Linking

15-213/18-243: Introduction to Computer Systems

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Today

- **Linking**
  - Linker mechanics: Why, How
  - Shared Libraries
  - Dynamic Libraries

Example C Program

main.c

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

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

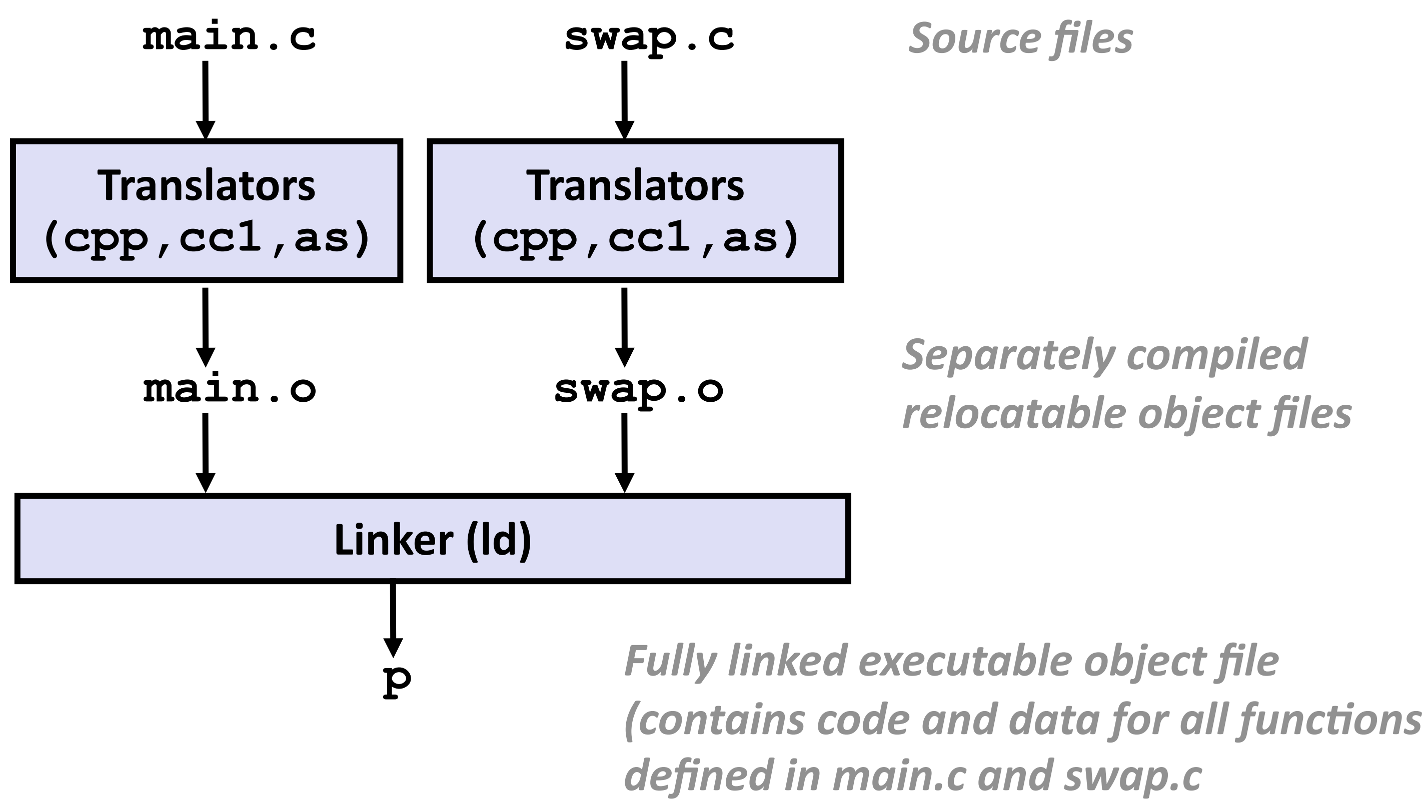
swap.c

```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? 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? 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 swap */
int *xp = &x;      /* define xp, reference x */
```

  - Symbol definitions are stored (by compiler) in a ***symbol table***
    - Symbol table is an array of structs
    - Each entry includes name, type, 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)

