Multiple file linking in C: A short detour

Ack: Example from slides on **Linking**

15-213: Introduction to Computer Systems
11th Lecture, Sept. 30, 2010

Instructors:
Randy Bryant and Dave O'Hallaron

1

Multiple file linking in C: A short detour

```c
/* main.c */
#include <stdio.h>

void swap();

int buf[2] = {0x137, 0x291};

int main()
{
    printf("%d, %d\n", buf[0], buf[1]);
    swap();
    printf("%d, %d\n", buf[0], buf[1]);
    return 0;
}
```

Ack: Example from slides on **Linking**

15-213: Introduction to Computer Systems
11th Lecture, Sept. 30, 2010

Instructors:
Randy Bryant and Dave O'Hallaron

1

Multiple file linking in C: A short detour

```c
/* main.c */
#include <stdio.h>

void swap();

int buf[2] = {0x137, 0x291};

int main()
{
    printf("%d, %d\n", buf[0], buf[1]);
    swap();
    printf("%d, %d\n", buf[0], buf[1]);
    return 0;
}
```

```c
/* swap.c */
extern int buf[];

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

#define BADVALUE 0x999

void swap()
{
    int temp = BADVALUE;

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

Ack: Example from slides on **Linking**

15-213: Introduction to Computer Systems
11th Lecture, Sept. 30, 2010

Instructors:
Randy Bryant and Dave O'Hallaron

1

How to get an executable program from multiple C files?

4

gcc options

gcc options

- Preprocessing only

```
gcc –E main.c
```

-- Output on stdout

gcc options

- Preprocessing only

```
gcc –E main.c
```

-- Output on stdout

- Object code generation

```
gcc –c main.c
```

-- Generates main.o

gcc options

- Preprocessing only

```
gcc –E main.c
```

-- Output on stdout

- Object code generation

```
gcc –c main.c
```

-- Generates main.o

- Assembly code generation

```
gcc –S main.c
```

-- Generates main.s

gcc options

- Preprocessing only

```
gcc –E main.c
```

-- Output on stdout

- Object code generation

```
gcc –c main.c
```

-- Generates main.o

- Assembly code generation

```
gcc –S main.c
```

-- Generates main.s

- Full compilation only

```
gcc main.c swap.c
```

-- Generates a.out

5

gcc options

- Use –g option to enable debugging

6

objdump

- Usage: objdump <option(s)> <file(s)>
- Display information from object <file(s)>

7

objdump

- Usage: objdump <option(s)> <file(s)>
- Display information from object <file(s)>

```
objdump –d a.out
```

-- dump only .text section

7

objdump

- Usage: objdump <option(s)> <file(s)>
- Display information from object <file(s)>

```
objdump -d a.out
objdump -D a.out
```

-- dump only .text section
-- dump all sections

objdump

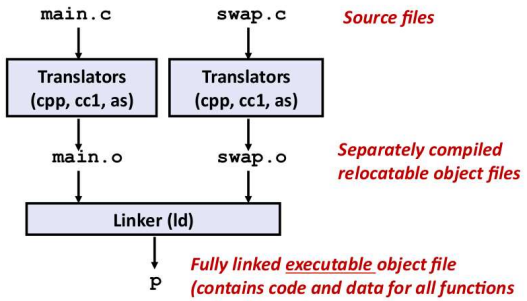
- Usage: objdump <option(s)> <file(s)>
- Display information from object <file(s)>

