

# 15-213

*“The course that gives CMU its Zip!”*

## Linking

### October 11, 2006

#### Topics

- Static linking
- Dynamic linking
- Case study: Library interpositioning

# Example C Program

main.c

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

int main()
{
    swap();
    return 0;
}
```

swap.c

```
extern int buf[];

static int *bufp0 = &buf[0];
static int *bufp1;

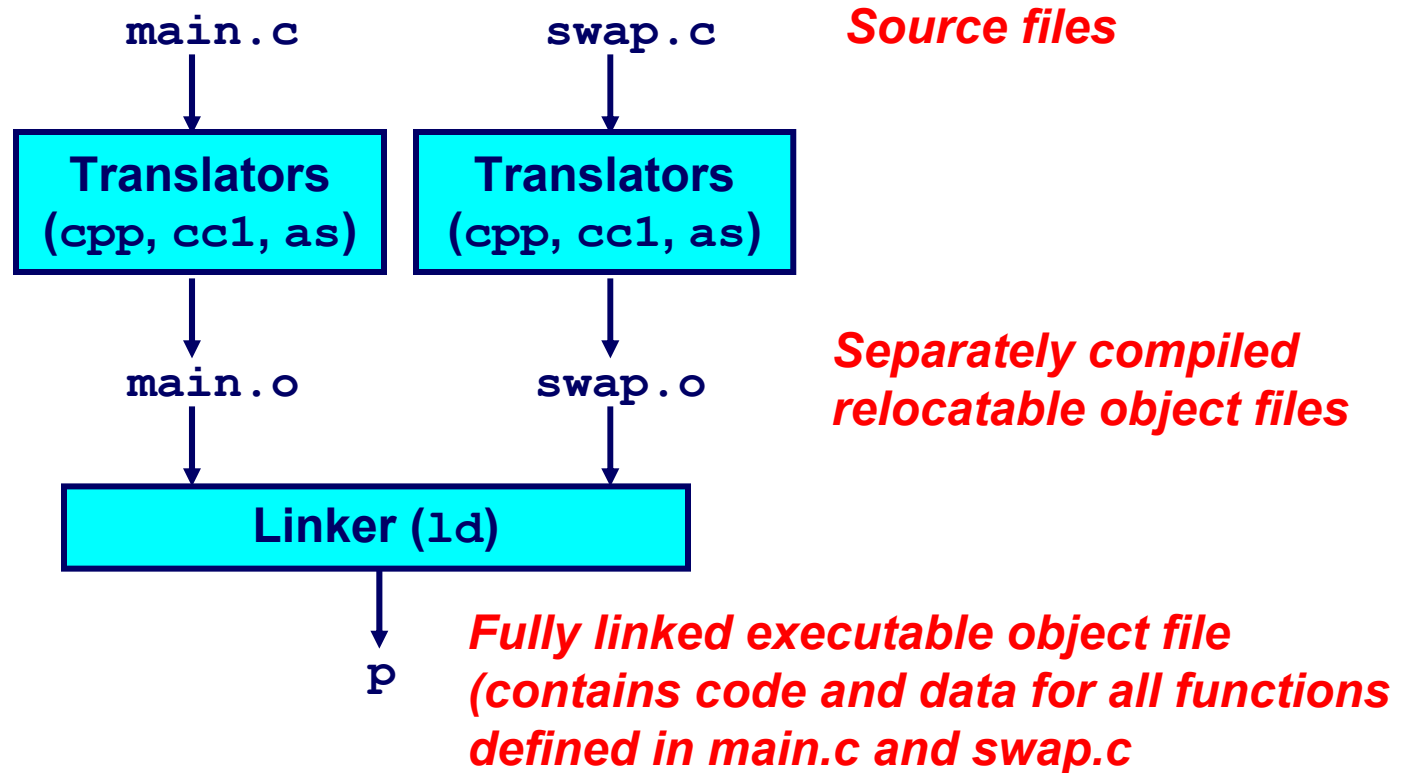
void swap()
{
    int temp;

