Linking

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

Randy Bryant, Dave O'Hallaron, and Greg Kesden

Today

- **Linking**
- Case study: Library interpositioning

Example C Program

main.c

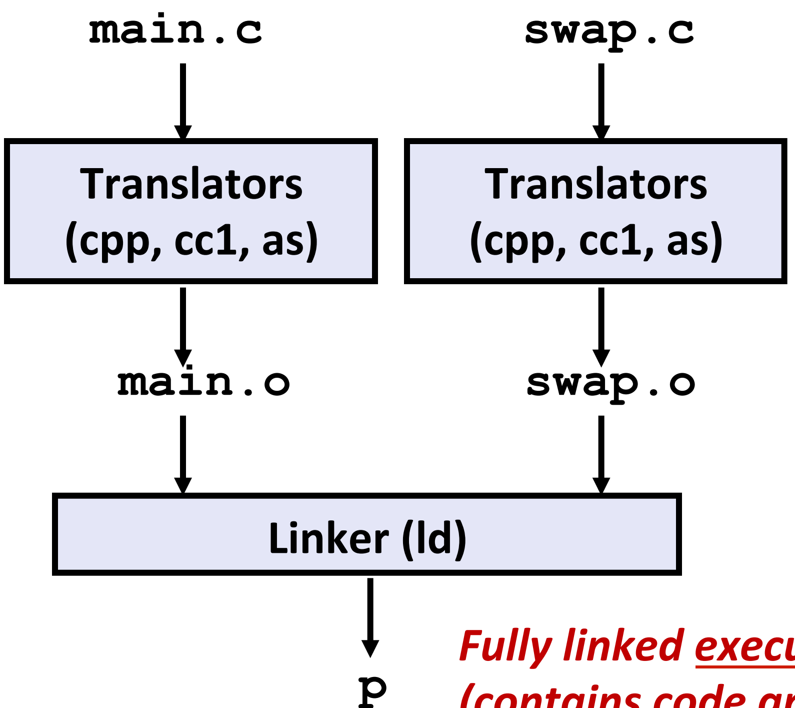
```c
int buf[2] = {1, 2};

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

swap.c

```c
extern int buf[];

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`



Source files

Separately compiled relocatable object files

Fully linked executable object file (contains code and data for all functions defined in `main.c` and `swap.c`)

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 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 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)

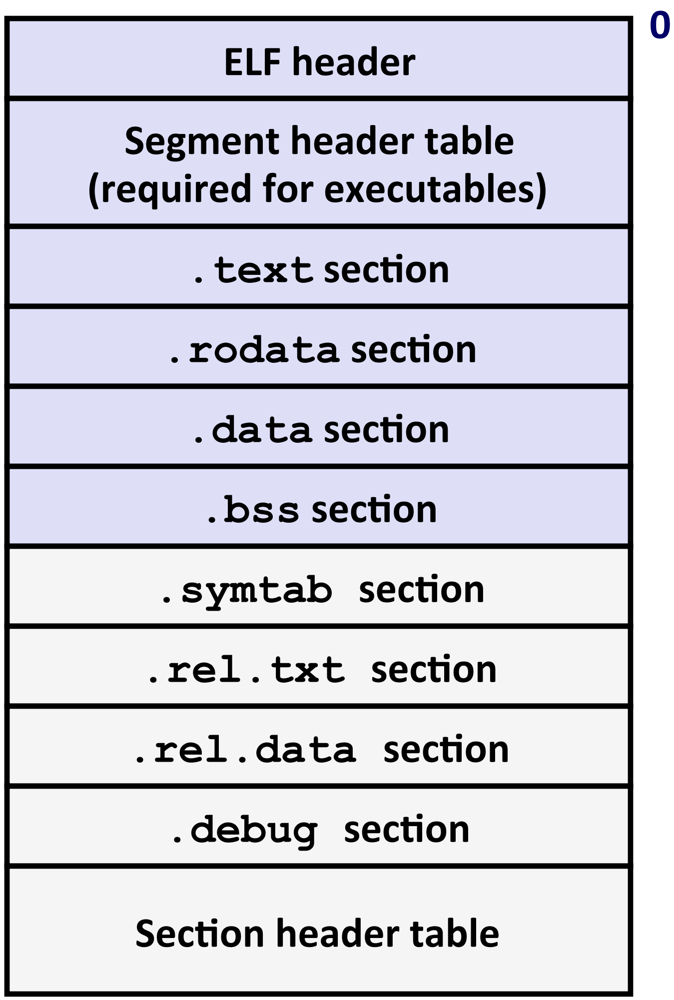
- **Standard binary format for object files**

- **One unified format for**
  - Relocatable object files (`.o`),
  - Executable object files (`a.out`)
  - Shared object files (`.so`)

