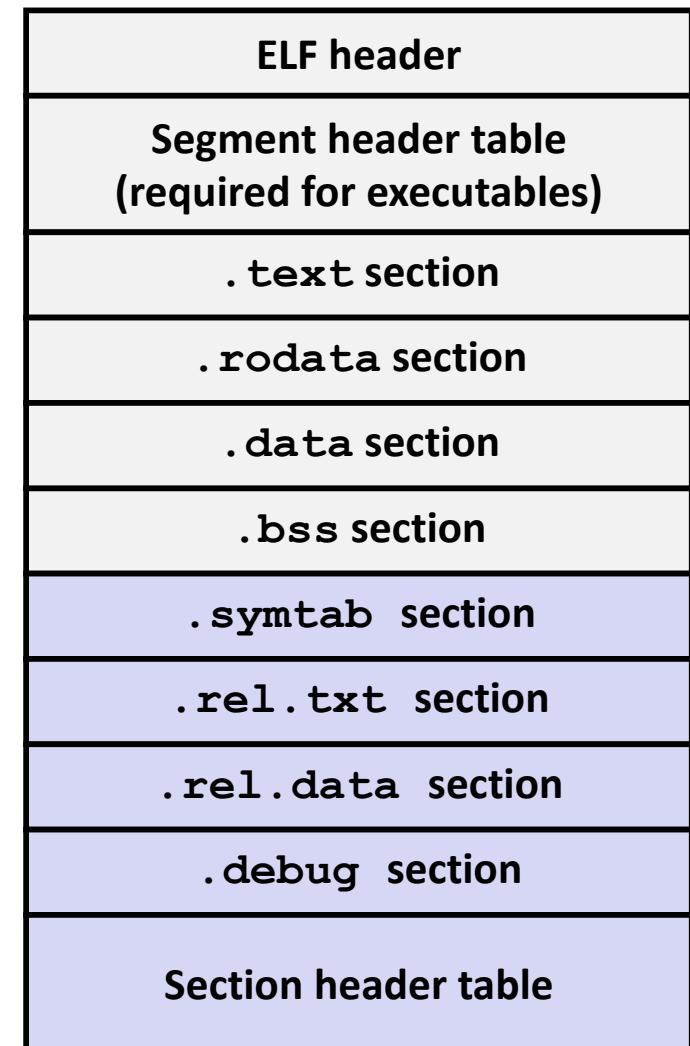
- Relocation info for .data section
- Addresses of pointer data that will need to be modified in the merged executable

## ■ .debug section

- Info for symbolic debugging (`gcc -g`)