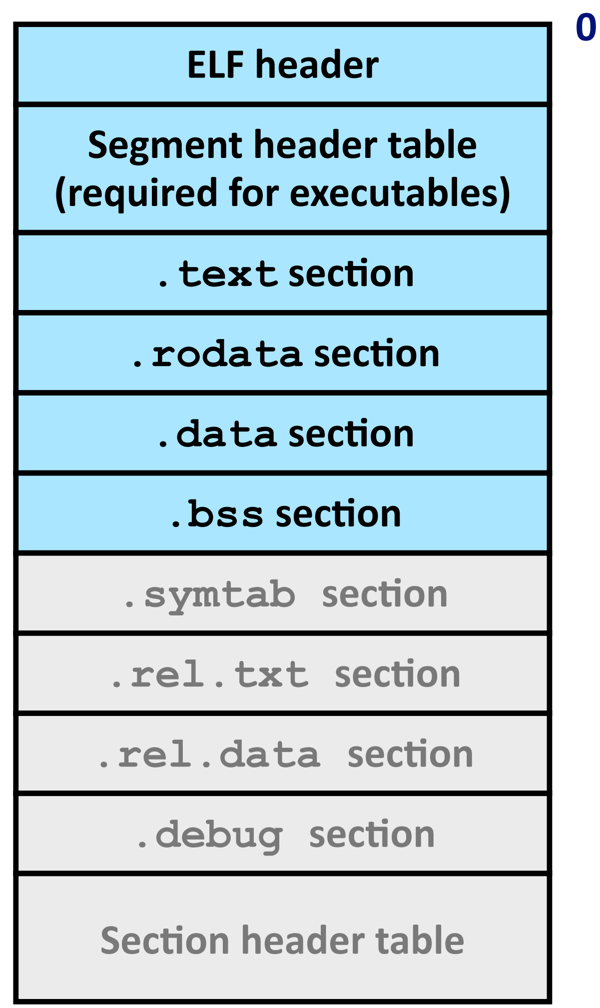
- **Executable object file**
  - Contains code and data in a form that can be copied directly into memory and then executed
- **Relocatable object file (`.o` file)**
  - Contains code and data in a form that can be combined with other relocatable object files to form executable object file
  - Each .o file is produced from *exactly one* source (.c) file
- **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**
  - Executable object files
  - Relocatable object files (`.o`)
  - Shared object files (`.so`)
- **Generic name: ELF binaries**

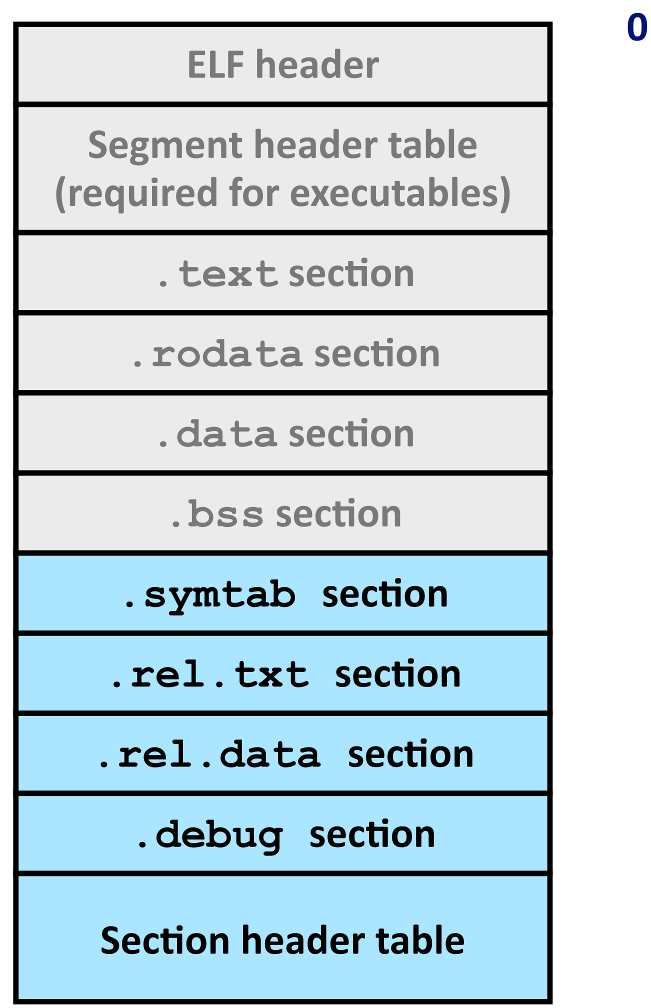
ELF Object File Format

- **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 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 merged 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 a module 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 a module but defined by some other module