- **Generic name: ELF binaries**

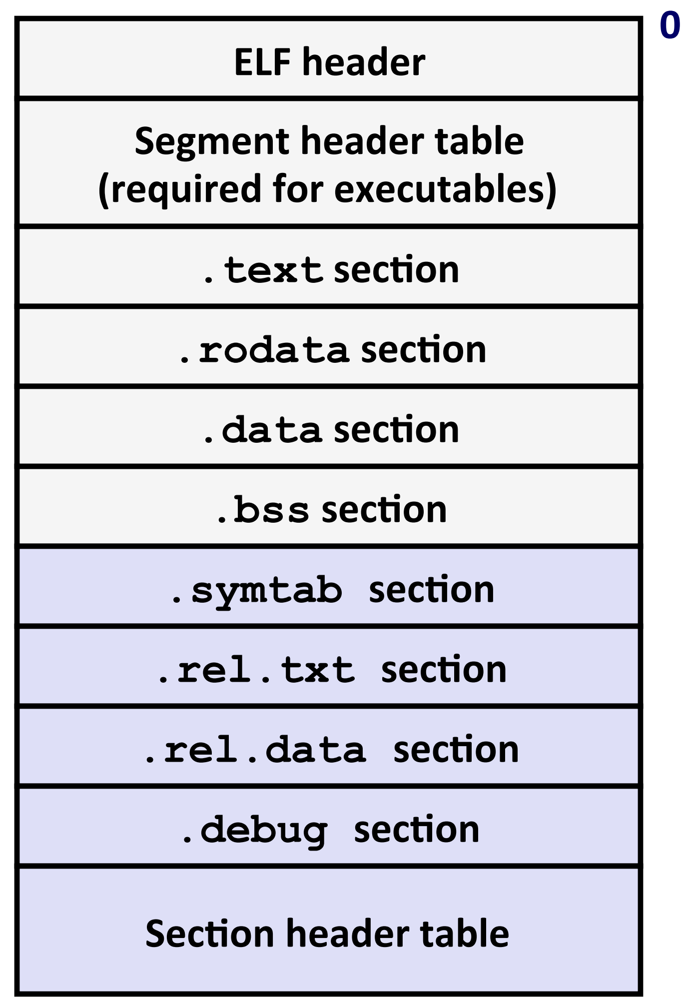
ELF Object File Format

- **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**

Resolving Symbols

Global

Global

External

Local

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

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

main.c

External

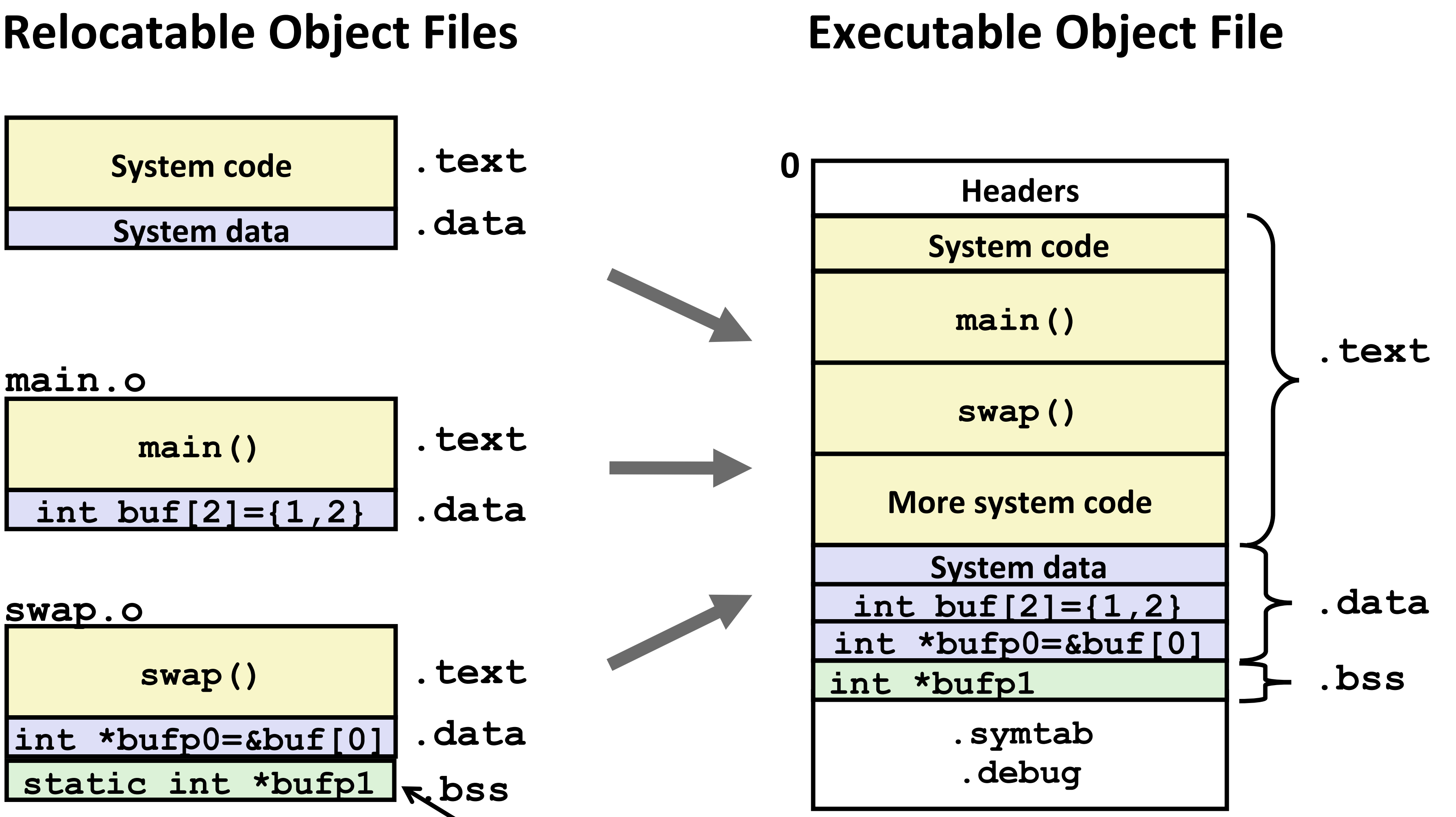
```
extern int buf[];

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

void swap()
{
   int temp;

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

Global

Linker knows nothing of temp

swap.c

Relocating Code and Data



Even though private to swap, requires allocation in .bss

Relocation Info (main)

main.c

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

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

main.o