    bufp1 = &buf[1];
    temp = *bufp0;
    *bufp0 = *bufp1;
    *bufp1 = temp;
}
```

# Static Linking

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

- `unix> gcc -O2 -g -o p main.c swap.c`
- `unix> ./p`



# 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* (variables and functions):
  - `void swap() {...} /* define symbol swap */`
  - `swap(); /* reference symbol a */`
  - `int *xp = &x; /* define symbol xp, reference x */`
- Symbol definitions are stored (by compiler) in *symbol table*.
  - Symbol table is an array of structs
  - Each entry includes name, size, and location of symbol.
- 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.

# Three Kinds of Object Files (Modules)

## 1. 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

## 2. Executable object file

- Contains code and data in a form that can be copied directly into memory and then executed.

## 3. 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**

**Originally proposed by AT&T System V Unix**

- Later adopted by BSD Unix variants and Linux

**One unified format for**

- Relocatable object files (.o),
- Executable object files
- Shared object files (.so)

**Generic name: ELF binaries**

# ELF Object File Format

## Elf header

- Magic number, type (.o, exec, .so), machine, byte ordering, etc.

## Segment header table

- Page size, virtual addresses memory segments (sections), segment sizes.

## .text section

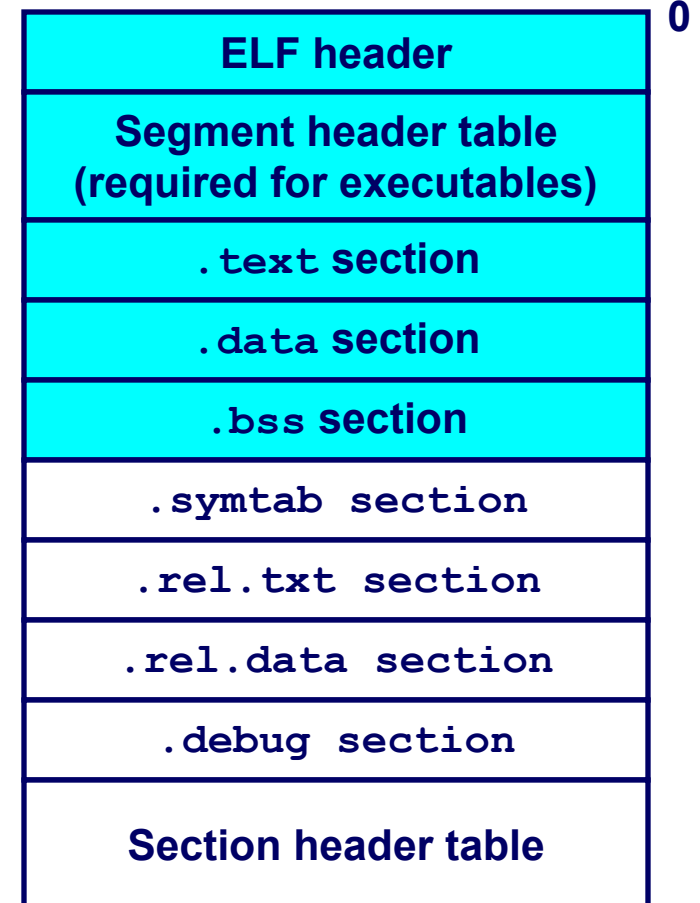
- Code

## .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**

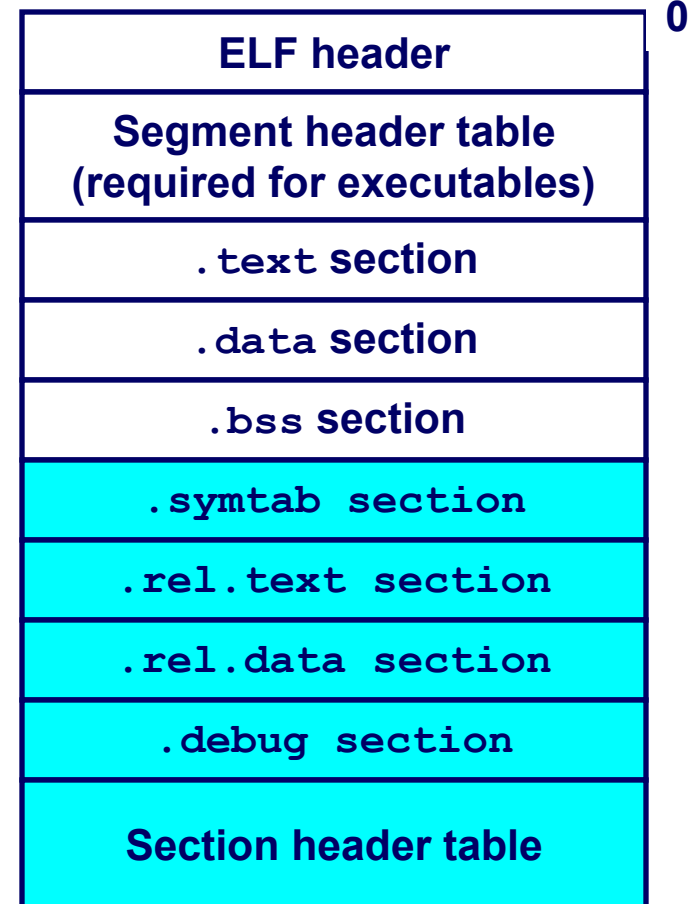
- Relocation info for .data section
- Addresses of pointer data that will need to be modified in the merged executable

## **.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.
- Ex: `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  $m$ .
- Ex: C functions and variables defined with the `static` attribute.

**Key Point: Local linker symbols are *not* local program variables**

# Resolving Symbols

Def of global symbol buf

main.c

```
int buf[2] = {1,2};  
  
int main()  
{  
    swap();  
    return 0;  
}
```

Ref to external symbol swap

Ref to external symbol buf

swap.c