## ■ Section header table

- Offsets and sizes of each section



# 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.

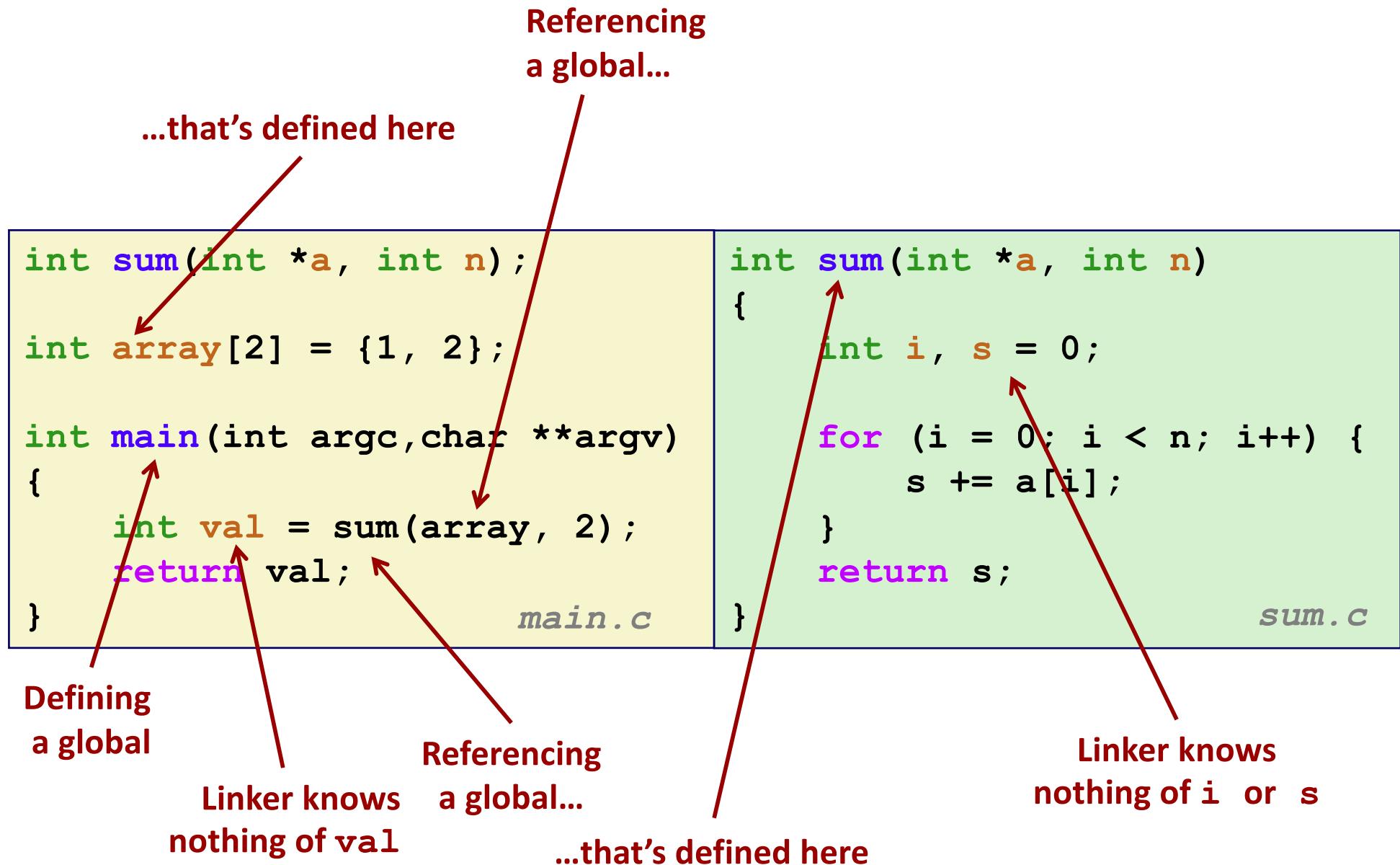
## ■ External symbols

- 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



# 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*

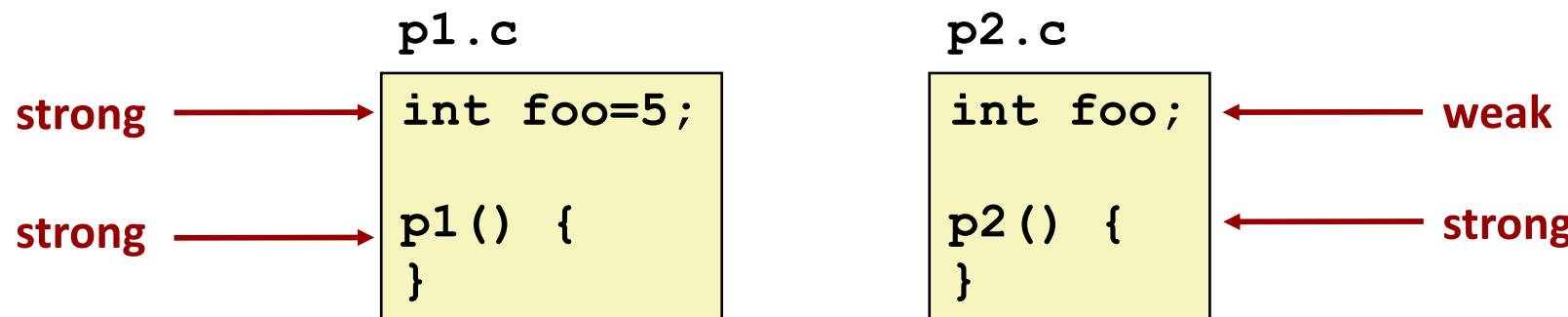
**Compiler allocates space in .data for each definition of x**