```
00000000 <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:   b8 00 00 00 00       mov    $0x0,%eax
  1b:   83 c4 04             add    $0x4,%esp
  1e:   59                   pop    %ecx
  1f:   5d                   pop    %ebp
  20:   8d 61 fc             lea    0xfffffffc(%ecx),%esp
  23:   c3                   ret
```

-4

Source: objdump -r -d main.o

```
Disassembly of section .data:

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

Source: objdump -j .data -d main.o

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

```
00000000 <swap>:
 0:    55                          push   %ebp
 1:    89 e5                       mov    %esp,%ebp
 3:    53                          push   %ebx
 4:    c7 05 00 00 00 00 04        movl   $0x4,0x0
 b:    00 00 00
                             6: R_386_32  .bss
                             a: R_386_32  buf
 e:    8b 0d 00 00 00 00           mov    0x0,%ecx
                            10: R_386_32  bufp0
14:    8b 19                       mov    (%ecx),%ebx
16:    ba 04 00 00 00              mov    $0x4,%edx
                            17: R_386_32  buf
1b:    8b 02                       mov    (%edx),%eax
1d:    89 01                       mov    %eax,(%ecx)
1f:    89 1a                       mov    %ebx,(%edx)
21:    5b                          pop    %ebx
22:    5d                          pop    %ebp
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)

```
00000000 <main>:
...
   e:    83 ec 04             sub    $0x4,%esp
  11:    e8 fc ff ff ff       call   12 <main+0x12>
                           12: R_386_PC32   swap
  16:    b8 00 00 00 00       mov    $0x0,%eax
 ...
```

Link time:

0x8048398 + (-4)
- 0x8048386 = 0xe

Runtime:

0x804838a + 0xe
= 0x8048398

```
08048374 <main>:
 8048374:       8d 4c 24 04             lea    0x4(%esp),%ecx
 8048378:       83 e4 f0                and    $0xfffffff0,%esp
 804837b:       ff 71 fc                pushl  0xfffffffc(%ecx)
 804837e:       55                      push   %ebp
 804837f:       89 e5                   mov    %esp,%ebp
 8048381:       51                      push   %ecx
 8048382:       83 ec 04                sub    $0x4,%esp
 8048385:       e8 0e 00 00 00          call   8048398 <swap>
 804838a:       b8 00 00 00 00          mov    $0x0,%eax
 804838f:       83 c4 04                add    $0x4,%esp
 8048392:       59                      pop    %ecx
 8048393:       5d                      pop    %ebp
 8048394:       8d 61 fc                lea    0xfffffffc(%ecx),%esp
 8048397:       c3                      ret
```

Before relocation

```
00000000 <swap>:
...
 4:   c7 05 00 00 00 00 04    movl    $0x4,0x0
 b:   00 00 00
                      6: R_386_32   .bss
                      a: R_386_32   buf
 e:   8b 0d 00 00 00 00       mov     0x0,%ecx
                     10: R_386_32   bufp0
14:   8b 19                   mov     (%ecx),%ebx
16:   ba 04 00 00 00          mov     $0x4,%edx
                     17: R_386_32   buf
```

After relocation