```
extern int buf[];  
  
static int *bufp0 = &buf[0];  
static int *bufp1;  
  
void swap()  
{  
    int temp;  
  
    bufp1 = &buf[1];  
    temp = *bufp0;  
    *bufp0 = *bufp1;  
    *bufp1 = temp;  
}
```

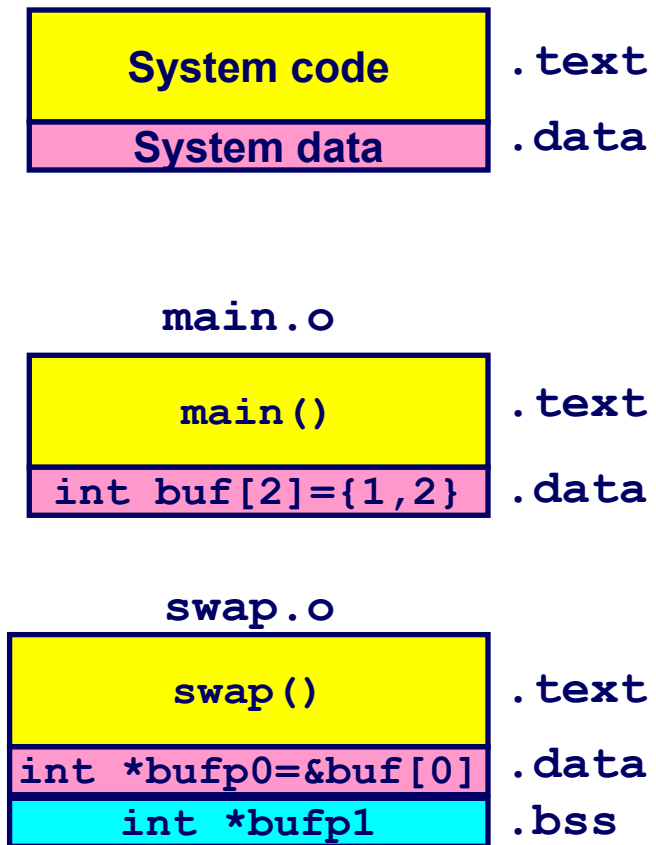
Def of local symbol bufp0

Def of global symbol swap

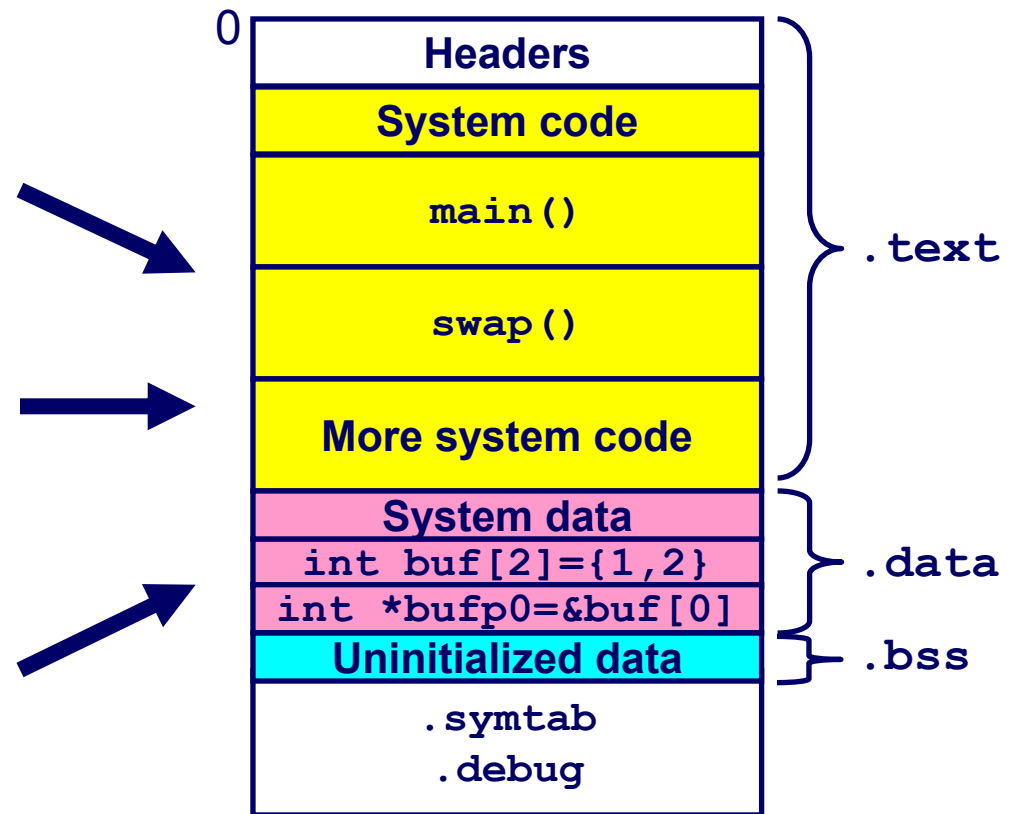
Linker knows nothing of temp

# Relocating Code and Data

## Relocatable Object Files



## Executable Object File



# main.o Relocation Info

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

int main()
{
    swap();
    return 0;
}
```

```
00000000 <main>:
 0: 55          push   %ebp
 1: 89 e5      mov    %esp,%ebp
 3: 83 ec 08   sub   $0x8,%esp
 6: e8 fc ff ff call   7 <main+0x7>
    7: R_386_PC32 swap
 b: 31 c0     xor   %eax,%eax
 d: 89 ec     mov   %ebp,%esp
 f: 5d       pop   %ebp
10: c3       ret
```