**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?

# 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*

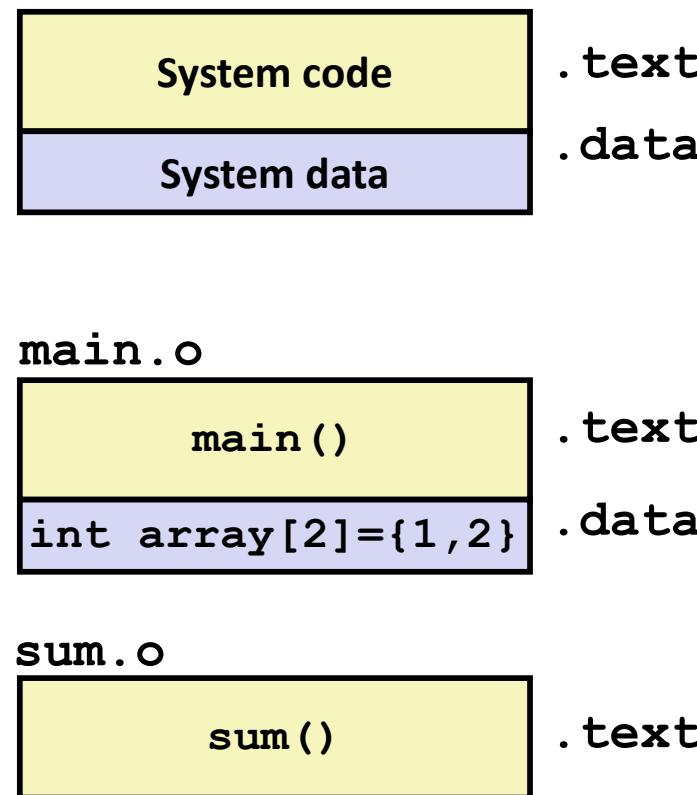
```
int sum(int *a, int n)
{
    int i, s = 0;

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

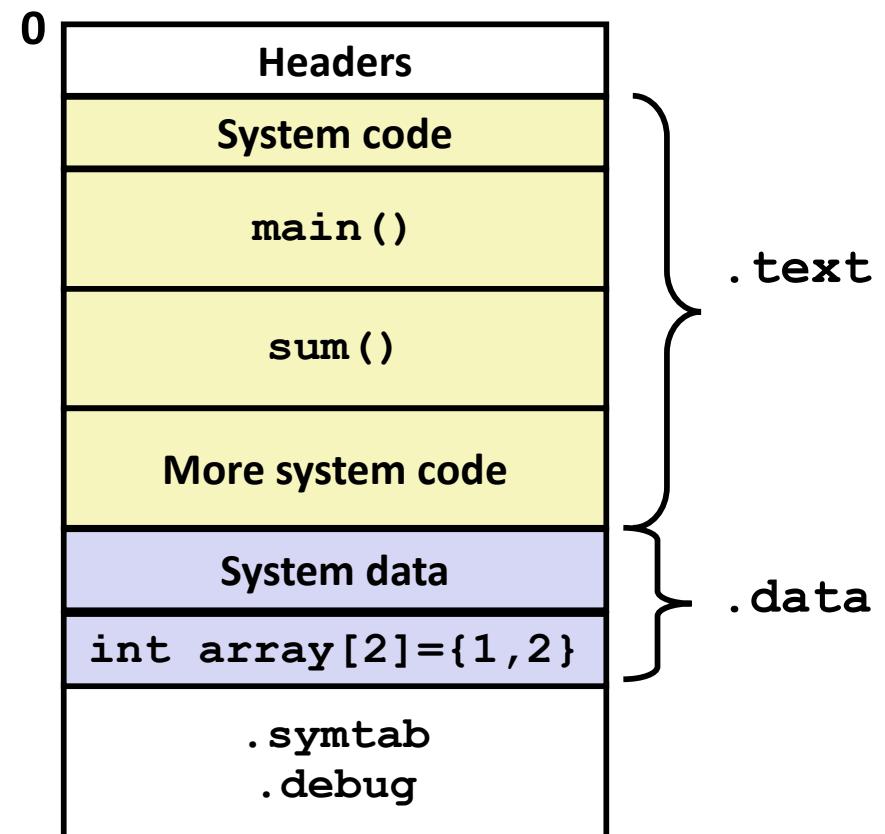
*sum.c*

# Step 2: Relocation

## Relocatable Object Files



## 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*