- **Local symbols**
  - Symbols that are defined and referenced exclusively by a module
  - E.g.: C functions and variables defined with the `static` attribute
  - **Local linker symbols are *not* local program variables**

Global, External or Local?

main.c

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

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

swap.c

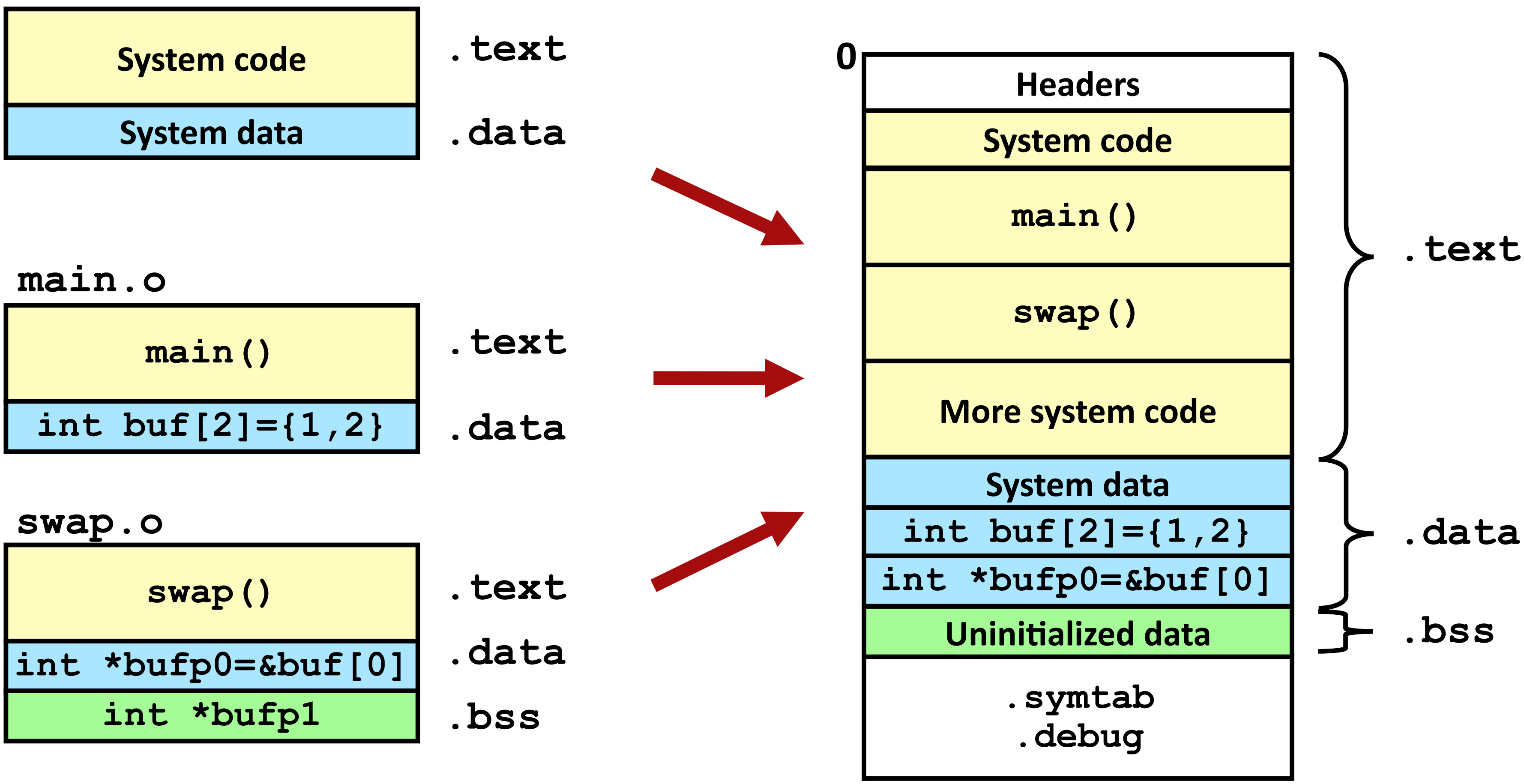
```
extern int buf[];

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

void swap()
{
   int temp;

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

- **In main.c**
  - buf
  - main
  - swap
- **In swap.c**
  - buf
  - bufp0 / bufp1
  - swap
  - temp

Relocating Code and Data

Relocatable Object Files

Executable Object File



Relocation Info (main)

main.c

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

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

main.o