```
objdump -d a.out
objdump -D a.out
objdump -S swap.o
```

-- dump only .text section
-- dump all sections
-- If .o is created with –g display source statements

Static Linking

- **Programs are translated and linked using a *compiler driver*:**
  - `unix> gcc -O2 -g -o p main.c swap.c`
  - `unix> ./p`



Ack: Bryant & O'Hallaron

Multiple File Linking : WHY?

- Modularity
  - How?
- Efficiency
  - How?

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 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)

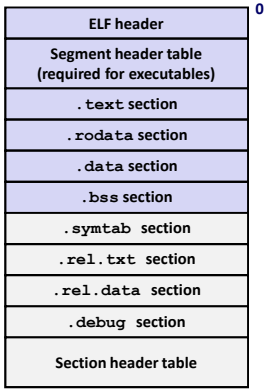
- **Relocatable object file (`.o` file)**
  - Contains code and data in a form that can be combined with other relocatable object files to form executable object file.
    - Each `.o` file is produced from exactly one `.c` source
- **Executable object file (`a.out` file)**
  - Contains code and data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

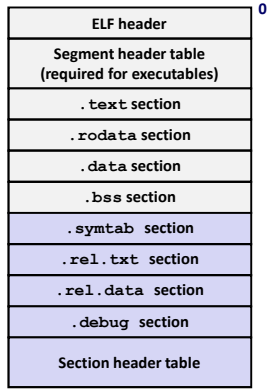
ELF Object File Format

- **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.)

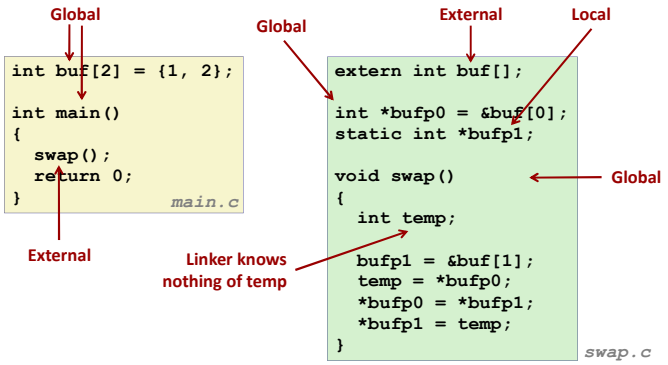
- **`.symtab` section**
  - Symbol table
  - Procedure and static variable names
  - Section names and locations
- **`.rel.text` section**
  - Relocation info for `.text` section
  - Addresses of instructions that will need to be modified in the executable
  - Instructions for modifying.
- **`.rel.data` 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



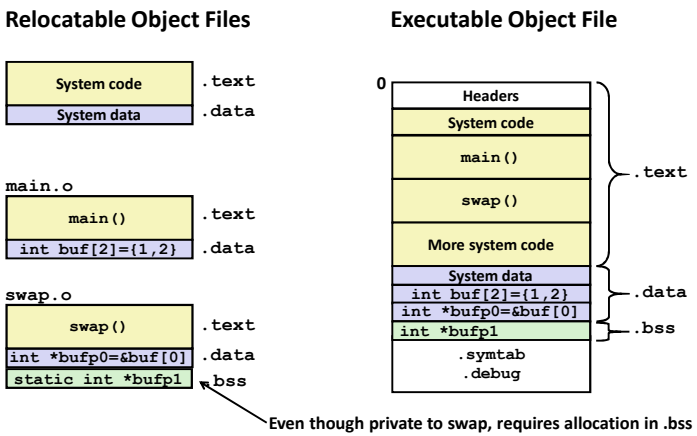
Linker Symbols

- **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 variables defined with the **`static`** attribute.
  - **Local linker symbols are *not* local program variables**

Resolving Symbols



Relocating Code and Data



Relocation Info (main)

main.c

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

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

main.o

```
0000000 <main>:
   0:   8d 4c 24 04         lea    0x4(%esp),%ecx
   4:   83 e4 f0            and    $0xfffffff0,%esp
   7:   ff 71 fc            pushl  0xfffffffc(%ecx)
   a:   55                  push   %ebp
   b:   89 e5               mov    %esp,%ebp
   d:   51                  push   %ecx
   e:   83 ec 04            sub    $0x4,%esp
  11:   e8 fc ff ff ff      call   12 <main+0x12>
                            12: R_386_PC32 swap
  16:   83 c4 04            add    $0x4,%esp
  19:   31 c0               xor    %eax,%eax
  1b:   59                  pop    %ecx
  1c:   5d                  pop    %ebp
  1d:   8d 61 fc            lea    0xfffffffc(%ecx),%esp
  20:   c3                  ret
```

Source: `objdump -r -d`

```
Disassembly of section .data:

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

Relocation Info (swap, `.text`)

swap.c

```
extern int buf[];

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:   8b 15 00 00 00 00       mov    0x0,%edx
                                2: R_386_32    buf
   6:   a1 04 00 00 00          mov    0x4,%eax
                                7: R_386_32    buf
   b:   55                      push   %ebp
   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   .bss
                                14: R_386_32   buf
  18:   8b 08                   mov    (%eax),%ecx
  1a:   89 10                   mov    %edx,(%eax)
  1c:   5d                      pop    %ebp
  1d:   89 0d 04 00 00 00       mov    %ecx,0x4
                                1f: R_386_32   buf
  23:   c3                      ret
```

Relocation Info (swap, `.data`)

swap.c

```
extern int buf[];

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 Before/After Relocation (.text)

```
0000000 <main>:
   . . .
   e:   83 ec 04          sub    $0x4,%esp
  11:   e8 fc ff ff ff    call   12 <main+0x12>
                        12: R_386_PC32 swap
  16:   83 c4 04          add    $0x4,%esp
   . . .
```

0x8048396 + 0x1a
= 0x80483b0