```
08048398 <swap>:
 8048398:     55                         push   %ebp
 8048399:     89 e5                      mov    %esp,%ebp
 804839b:     53                         push   %ebx
 804839c:     c7 05 14 96 04 08 04       movl   $0x8049604,0x8049614
 80483a3:     96 04 08
 80483a6:     8b 0d 08 96 04 08          mov    0x8049608,%ecx
 80483ac:     8b 19                      mov    (%ecx),%ebx
 80483ae:     ba 04 96 04 08             mov    $0x8049604,%edx
 80483b3:     8b 02                      mov    (%edx),%eax
 80483b5:     89 01                      mov    %eax,(%ecx)
 80483b7:     89 1a                      mov    %ebx,(%edx)
 80483b9:     5b                         pop    %ebx
 80483ba:     5d                         pop    %ebp
 80483bb:     c3                         ret
```

Executable After Relocation (.data)

```
Disassembly of section .data:
08049600 <buf>:
 8049600:       01 00 00 00 02 00 00 00

08049608 <bufp0>:
 8049608:       00 96 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() {
}
```

weak (`int foo;`)
strong (`p2() {`)

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
```

-DINITIALIZE

```
int g = 23;
static int init = 1;
int f() {
  return g+1;
}
```

no initialization

```
int g;
static int init = 0;
int f() {
  return g+1;
}
```

`#include` causes C preprocessor to insert file verbatim (Use `gcc -E` to view result)

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

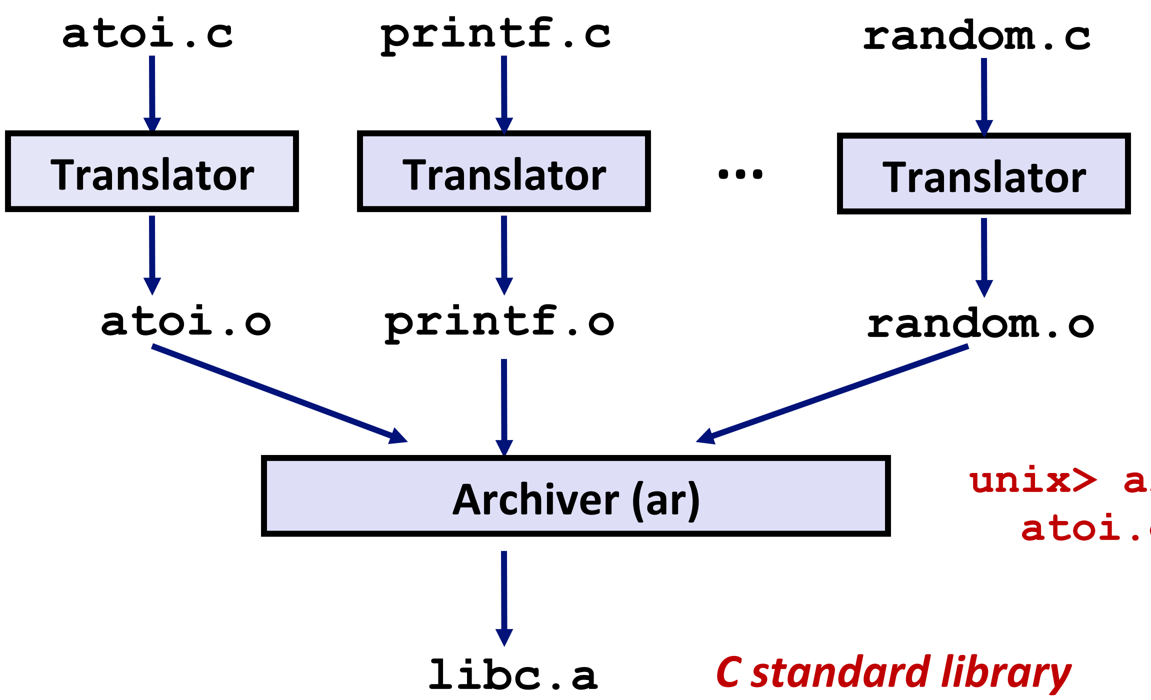
- **How to package functions commonly used by programmers?**
  - Math, I/O, memory management, string manipulation, etc.