Disassembly of section .data:

```
00000000 <buf>:
 0: 01 00 00 00 02 00 00 00
```

Source: objdump

# swap.o Relocation Info (.text)

```
extern int buf[];

static int *bufp0 =
    &buf[0];
static int *bufp1;

void swap()
{
    int temp;

    bufp1 = &buf[1];
    temp = *bufp0;
    *bufp0 = *bufp1;
    *bufp1 = temp;
}
```

Disassembly of section .text:

00000000 <swap>:

```
0: 55                push   %ebp
1: 8b 15 00 00 00 00  mov    0x0,%edx
3: R_386_32 bufp0
7: a1 0 00 00 00    mov    0x4,%eax
8: R_386_32 buf
c: 89 e5            mov    %esp,%ebp
e: c7 05 00 00 00 00 04 movl   $0x4,0x0
15: 00 00 00
10: R_386_32 bufp1
14: R_386_32 buf
18: 89 ec            mov    %ebp,%esp
1a: 8b 0a            mov    (%edx),%ecx
1c: 89 02            mov    %eax,(%edx)
1e: a1 00 00 00 00  mov    0x0,%eax
1f: R_386_32 bufp1
23: 89 08            mov    %ecx,(%eax)
25: 5d                pop    %ebp
26: c3                ret
```



# swap.o Relocation Info (.data)

```
extern int buf[];

static int *bufp0 =
    &buf[0];
static int *bufp1;

void swap()
{
    int temp;

    bufp1 = &buf[1];
    temp = *bufp0;
    *bufp0 = *bufp1;
    *bufp1 = temp;
}
```

Disassembly of section .data:

```
00000000 <bufp0>:
    0:  00 00 00 00

    0:  R_386_32 buf
```

# Executable After Relocation (.text)

```
080483b4 <main>:
 80483b4:      55                push   %ebp
 80483b5:      89 e5            mov    %esp,%ebp
 80483b7:      83 ec 08        sub    $0x8,%esp
 80483ba:      e8 09 00 00 00   call  80483c8 <swap>
 80483bf:      31 c0            xor    %eax,%eax
 80483c1:      89 ec            mov    %ebp,%esp
 80483c3:      5d                pop    %ebp
 80483c4:      c3                ret

080483c8 <swap>:
 80483c8:      55                push   %ebp
 80483c9:      8b 15 5c 94 04 08 mov    0x804945c,%edx
 80483cf:      a1 58 94 04 08   mov    0x8049458,%eax
 80483d4:      89 e5            mov    %esp,%ebp
 80483d6:      c7 05 48 95 04 08 58 movl   $0x8049458,0x8049548
 80483dd:      94 04 08
 80483e0:      89 ec            mov    %ebp,%esp
 80483e2:      8b 0a            mov    (%edx),%ecx
 80483e4:      89 02            mov    %eax,(%edx)
 80483e6:      a1 48 95 04 08   mov    0x8049548,%eax
 80483eb:      89 08            mov    %ecx,(%eax)
 80483ed:      5d                pop    %ebp
 80483ee:      c3                ret
```

# Executable After Relocation (.data)

```
Disassembly of section .data:
```

```
08049454 <buf>:
```

```
8049454:      01 00 00 00 02 00 00 00
```

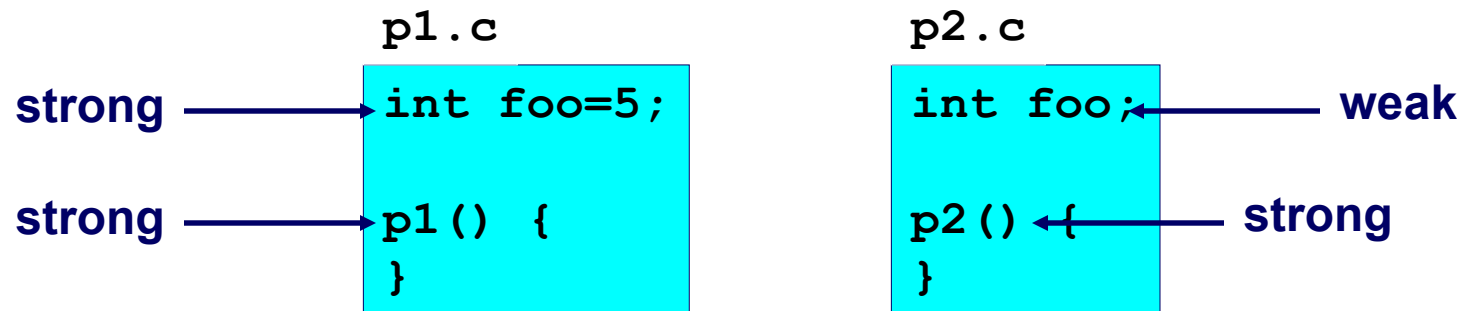
```
0804945c <bufp0>:
```

```
804945c:      54 94 04 08
```

# Strong and Weak Symbols

Program symbols are either strong or weak

- **strong**: procedures and initialized globals
- **weak**: uninitialized globals



# Linker's Symbol Rules

**Rule 1. A strong symbol can only appear once.**

**Rule 2. A weak symbol can be overridden by a strong symbol of the same name.**

- references to the weak symbol resolve to the strong symbol.