```
0000000 <main>:
   0:    55                     push    %ebp
   1:    89 e5                  mov     %esp,%ebp
   3:    83 ec 08               sub     $0x8,%esp
   6:    e8 fc ff 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`

Relocation Info (swap, .text)

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;
}
```

swap.o

```
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 04movl   $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
```

Relocation Info (swap, .data)

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;
}
```

```
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

`p1.c`

```
int foo=5;

p1() {
}
```

strong → `int foo=5;`

strong → `p1() {`

`p2.c`

```
int foo;

p2() {
}
```

`int foo;` ← **weak**

`p2() {` ← **strong**

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, select one (arbitrarily)**
  - Can override this with `gcc -fno-common`

Linker Puzzles

```
int x;
p1() {}
```

```
p1() {}
```

```
int x;
p1() {}
```

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

```
int x;
int y;
p1() {}
```

```
double x;
p2() {}
```

```
int x=7;
int y=5;
p1() {}
```

```
double x;
p2() {}
```

```
int x=7;
p1() {}
```

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

Global Variables

- **Avoid if you can**

- **Otherwise**
  - Use **`static`** if you can
  - Initialize if you define a global variable
  - Use **`extern`** if you use external global variable

Packaging Commonly Used Functions

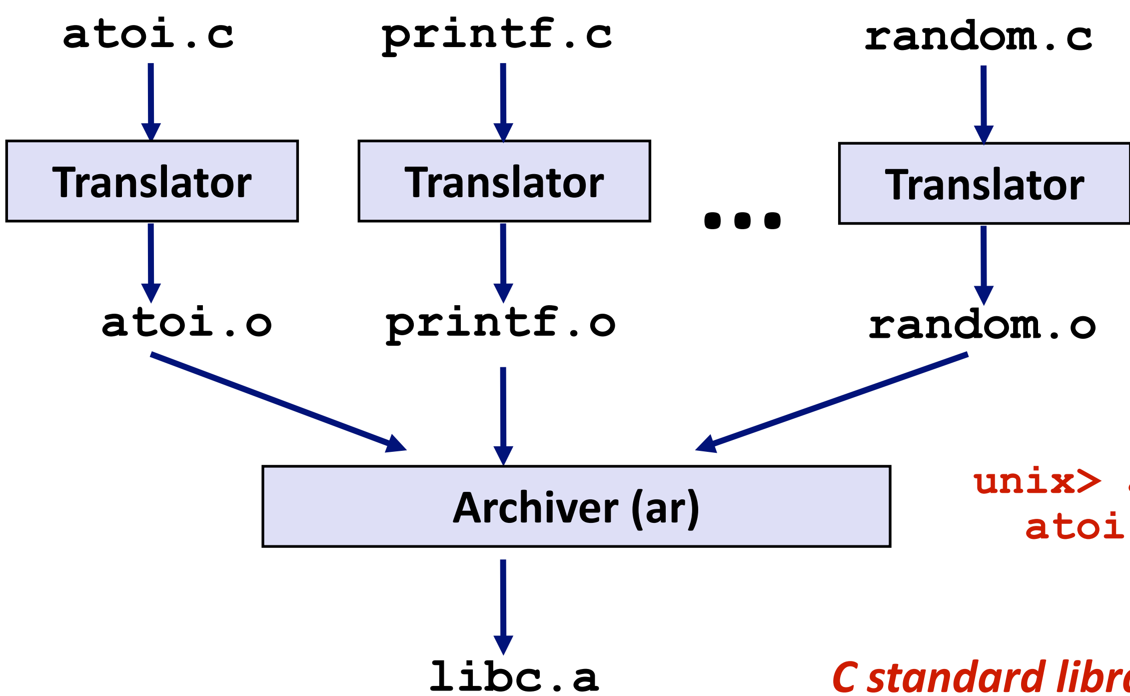
- **How to package functions commonly used by programmers?**
  - Math, I/O, memory management, string manipulation, etc.

- **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

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 into executable

Creating Static Libraries