```

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*

# 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>:
```

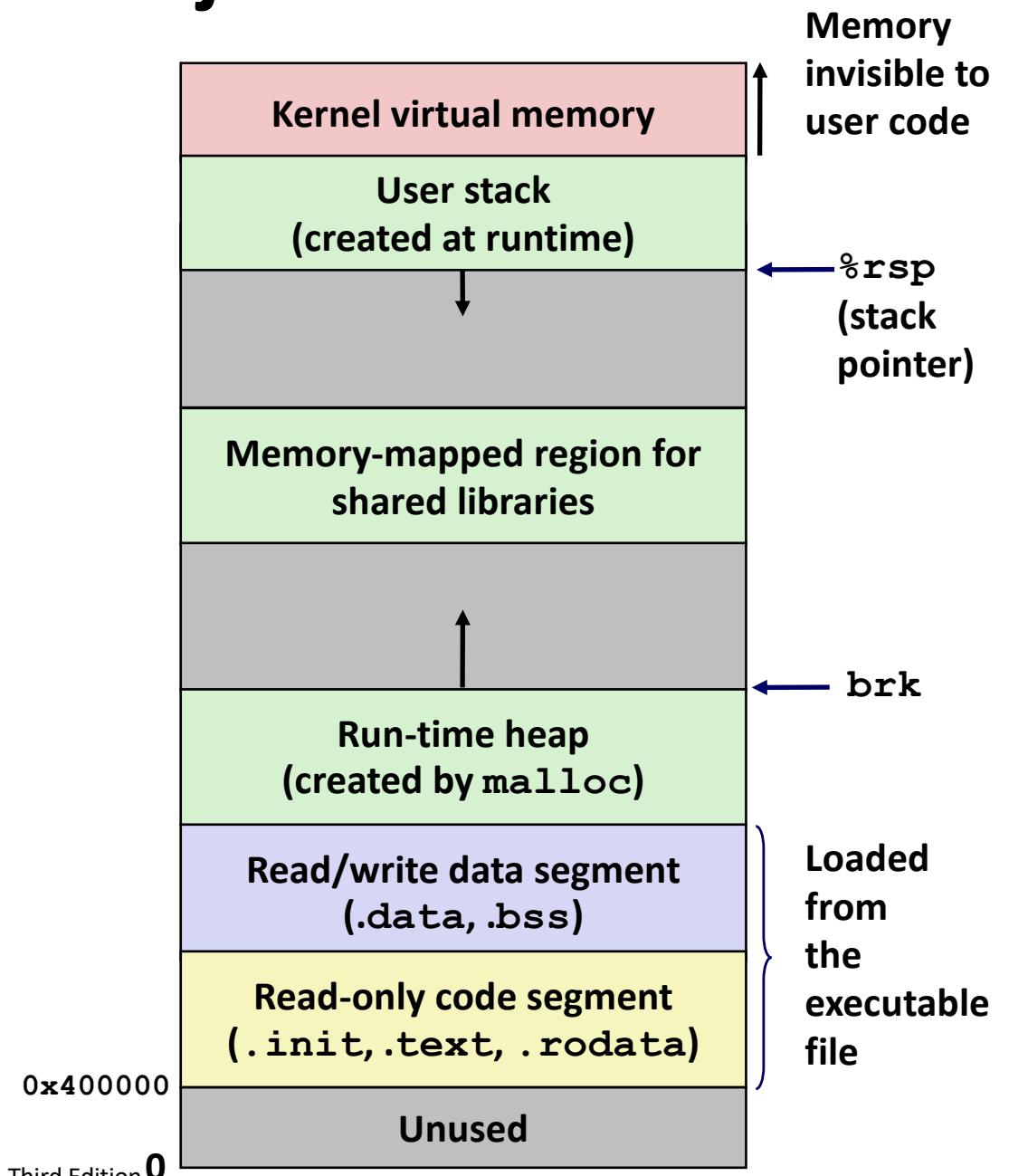
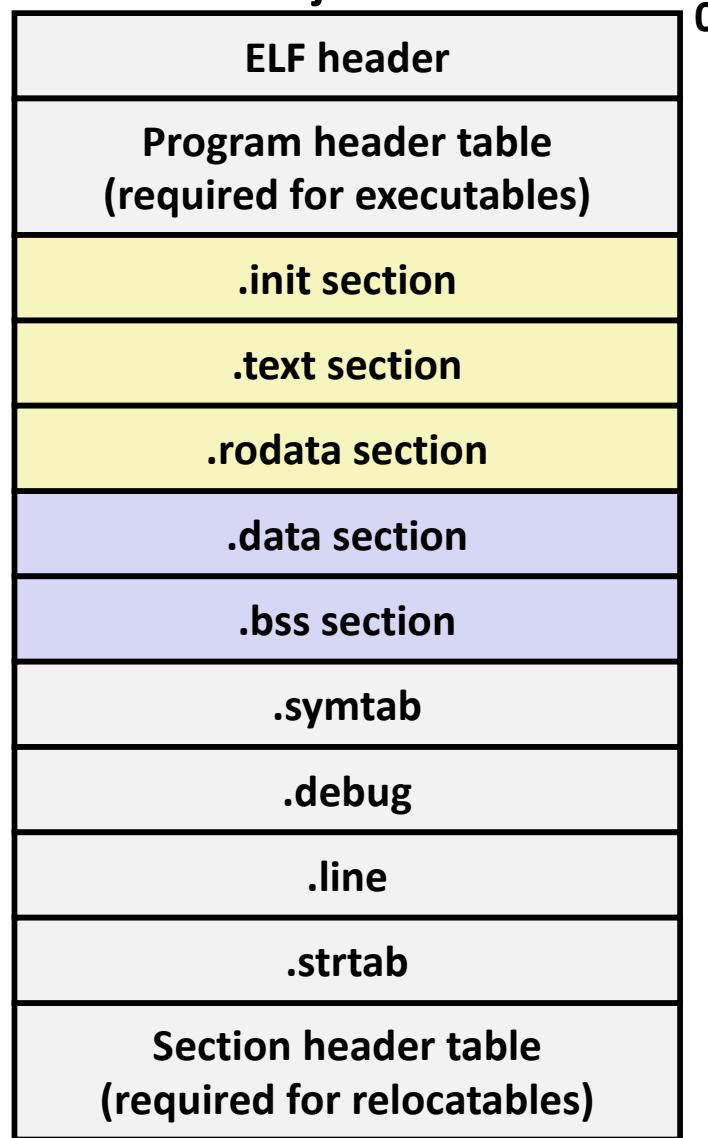
4004e8:	b8 00 00 00 00	mov	\$0x0,%eax
4004ed:	ba 00 00 00 00	mov	\$0x0,%edx
4004f2:	eb 09	jmp	4004fd <sum+0x15>
4004f4:	48 63 ca	movslq	%edx,%rcx
4004f7:	03 04 8f	add	(%rdi,%rcx,4),%eax
4004fa:	83 c2 01	add	\$0x1,%edx
4004fd:	39 f2	cmp	%esi,%edx
4004ff:	7c f3	jl	4004f4 <sum+0xc>
400501:	f3 c3	repz	retq

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

**0x4004e8 = 0x4004e3 + 0x5**

# Loading Executable Object Files

Executable Object File



# Quiz Time!

Check out:

<https://canvas.cmu.edu/courses/10968>

# Libraries: Packaging a Set of Functions

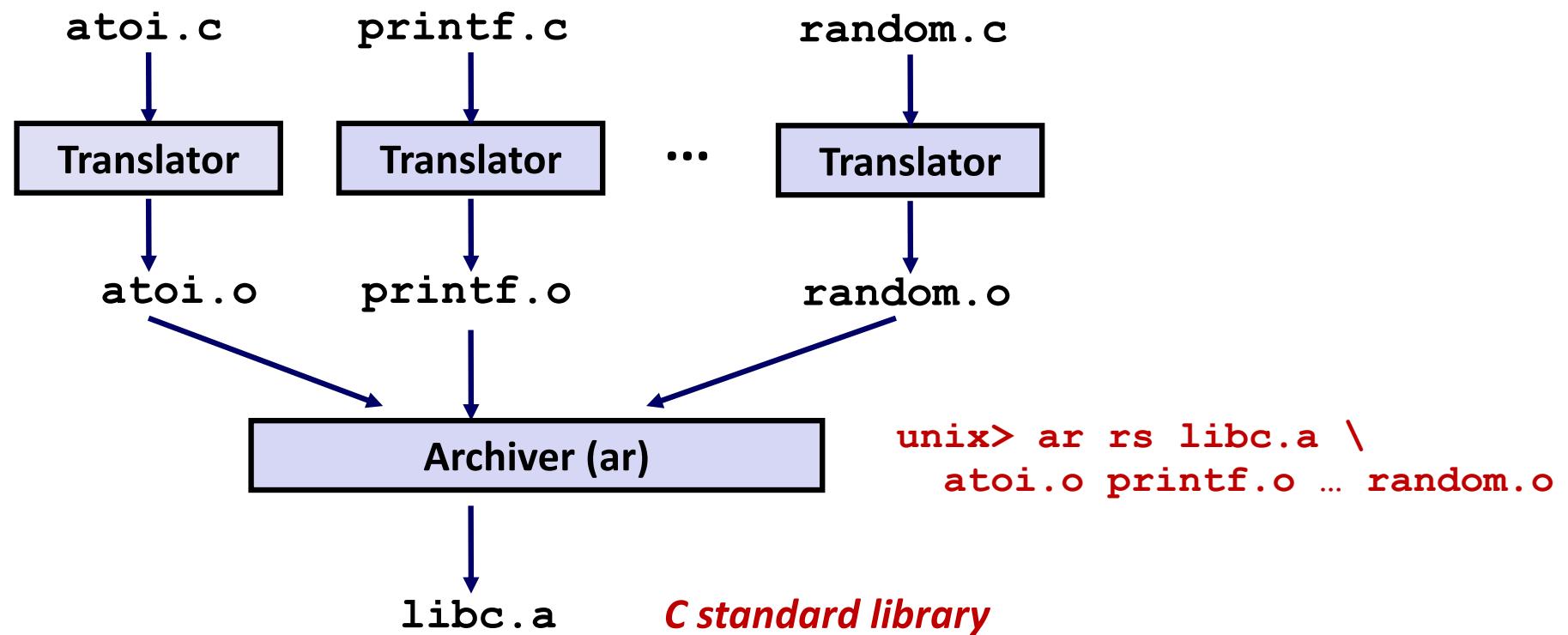
- **How to package functions commonly used by programmers?**
  - Math, I/O, memory management, string manipulation, etc.
- **Awkward, given the linker framework so far:**
  - **Option 1:** Put all functions into a single source file
    - Programmers link big object file into their programs
    - Space 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 /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];
}
```

