# Linking

15-213 / 18-213: Introduction to Computer Systems
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# Today

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

# Example C Program

**main.c**

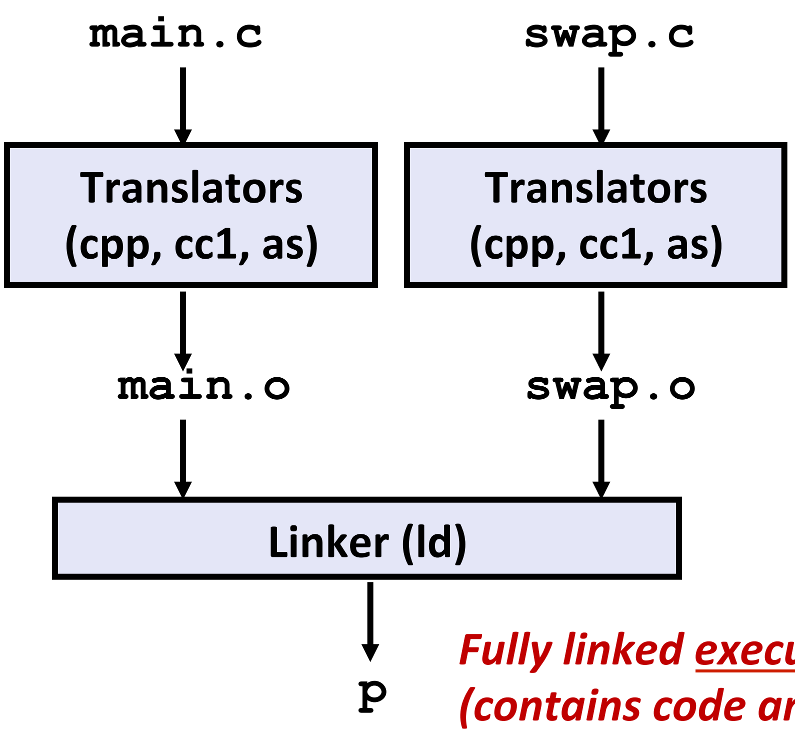
```
int buf[2] = {1, 2};

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

**swap.c**

```
extern int buf[];

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 -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 assembler) 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.

**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)

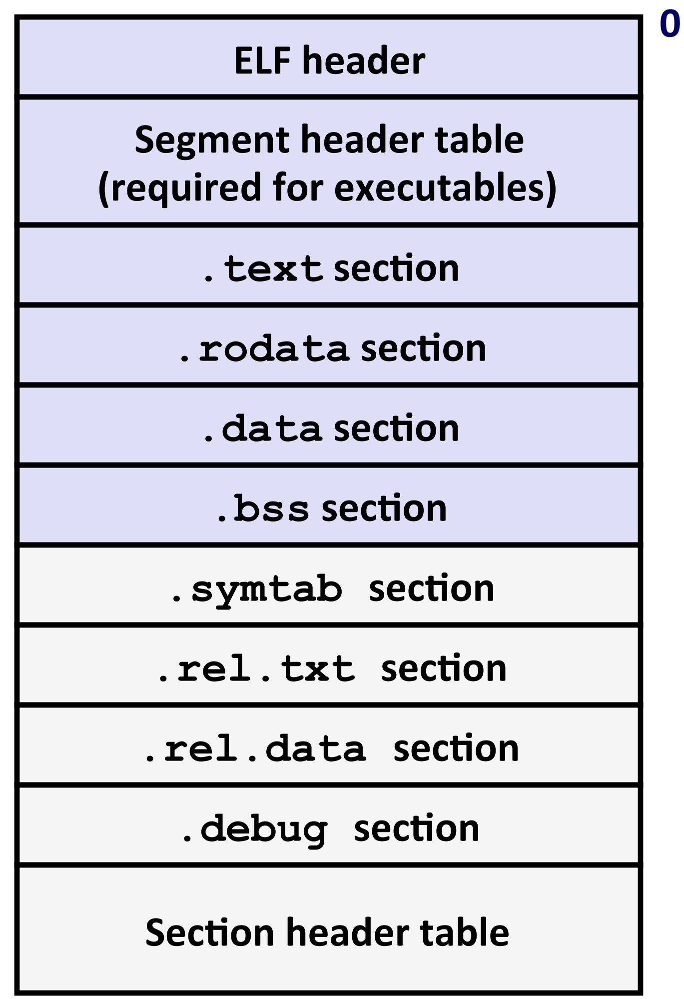
- **Standard binary format for object files**