- **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




```
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 1392 object files.
- I/O, memory allocation, signal handling, string handling, data and time, random numbers, integer math

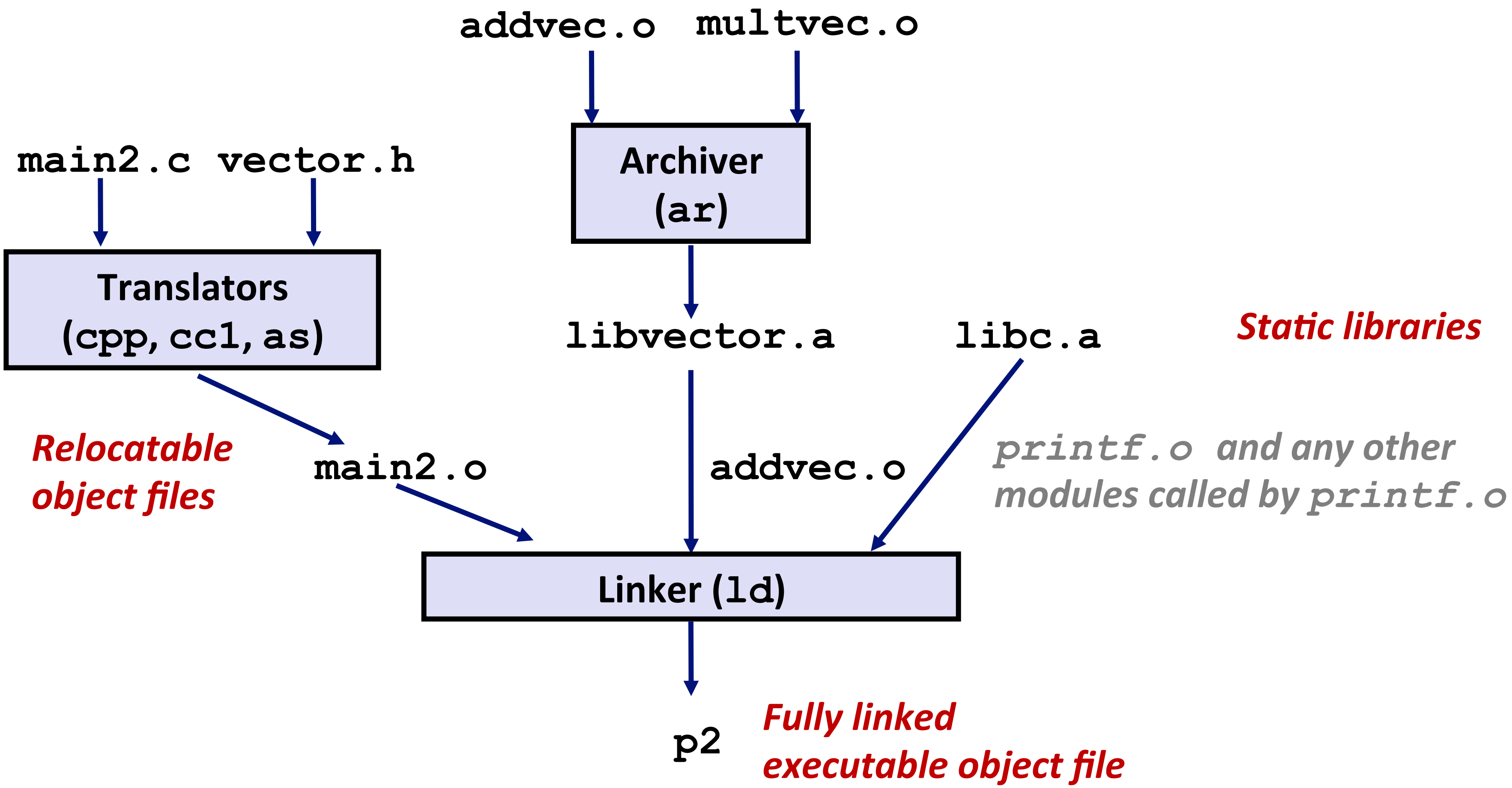
`libm.a` (the C math library)

- 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

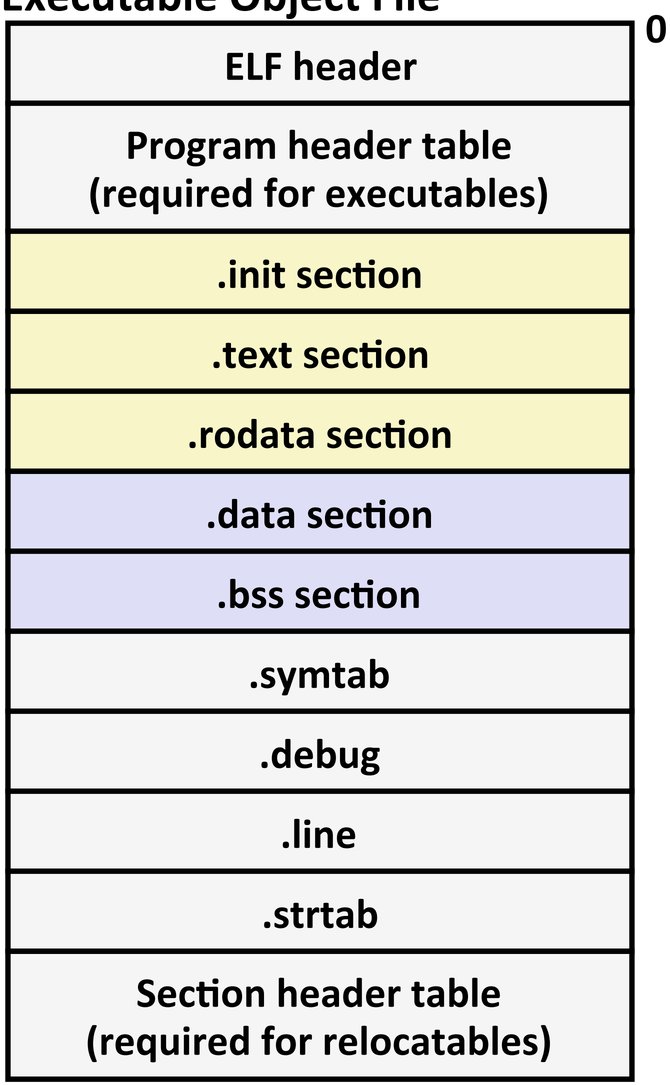
- **Linker's algorithm for resolving external references:**