```
unix> ar rs libc.a \
  atoi.o printf.o … random.o
```

C standard library

- Archiver allows incremental updates
- Recompile function that changes and replace `.o` file in archive

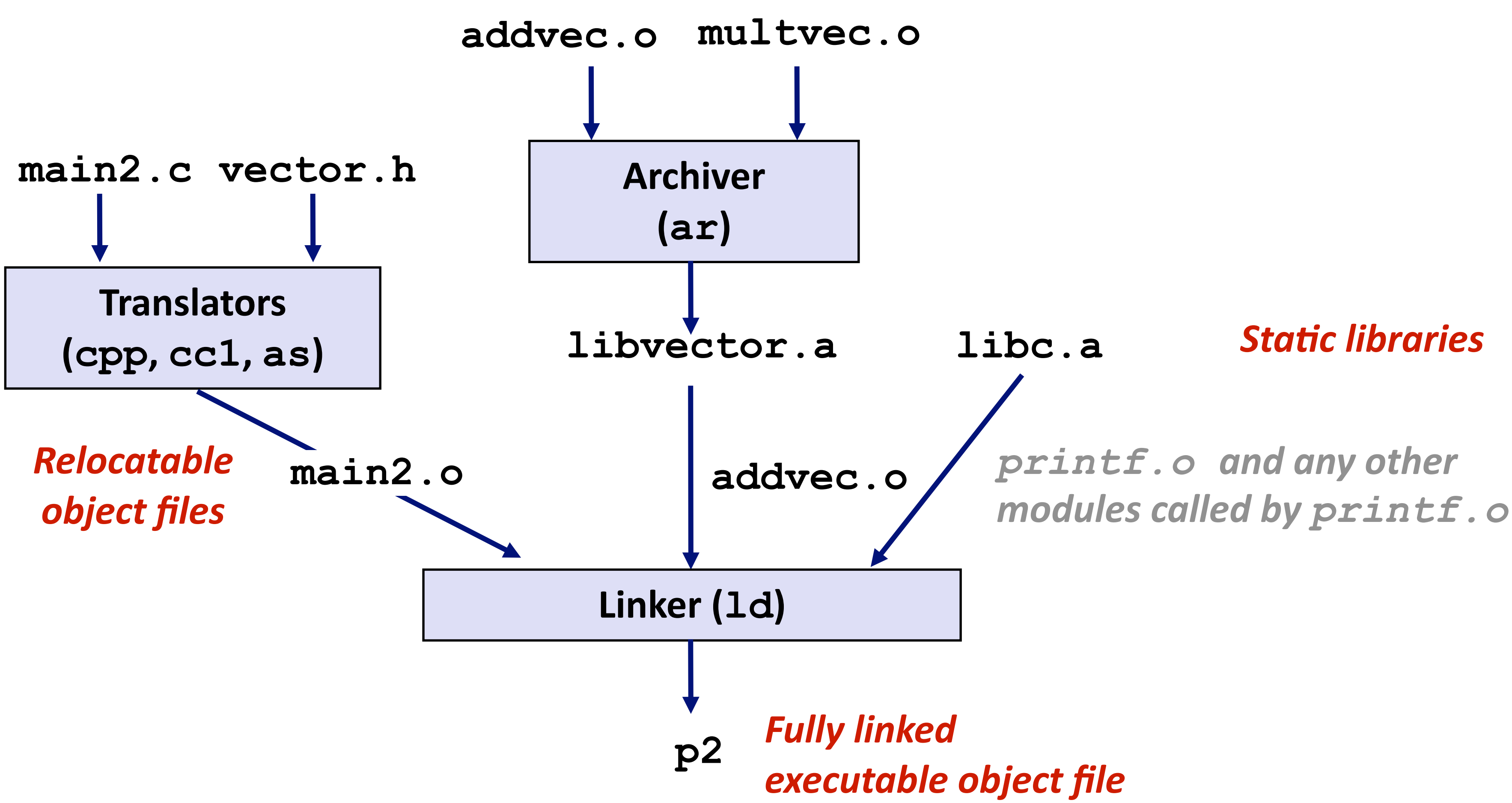
Commonly Used Libraries

- **`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
…
```

```
% 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
…
```