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

- **Generic name: ELF binaries**

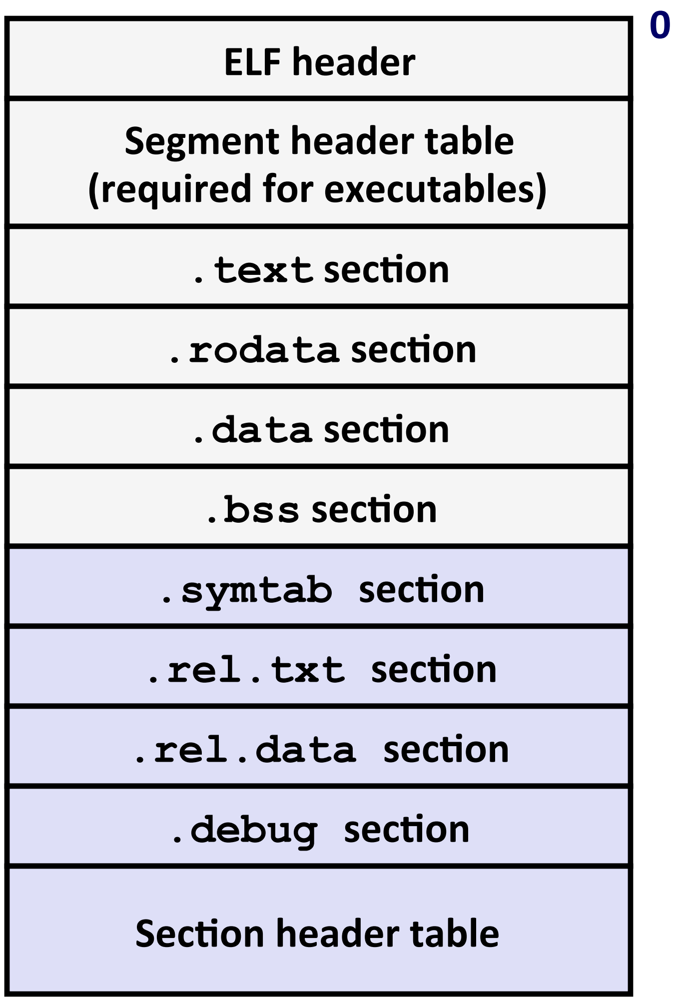
# ELF Object File Format

- **Elf header**
  - Word size, byte ordering, file type (.o, exec, .so), machine type, etc.
- **Segment header table**
  - Page size, virtual 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**

# Step 1: Symbol Resolution

Global

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

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

*main.c*

External

Global

External

Local

```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.c*

Global

Linker knows nothing of temp

- **Question: How do linkers resolve duplicate names?**

# Strong and Weak Symbols

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

`p1.c`

```
int foo=5;      <- strong

p1() {          <- strong
}
```

`p2.c`

```
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 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

| Module 1 | Module 2 | Result |
|---|---|---|
| `int x;`<br>`p1() {}` | `p1() {}` | Link time error: two strong symbols (**`p1`**) |
| `int x;`<br>`p1() {}` | `int x;`<br>`p2() {}` | References to **`x`** will refer to the same uninitialized int. Is this what you really want? |
| `int x;`<br>`int y;`<br>`p1() {}` | `double x;`<br>`p2() {}` | Writes to **`x`** in **`p2`** might overwrite **`y`**! Evil! |
| `int x=7;`<br>`int y=5;`<br>`p1() {}` | `double x;`<br>`p2() {}` | Writes to **`x`** in **`p2`** will overwrite **`y`**! Nasty! |
| `int x=7;`<br>`p1() {}` | `int x;`<br>`p2() {}` | References to **`x`** will refer to the same initialized variable. |