  - Scan `.o` files and `.a` files in the command line order.
  - During the scan, keep a list of the current unresolved references.
  - As each new `.o` or `.a` file, *obj*, is encountered, try to resolve each unresolved reference in the list against the symbols defined in *obj*.
  - If any entries in the unresolved list at end of scan, then error.

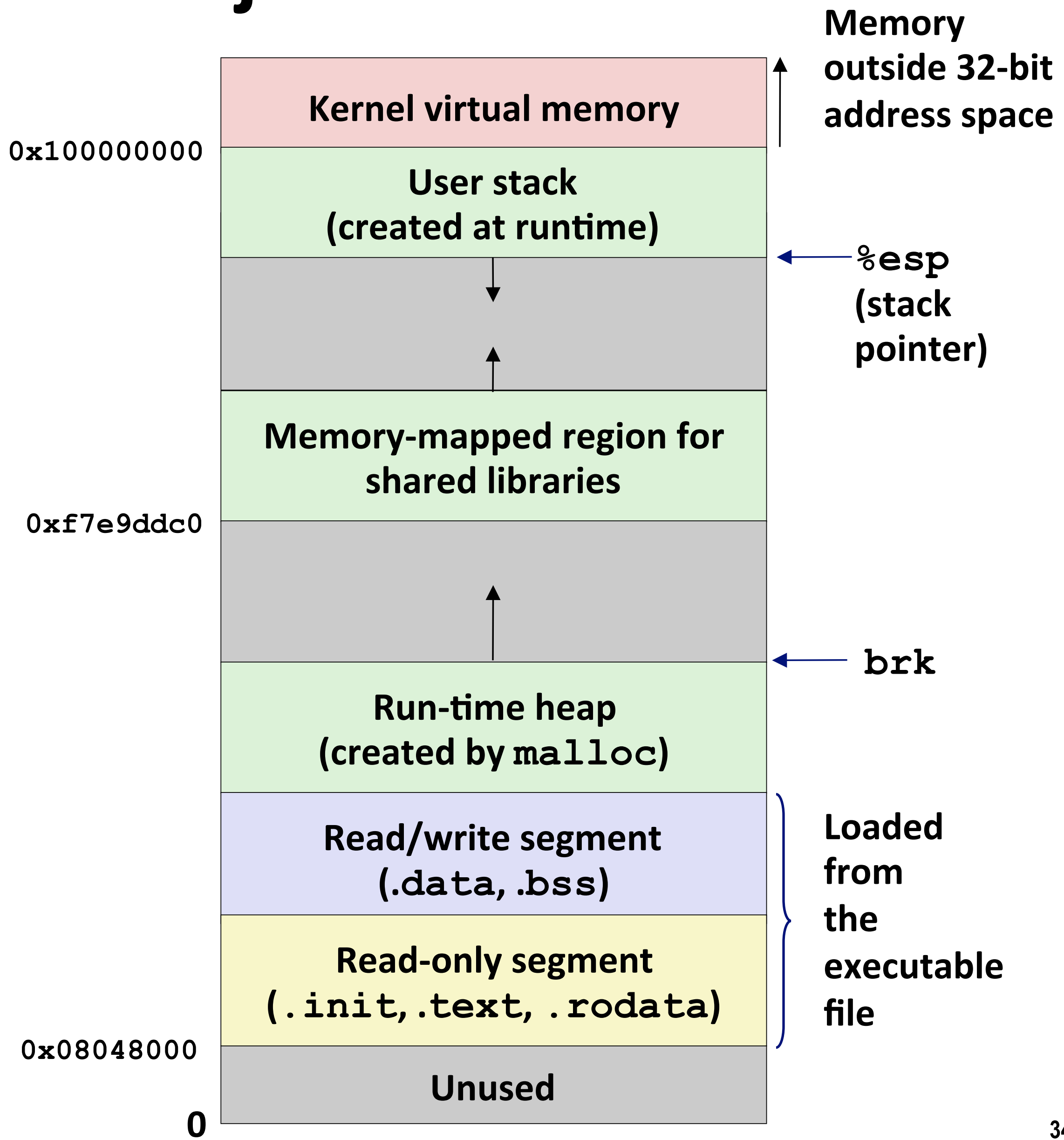
- **Problem:**
  - Command line order matters!
  - Moral: put libraries at the end of the command line.