Linking with Static Libraries



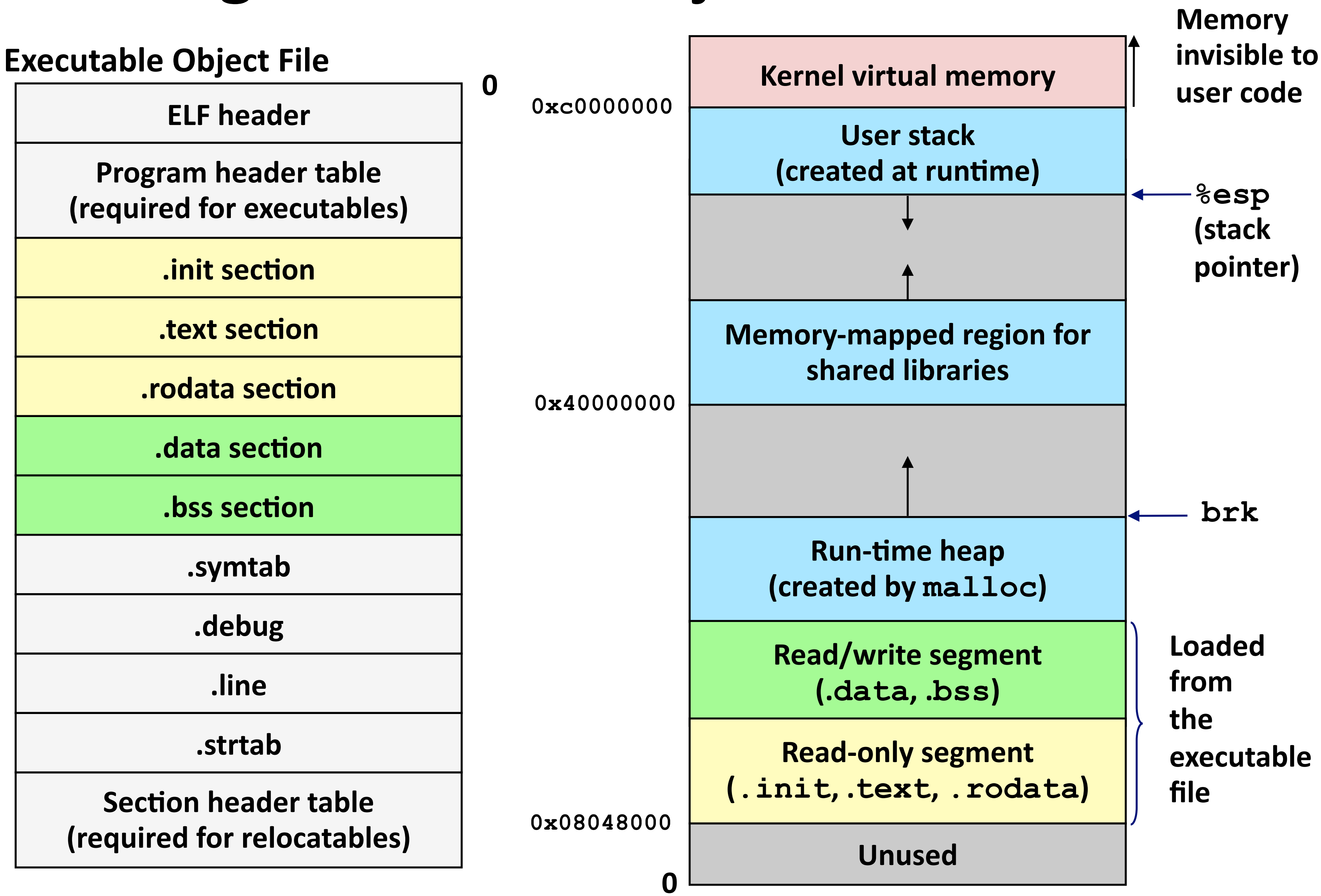
Using Static Libraries

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

Loading Executable Object Files



Shared Libraries

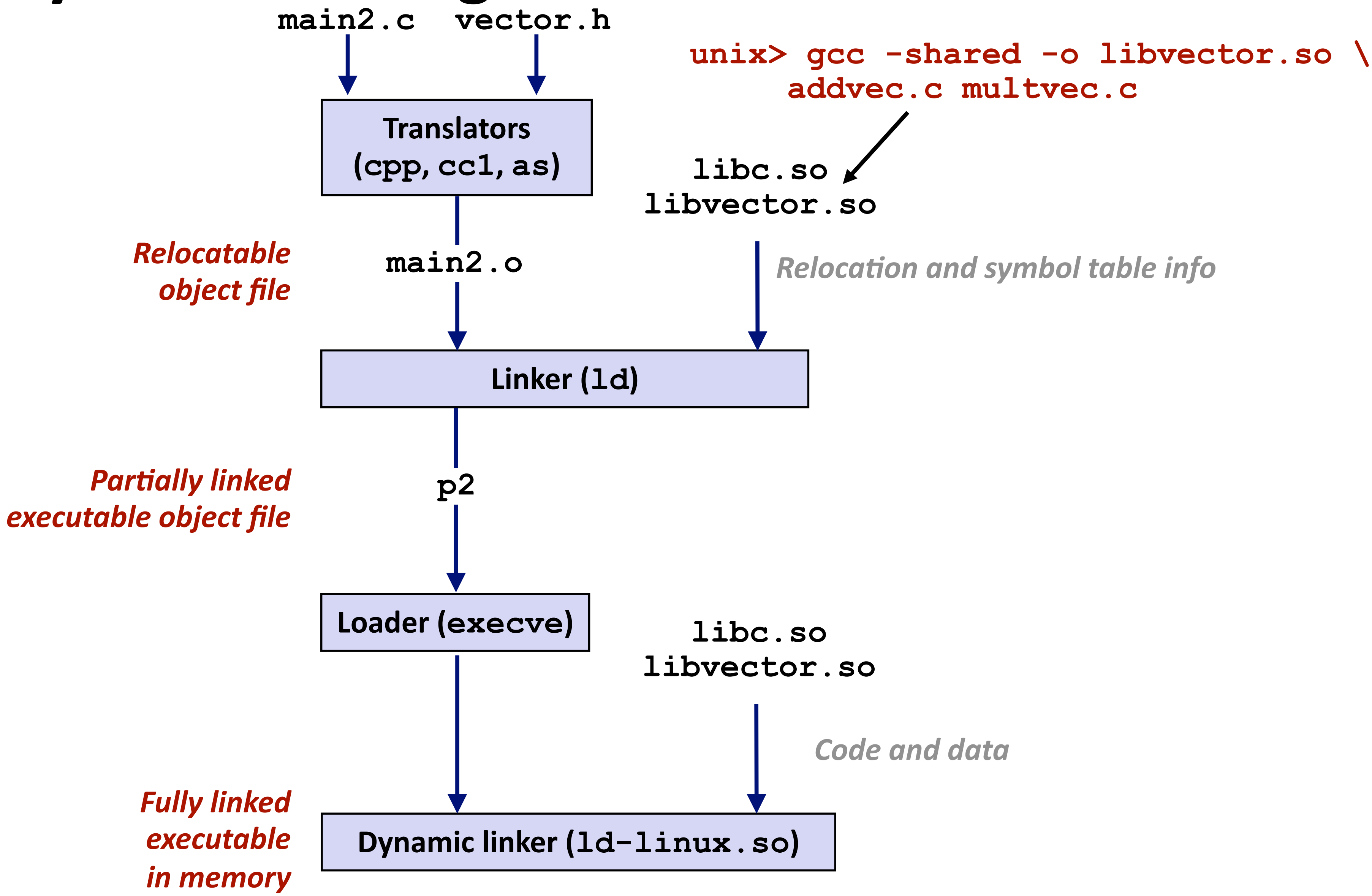
- **Static libraries have the following disadvantages:**
  - Duplication in the stored executables (every function need std libc)
  - Duplication in the running executables
  - Minor bug fixes of system libraries require each application to explicitly relink

- **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 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 Runtime

```
#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;
}
```

Summary

- **Linking**
  - Linker mechanics
  - Shared libraries
  - Dynamic Libraries

- **Next Time:**
  - Web Services