**Rule 3. If there are multiple weak symbols, the linker will 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.

# 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 in 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

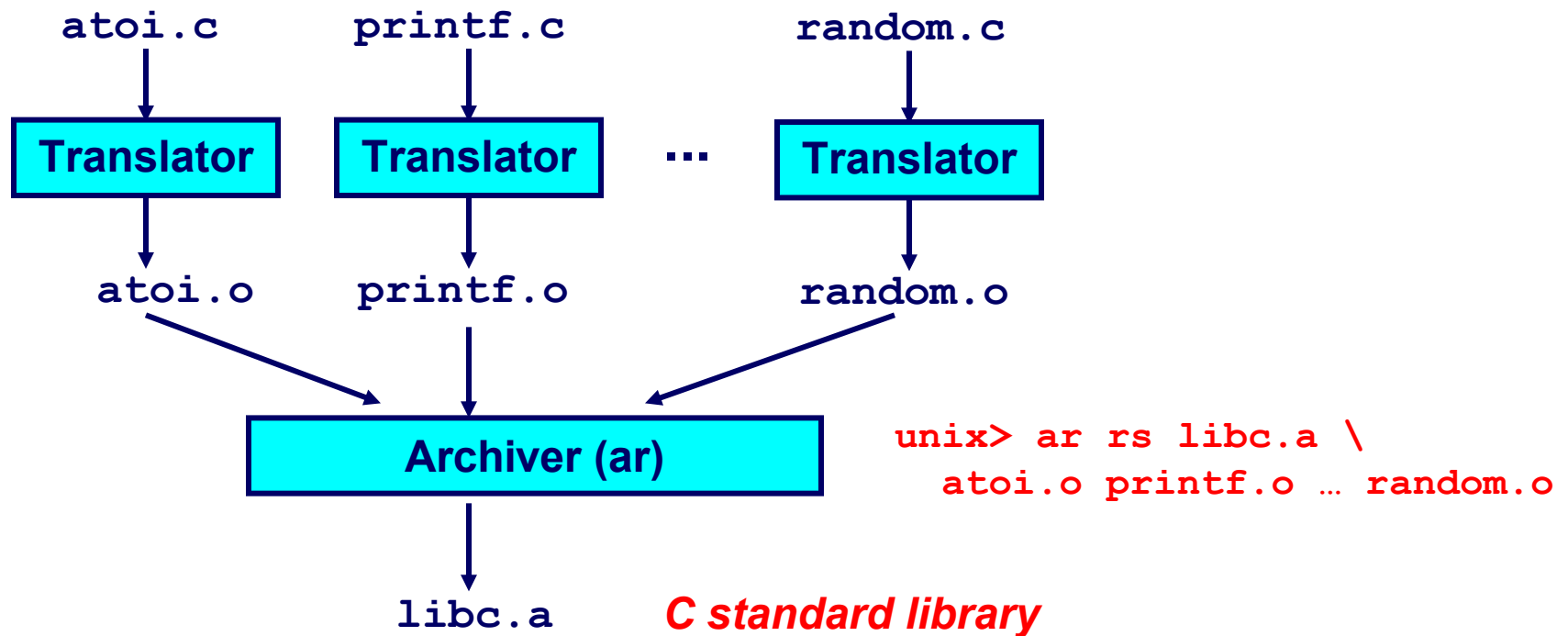
# Static Libraries

## Solution: *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 into 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)

- 8 MB archive of 900 object files.
- I/O, memory allocation, signal handling, string handling, data and time, random numbers, integer math