```
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

Executable Object File





Shared Libraries

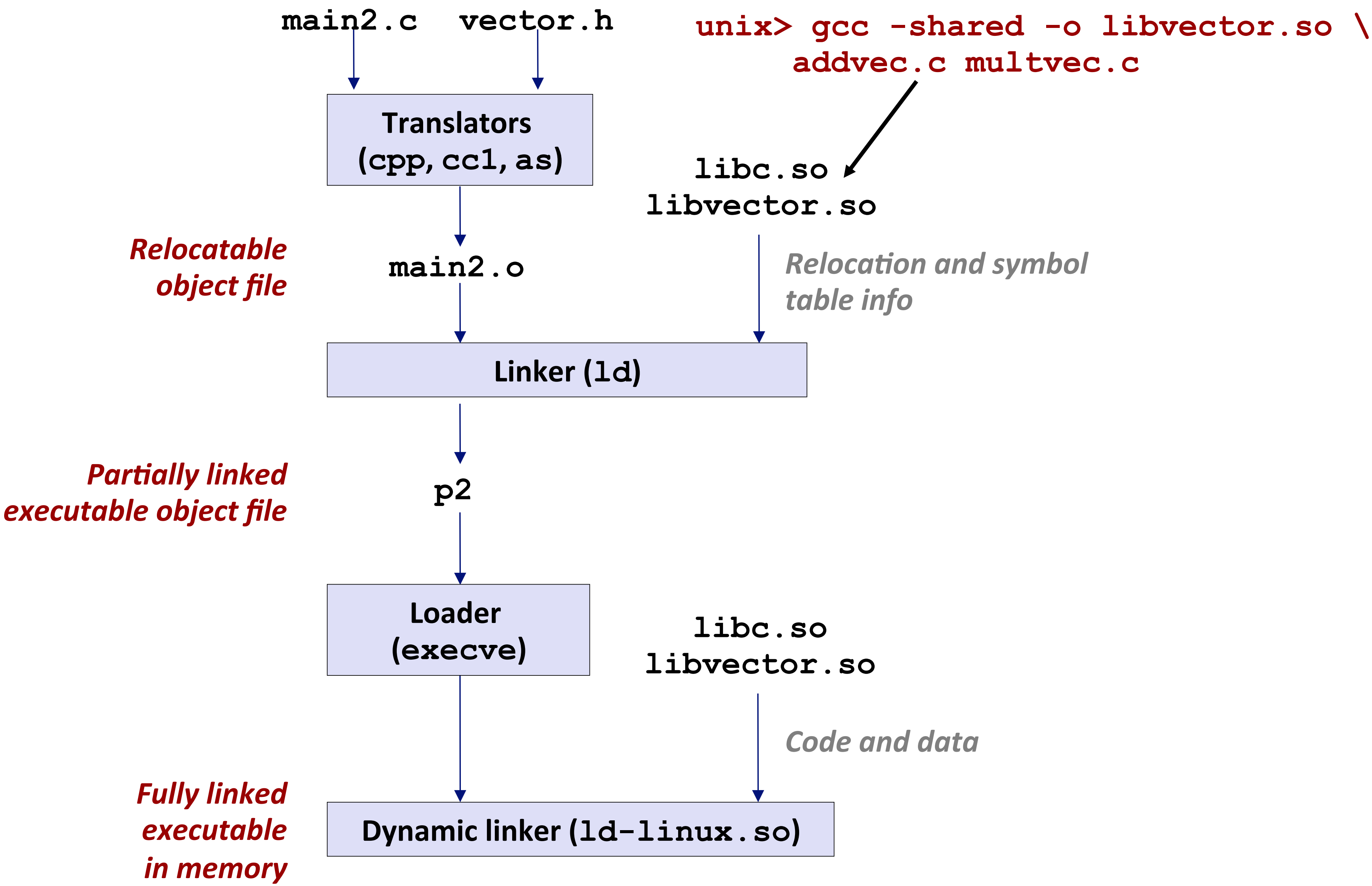
- **Static libraries have the following disadvantages:**
  - Duplication in the stored executables (every function need std libc)
  - Duplication in the running executables
  - Minor bug fixes of system libraries require each application to explicitly relink