```
08048380 <main>:
 8048380:       8d 4c 24 04             lea    0x4(%esp),%ecx
 8048384:       83 e4 f0                and    $0xfffffff0,%esp
 8048387:       ff 71 fc                pushl  0xfffffffc(%ecx)
 804838a:       55                      push   %ebp
 804838b:       89 e5                   mov    %esp,%ebp
 804838d:       51                      push   %ecx
 804838e:       83 ec 04                sub    $0x4,%esp
 8048391:       e8 1a 00 00 00          call   80483b0 <swap>
 8048396:       83 c4 04                add    $0x4,%esp
 8048399:       31 c0                   xor    %eax,%eax
 804839b:       59                      pop    %ecx
 804839c:       5d                      pop    %ebp
 804839d:       8d 61 fc                lea    0xfffffffc(%ecx),%esp
 80483a0:       c3                      ret
```

```
   0:   8b 15 00 00 00 00       mov    0x0,%edx
                        2: R_386_32     buf
   6:   a1 04 00 00 00          mov    0x4,%eax
                        7: R_386_32     buf
   ...
   e:   c7 05 00 00 00 00 04    movl   $0x4,0x0
  15:   00 00 00
                        10: R_386_32    .bss
                        14: R_386_32    buf
   . . .
  1d:   89 0d 04 00 00 00       mov    %ecx,0x4
                        1f: R_386_32    buf
  23:   c3                      ret
```

```
080483b0 <swap>:
 80483b0:       8b 15 20 96 04 08       mov    0x8049620,%edx
 80483b6:       a1 24 96 04 08          mov    0x8049624,%eax
 80483bb:       55                      push   %ebp
 80483bc:       89 e5                   mov    %esp,%ebp
 80483be:       c7 05 30 96 04 08 24    movl   $0x8049624,0x8049630
 80483c5:       96 04 08
 80483c8:       8b 08                   mov    (%eax),%ecx
 80483ca:       89 10                   mov    %edx,(%eax)
 80483cc:       5d                      pop    %ebp
 80483cd:       89 0d 24 96 04 08       mov    %ecx,0x8049624
 80483d3:       c3                      ret
```

Executable After Relocation (.data)

```
Disassembly of section .data:

08049620 <buf>:
 8049620:       01 00 00 00 02 00 00 00

08049628 <bufp0>:
 8049628:       20 96 04 08
```

Strong and Weak Symbols

- **Program symbols are either strong or weak**
  - ***Strong***: procedures and initialized globals
  - ***Weak***: uninitialized globals

	p1.c	p2.c	
strong	`int foo=5;`	`int foo;`	weak
strong	`p1() { }`	`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 symbol, 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

`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.

Role of .h Files

`c1.c`

```
#include "global.h"

int f() {
  return g+1;
}
```

`global.h`

```
#ifdef INITIALIZE
int g = 23;
static int init = 1;
#else
int g;
static int init = 0;
#endif
```

`c2.c`

```
#include <stdio.h>
#include "global.h"

int main() {
  if (!init)
    g = 37;
  int t = f();
  printf("Calling f yields %d\n", t);
  return 0;
}
```

Running Preprocessor

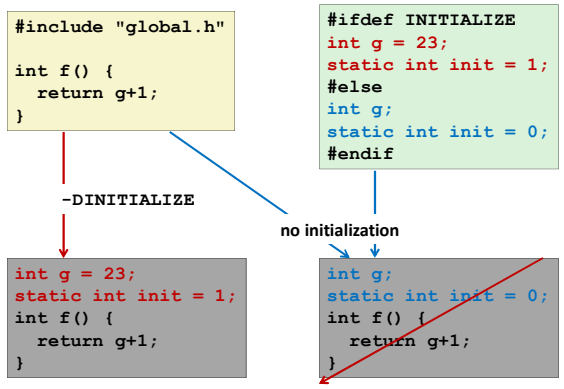
`c1.c`

```
#include "global.h"

int f() {
  return g+1;
}
```

`global.h`

```
#ifdef INITIALIZE
int g = 23;
static int init = 1;
#else
int g;
static int init = 0;
#endif
```



#include causes C preprocessor to insert file verbatim

Role of .h Files (cont.)

c1.c

```
#include "global.h"

int f() {
  return g+1;
}
```

global.h

```
#ifdef INITIALIZE
int g = 23;
static int init = 1;
#else
int g;
static int init = 0;
#endif
```

c2.c