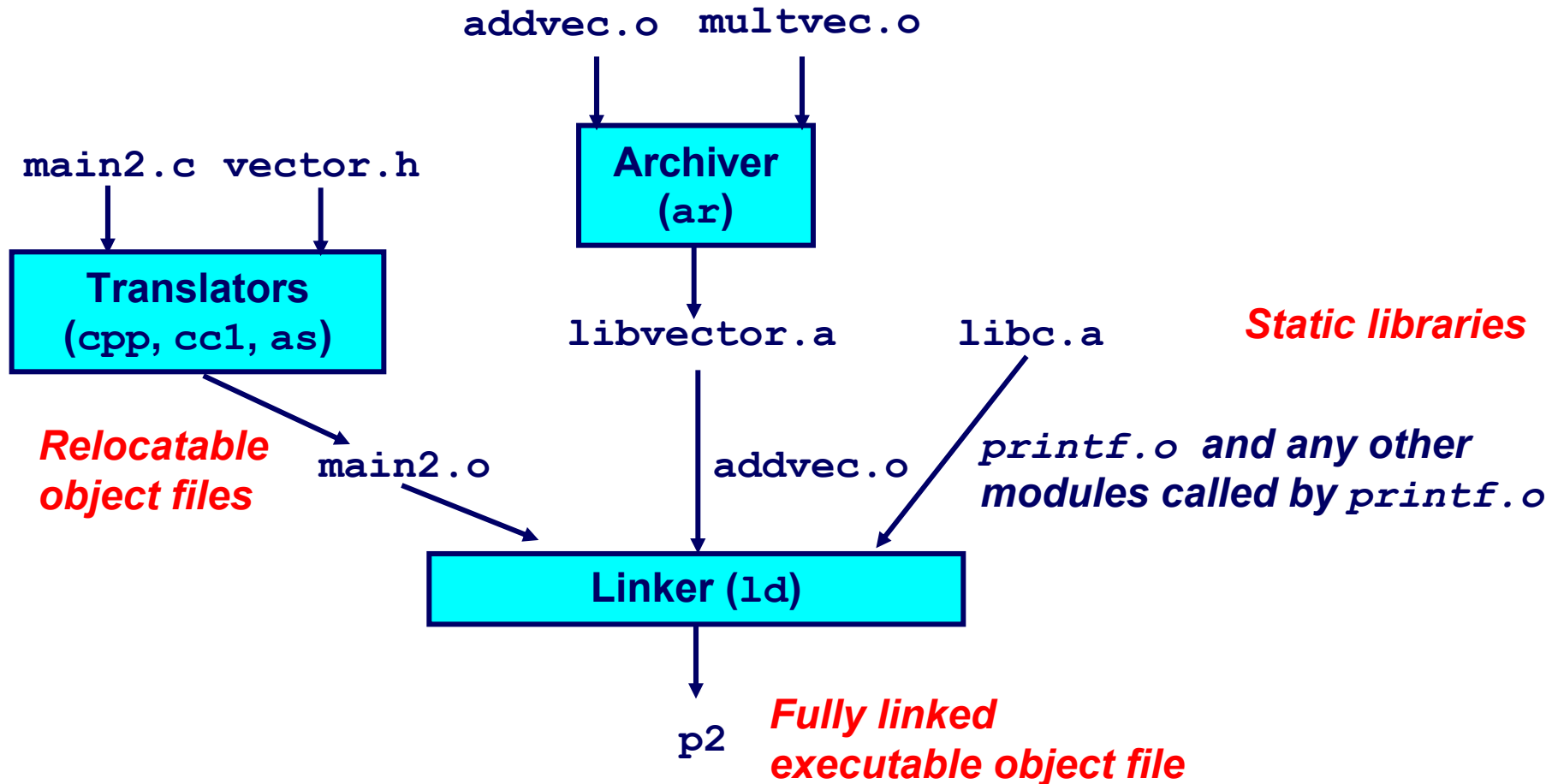
## `libm.a` (the C math library)

- 1 MB archive of 226 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



# 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.

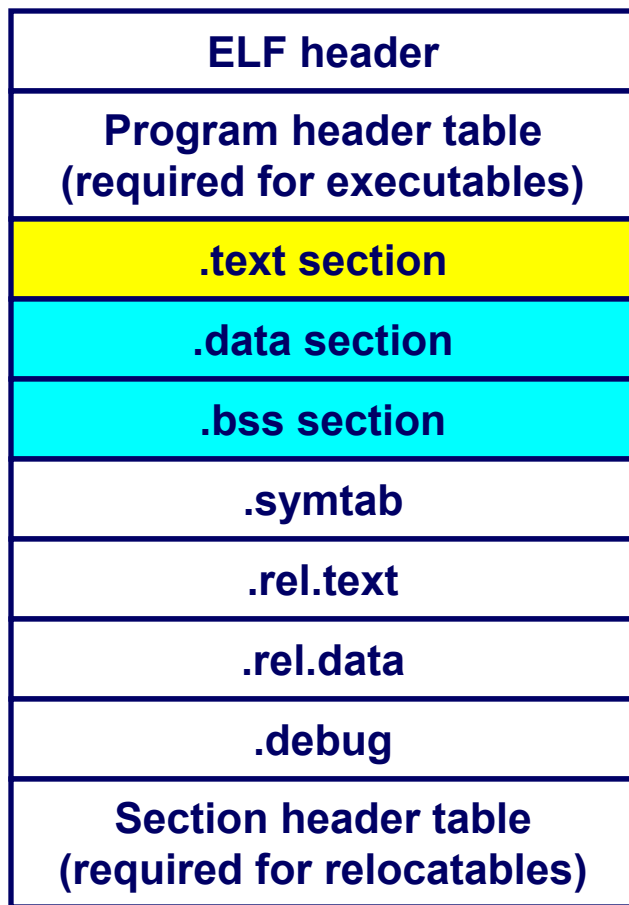
## Problem:

- Command line order matters!
- Moral: put libraries at the end of the command line.