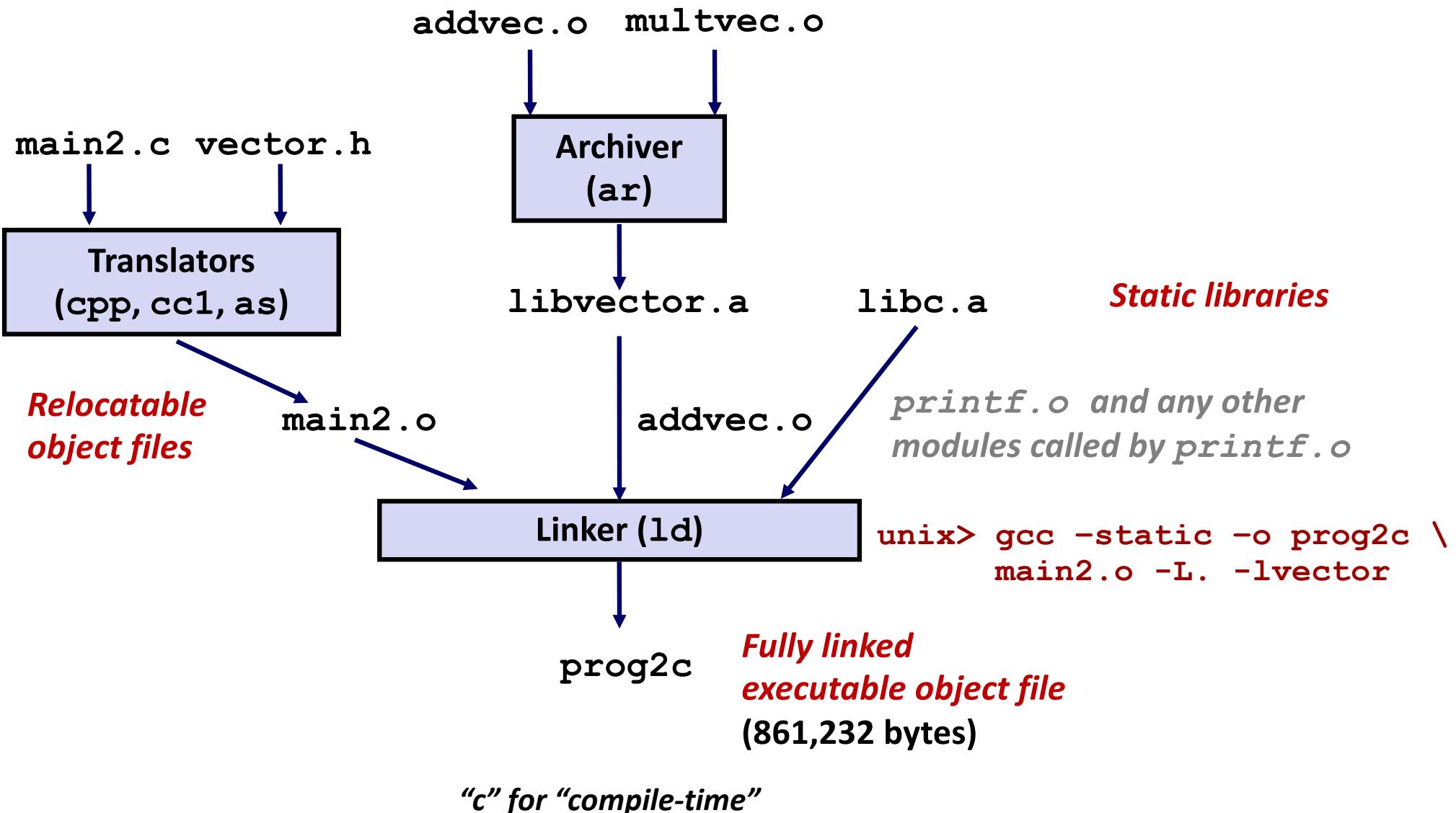
*addvec.c*

```
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



# 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
```