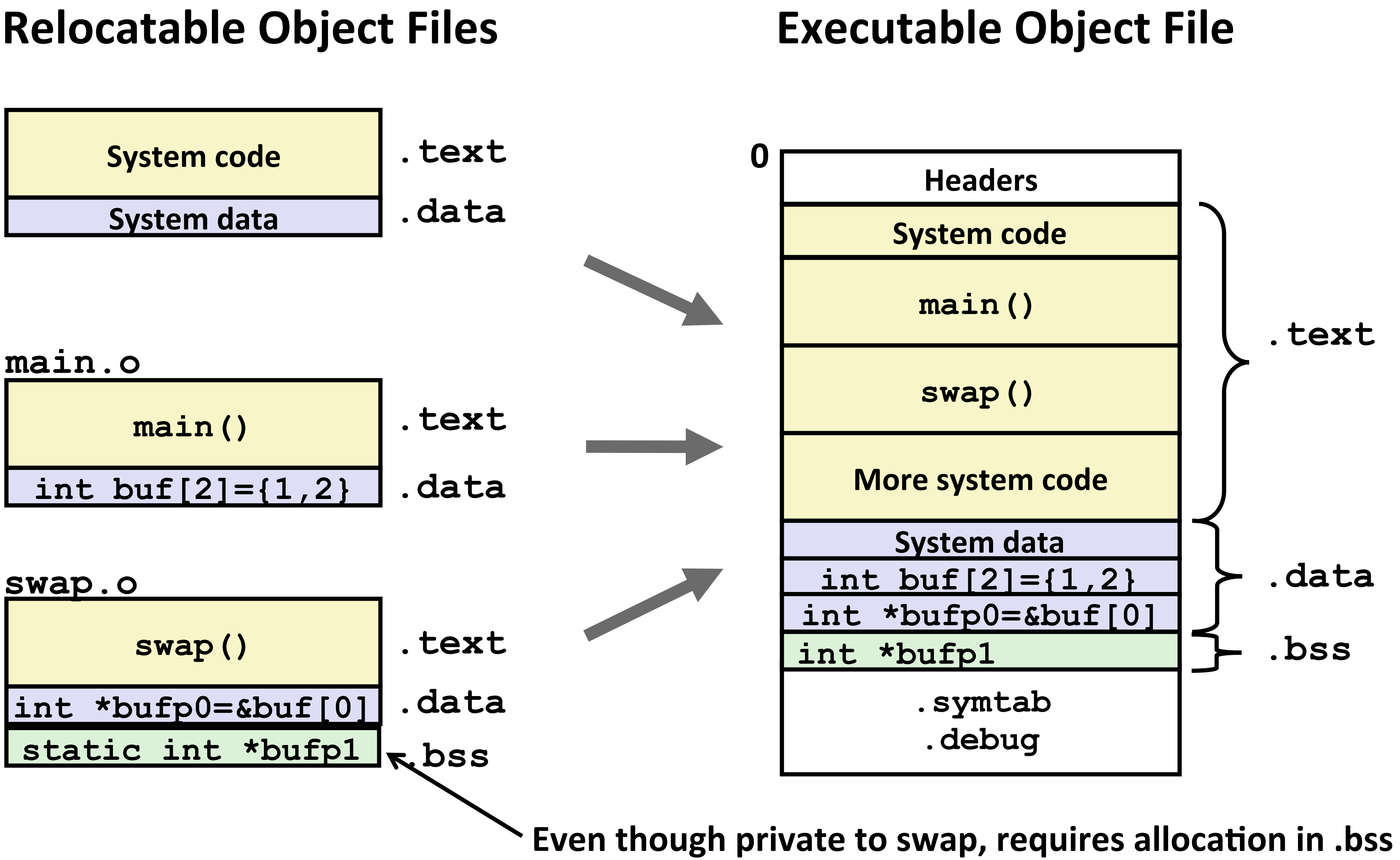
**Nightmare scenario: two identical weak structs, compiled by different compilers with different alignment rules.**