- **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

```
    ...

    /* 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;
}
```

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

- **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)
    - 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 address traces**

Example program

```c
#include <stdio.h>
#include <stdlib.h>
#include <malloc.h>

int main()
{
    free(malloc(10));
    printf("hello, world\n");
    exit(0);
}
```
hello.c

- Goal: trace the addresses and sizes of the allocated and freed blocks, without modifying the source code.
- Three solutions: interpose on the `lib` `malloc` and `free` functions at compile time, link time, and load/run time.

Compile-time Interpositioning

```
#ifdef COMPILETIME
/* Compile-time interposition of malloc and free using C
 * preprocessor. A local malloc.h file defines malloc (free)
 * as wrappers mymalloc (myfree) respectively.
 */

#include <stdio.h>
#include <malloc.h>

/*
 * mymalloc - malloc wrapper function
 */
void *mymalloc(size_t size, char *file, int line)
{
    void *ptr = malloc(size);
    printf("%s:%d: malloc(%d)=%p\n", file, line, (int)size,
ptr);
    return ptr;
}
```

mymalloc.c

Compile-time Interpositioning

```
#define malloc(size) mymalloc(size, __FILE__, __LINE__ )
#define free(ptr) myfree(ptr, __FILE__, __LINE__ )

void *mymalloc(size_t size, char *file, int line);
void myfree(void *ptr, char *file, int line);
                                                    malloc.h
```

```
linux> make helloc
gcc -O2 -Wall -DCOMPILETIME -c mymalloc.c
gcc -O2 -Wall -I. -o helloc hello.c mymalloc.o
linux> make runc
./helloc
hello.c:7: malloc(10)=0x501010
hello.c:7: free(0x501010)
hello, world
```

Link-time Interpositioning

```
#ifdef LINKTIME
/* Link-time interposition of malloc and free using the
static linker's (ld) "--wrap symbol" flag. */

#include <stdio.h>

void *__real_malloc(size_t size);
void __real_free(void *ptr);

/*
 * __wrap_malloc - malloc wrapper function
 */
void *__wrap_malloc(size_t size)
{
    void *ptr = __real_malloc(size);
    printf("malloc(%d) = %p\n", (int)size, ptr);
    return ptr;
}
```

mymalloc.c

Link-time Interpositioning

```
linux> make hellol
gcc -O2 -Wall -DLINKTIME -c mymalloc.c
gcc -O2 -Wall -Wl,--wrap,malloc -Wl,--wrap,free \
-o hellol hello.c mymalloc.o
linux> make runl
./hellol
malloc(10) = 0x501010
free(0x501010)
hello, world
```

- **The "`-Wl`" flag passes argument to linker**
- **Telling linker "`--wrap,malloc`" tells it 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`

```c
#ifdef RUNTIME
 /* Run-time interposition of malloc and free based on
 * dynamic linker's (ld-linux.so) LD_PRELOAD mechanism */
#define _GNU_SOURCE
#include <stdio.h>
#include <stdlib.h>
#include <dlfcn.h>

void *malloc(size_t size)
{
    static void *(*mallocp)(size_t size);
    char *error;
    void *ptr;

    /* get address of libc malloc */
    if (!mallocp) {
        mallocp = dlsym(RTLD_NEXT, "malloc");
        if ((error = dlerror()) != NULL) {
            fputs(error, stderr);
            exit(1);
        }
    }
    ptr = mallocp(size);
    printf("malloc(%d) = %p\n", (int)size, ptr);
    return ptr;
}
```

mymalloc.c

Load/Run-time Interpositioning

Load/Run-time Interpositioning

```
linux> make hellor
gcc -O2 -Wall -DRUNTIME -shared -fPIC -o mymalloc.so mymalloc.c
gcc -O2 -Wall -o hellor hello.c
linux> make runr
(LD_PRELOAD="/usr/lib64/libdl.so ./mymalloc.so" ./hellor)
malloc(10) = 0x501010
free(0x501010)
hello, world
```

- The `LD_PRELOAD` environment variable tells the dynamic linker to resolve unresolved refs (e.g., to `malloc`) by looking in `libdl.so` and `mymalloc.so` first.
  - `libdl.so` necessary to resolve references to the `dlopen` functions.

Interpositioning Recap

- **Compile Time**
  - Apparent calls to malloc/free get macro-expanded into calls to mymalloc/myfree
- **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