# 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)

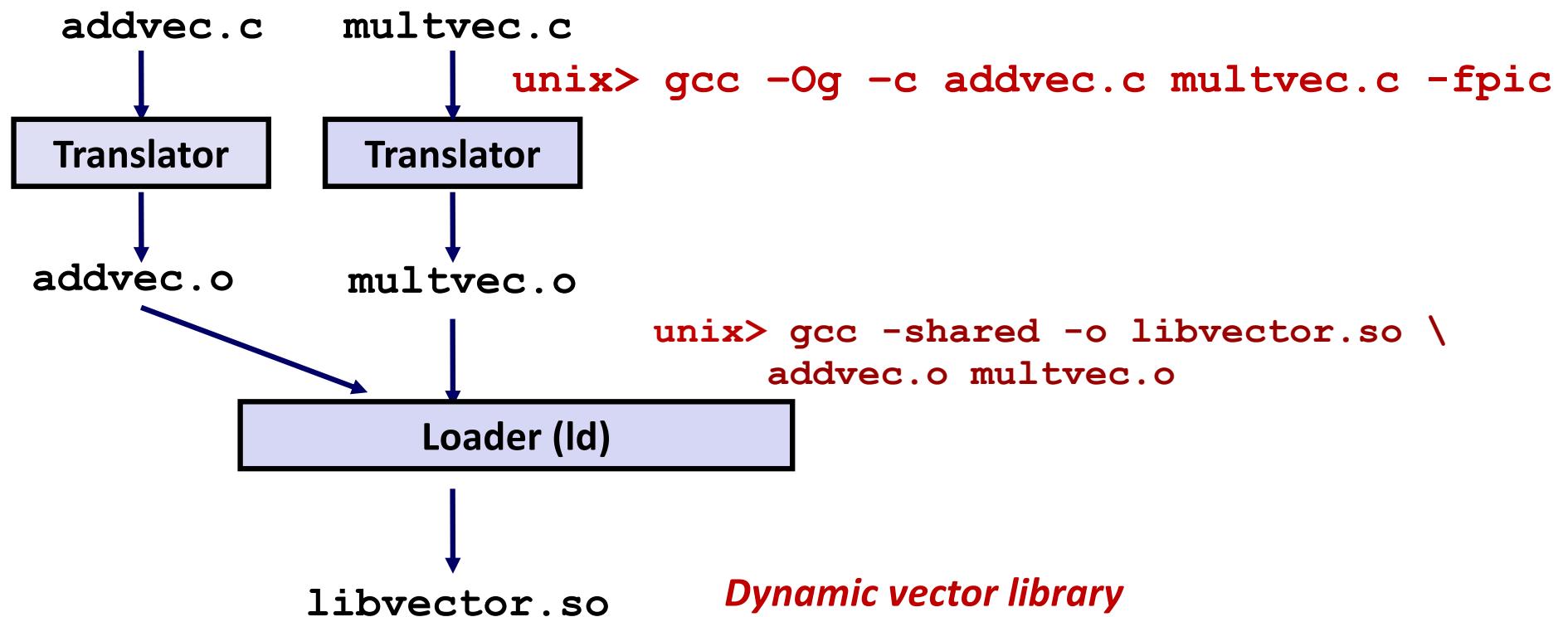
Shared library: [libm.so.6]