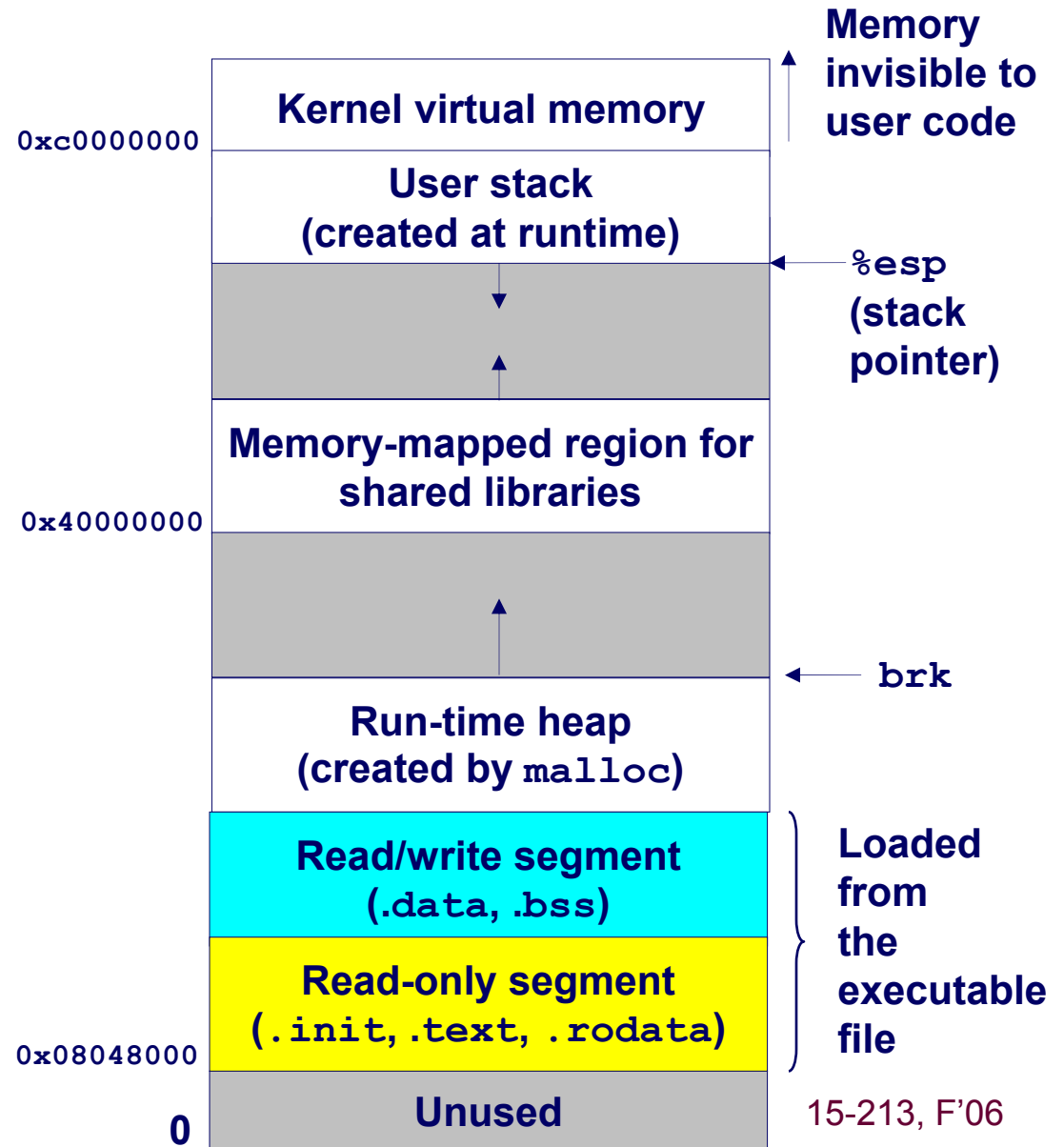
```
bass> gcc -L. libtest.o -lmine
bass> gcc -L. -lmine libtest.o
libtest.o: In function `main':
libtest.o(.text+0x4): undefined reference to `libfun'
```

# Loading Executable Object Files

Executable Object File



0



# Shared Libraries

## Static libraries have the following disadvantages:

- Potential for duplicating lots of common code in the executable files on a filesystem.
  - e.g., every C program needs the standard C library
- Potential for duplicating lots of code in the virtual memory space of many processes.
- 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.