```
#include <stdio.h>
#include "global.h"

int main() {
  if (!init)
    g = 37;
  int t = f();
  printf("Calling f yields %d\n", t);
  return 0;
}
```

What happens:

```
gcc -o p c1.c c2.c
   ??
gcc -o p c1.c c2.c \
  -DINITIALIZE
   ??
```

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

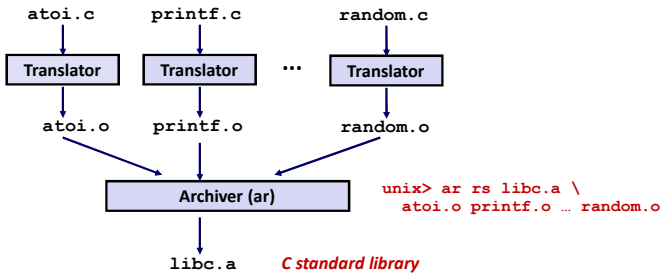
Packaging Commonly Used Functions

- **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 it into the executable.

Creating Static Libraries



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

Commonly Used Libraries

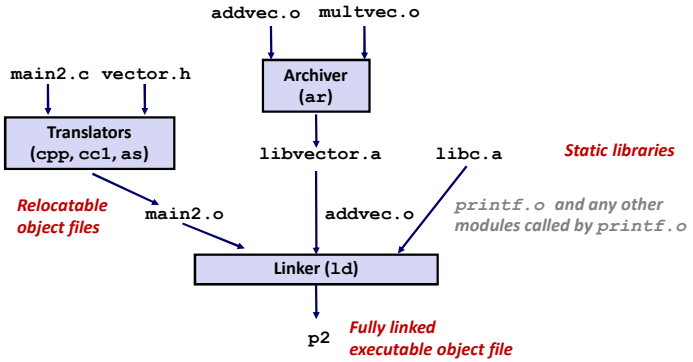
`libc.a` (the C standard library)
- 8 MB archive of 1392 object files.
- I/O, memory allocation, signal handling, string handling, data and time, random numbers, integer math

`libm.a` (the C math library)
- 1 MB archive of 401 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

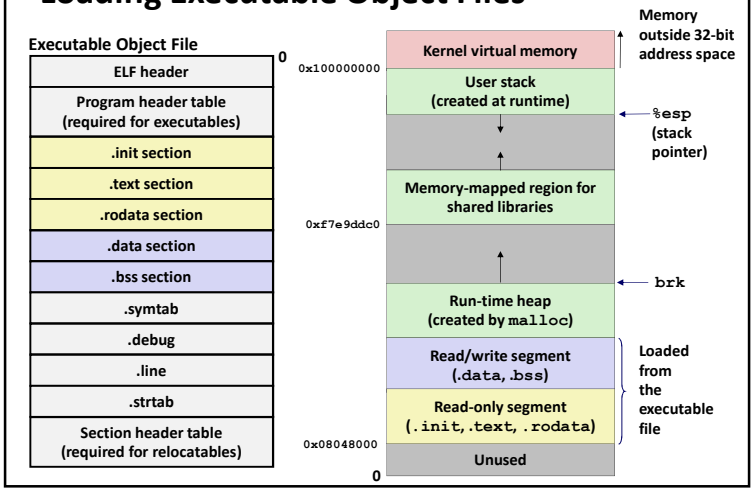


Using Static Libraries

- **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.

```
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



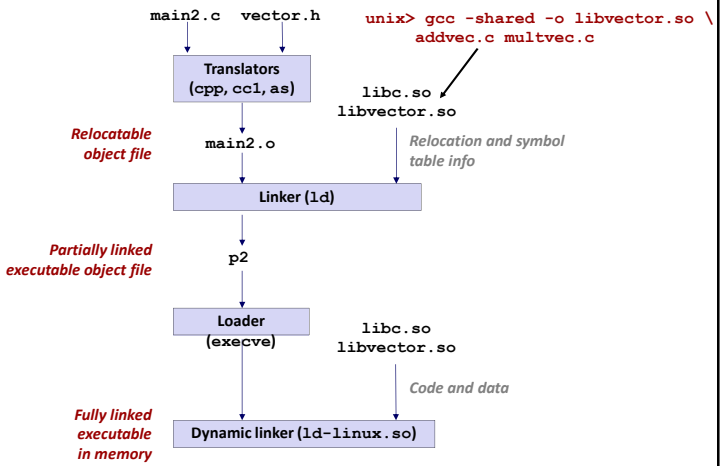
Shared Libraries

- **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 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

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

```
#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);
    }
```