## ■ **Where are the libraries found?**

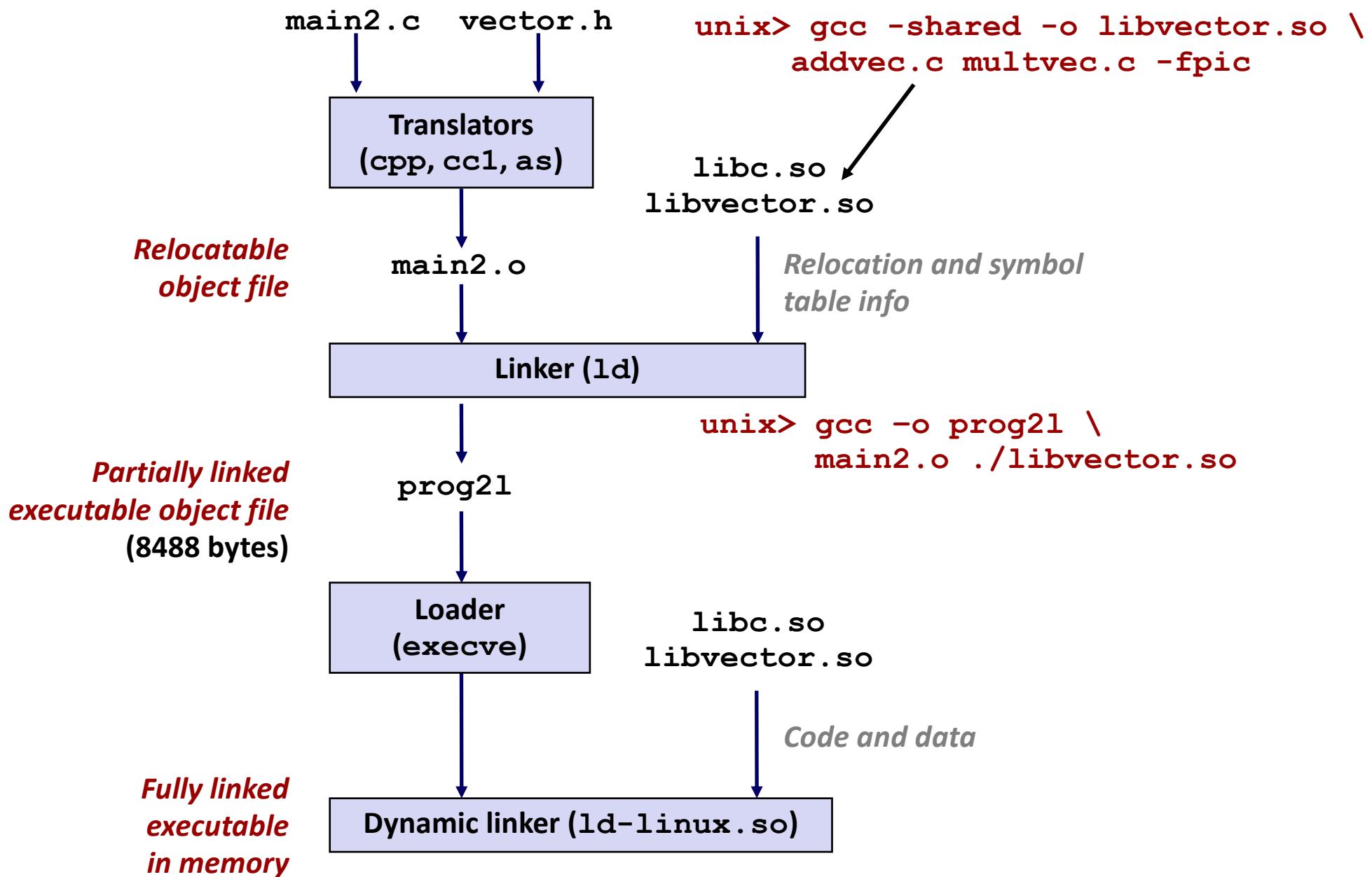
- Use “`ldd`” to find out:

```
unix> ldd prog
linux-vdso.so.1 => (0x00007ffcfcf2998000)
libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007f99ad927000)
/lib64/ld-linux-x86-64.so.2 (0x00007f99adcef000)
```