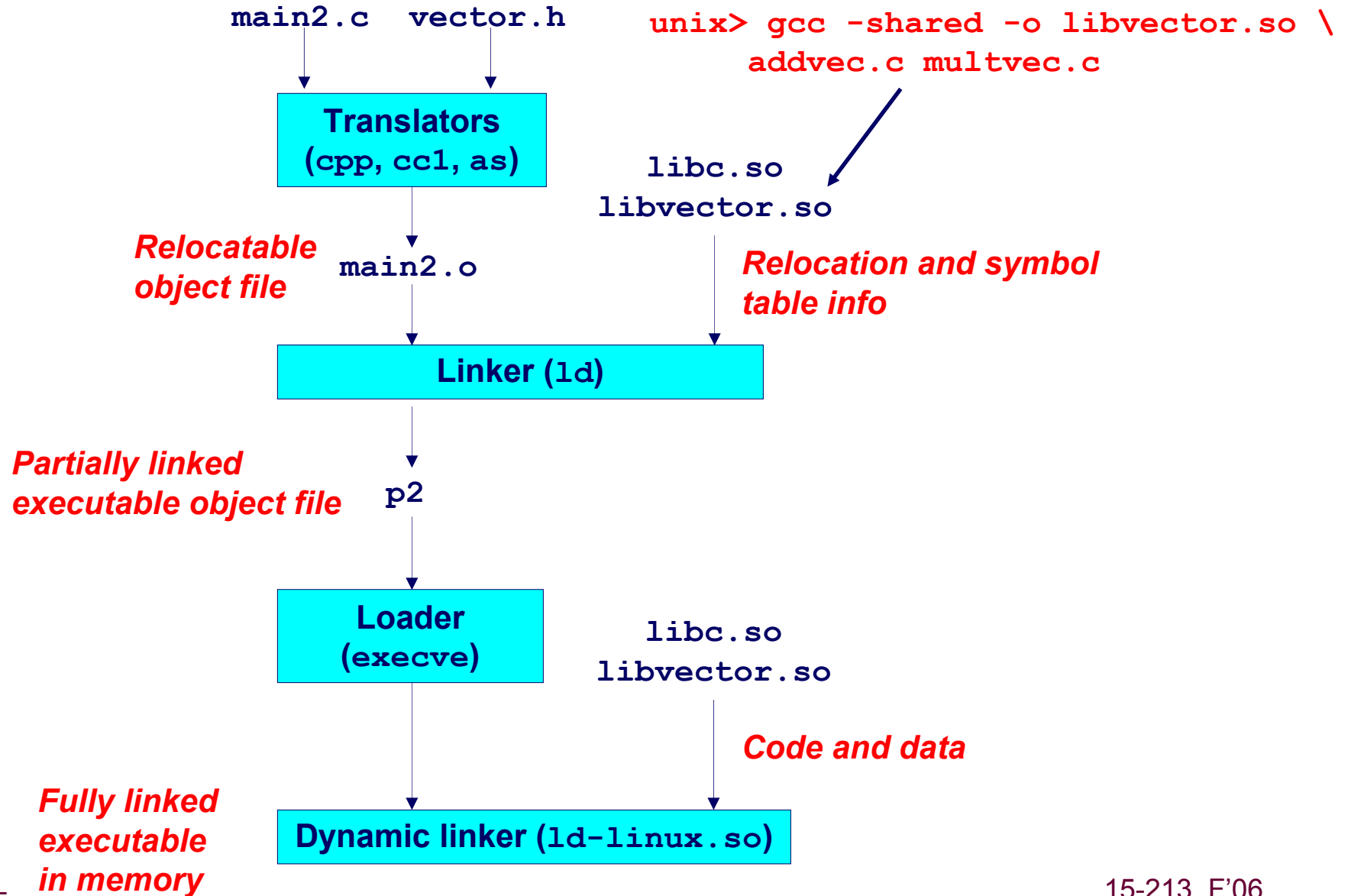
**Dynamic linking can also occur after program has begun (run-time linking).**

- In Unix, this is done by calls to the `dlopen()` interface.
  - 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 <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 lib that contains addvec() */
    handle = dlopen("./libvector.so", RTLD_LAZY);
    if (!handle) {
        fprintf(stderr, "%s\n", dlerror());
        exit(1);
    }
}
```

# 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() it 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;
}
```

# Case Study: Library Interpositioning

**Library interpositioning is a 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 linked to form an executable object file**
- **load/run time**
  - **When an executable object file is loaded into memory, dynamically linked, and then executed.**

**See Lectures page for real examples of using all three interpositioning techniques to generate malloc traces.**

# Some Interpositioning Applications

## Security

- **Confinement (sandboxing)**
  - Interpose calls to libc functions.
- **Behind the scenes encryption**
  - Automatically encrypt otherwise unencrypted network connections.

## Monitoring and Profiling

- **Count number of calls to functions**
- **Characterize call sites and arguments to functions**
- **Malloc tracing**
  - Detecting memory leaks
  - **Generating malloc traces**

# Example: malloc () Statistics

Count how much memory is allocated by a function

```
void *malloc(size_t size){
    static void *(*fp)(size_t) = 0;
    void *mp;
    char *errorstr;

    /* Get a pointer to the real malloc() */
    if (!fp) {
        fp = dlsym(RTLD_NEXT, "malloc");
        if ((errorstr = dlerror()) != NULL) {
            fprintf(stderr, "%s(): %s\n", fname, errorstr);
            exit(1);
        }
    }

    /* Call the real malloc function */
    mp = fp(size);

    mem_used += size;

    return mp;
}
```