# Dynamic Library Example



# 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);
    }
    . . .

```

*dll.c*

# Dynamic Linking at Run-time (cont)

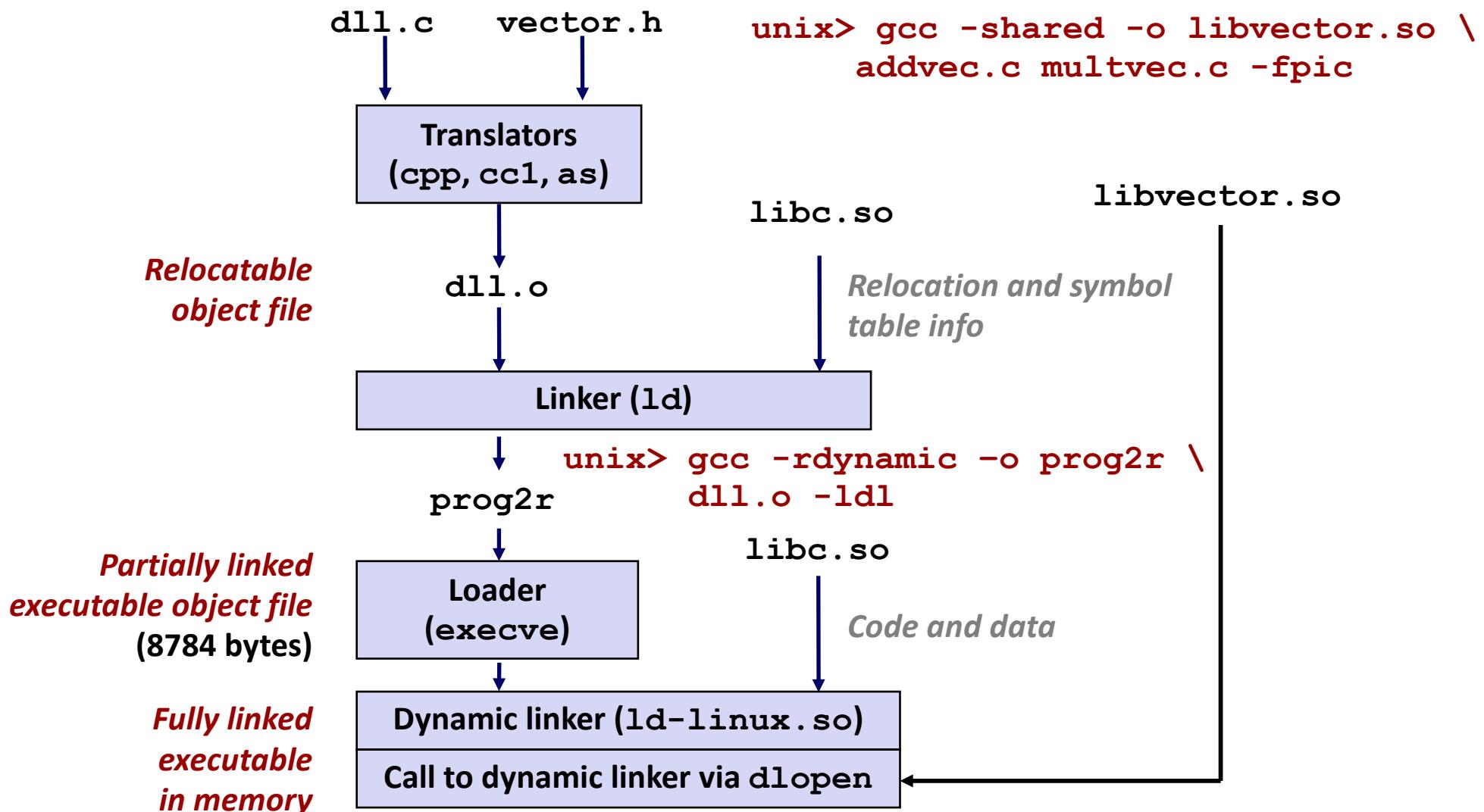
```
...
/* Get a pointer to the addvec() function we just loaded */
addvec = dlsym(handle, "addvec");
if ((error = dlerror()) != NULL) {
    fprintf(stderr, "%s\n", error);
    exit(1);
}

/* 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



# 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
- 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)
- 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 call sites and 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
- Other labs (malloc, shell, proxy) also use interpositioning to enhance checking capabilities

# 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

```
#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:

```
env 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

```
env 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