# 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

# Step 2: Relocation



# 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

# 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 :

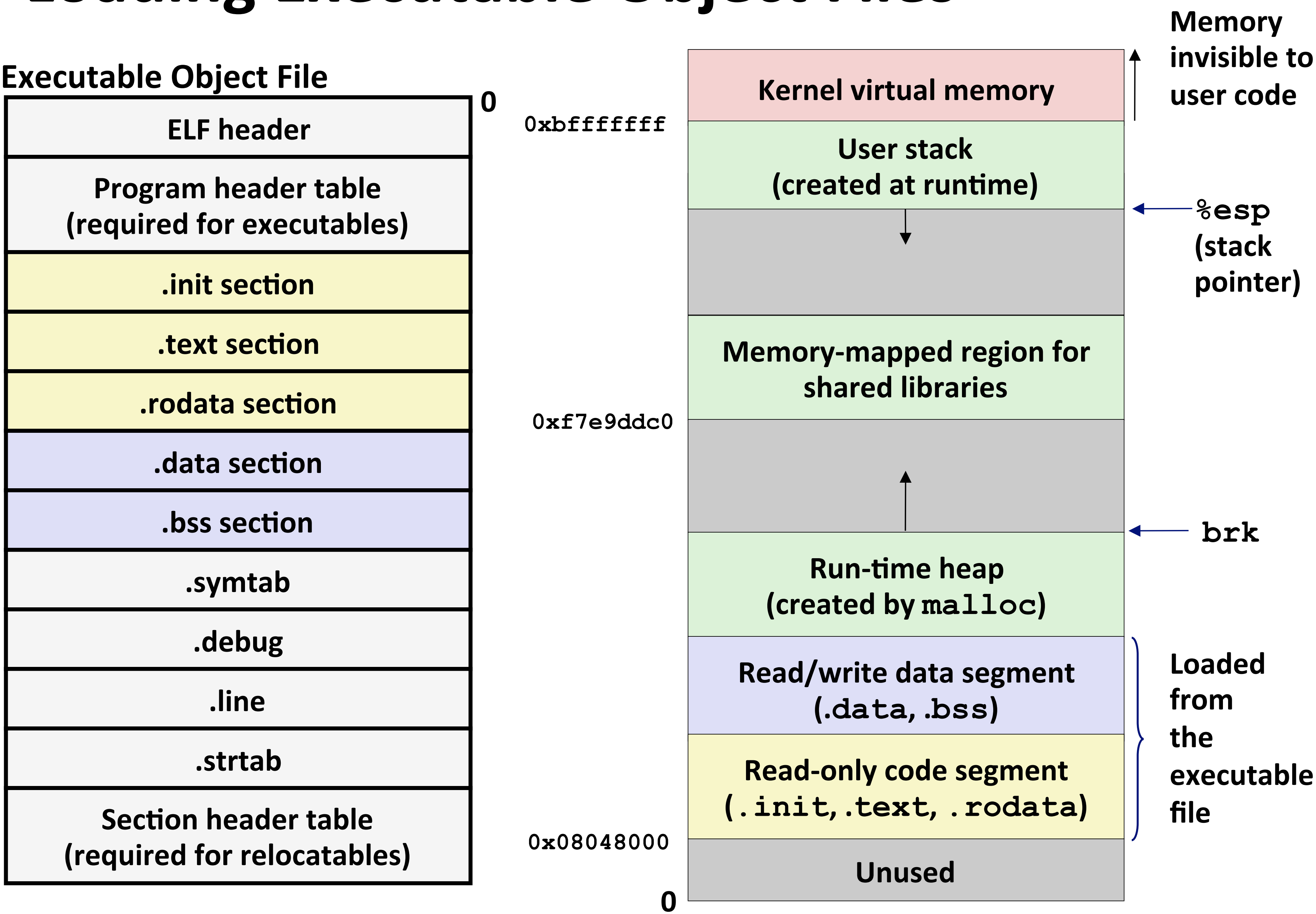
0x8048398 + (-4)
- 0x8048386 = 0xe

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
```

# Loading Executable Object Files



# Packaging Commonly Used Functions

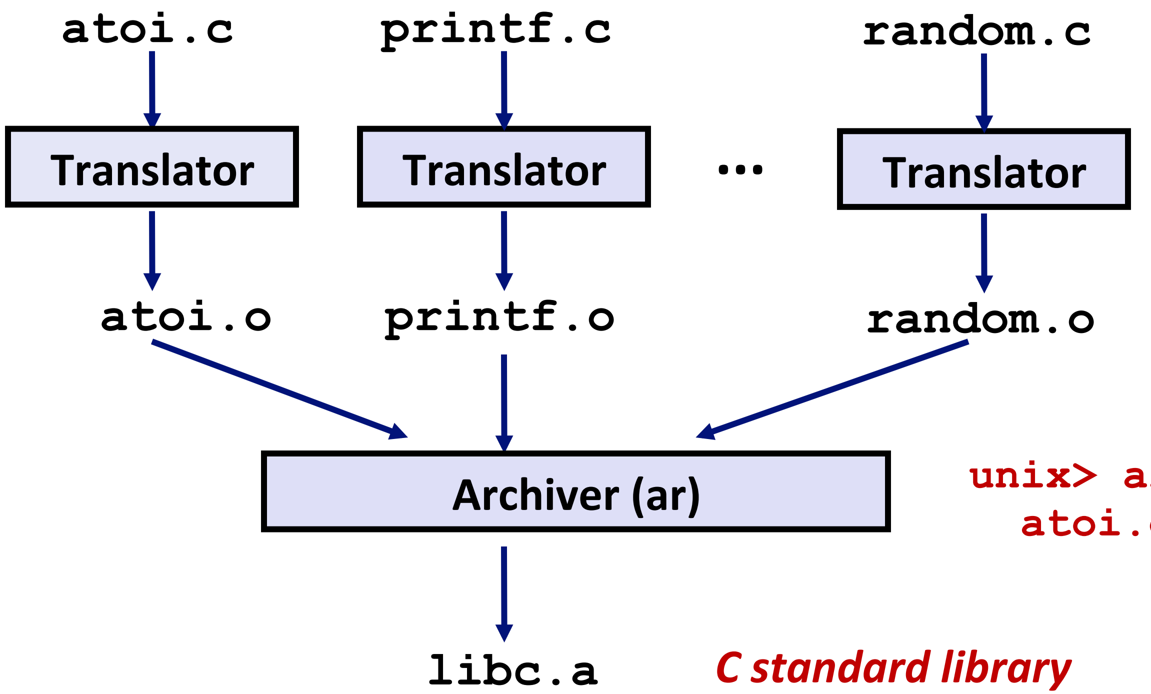
- **How to package functions commonly used by programmers?**
  - Math, I/O, memory management, string manipulation, etc.

- **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

# 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




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

- 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

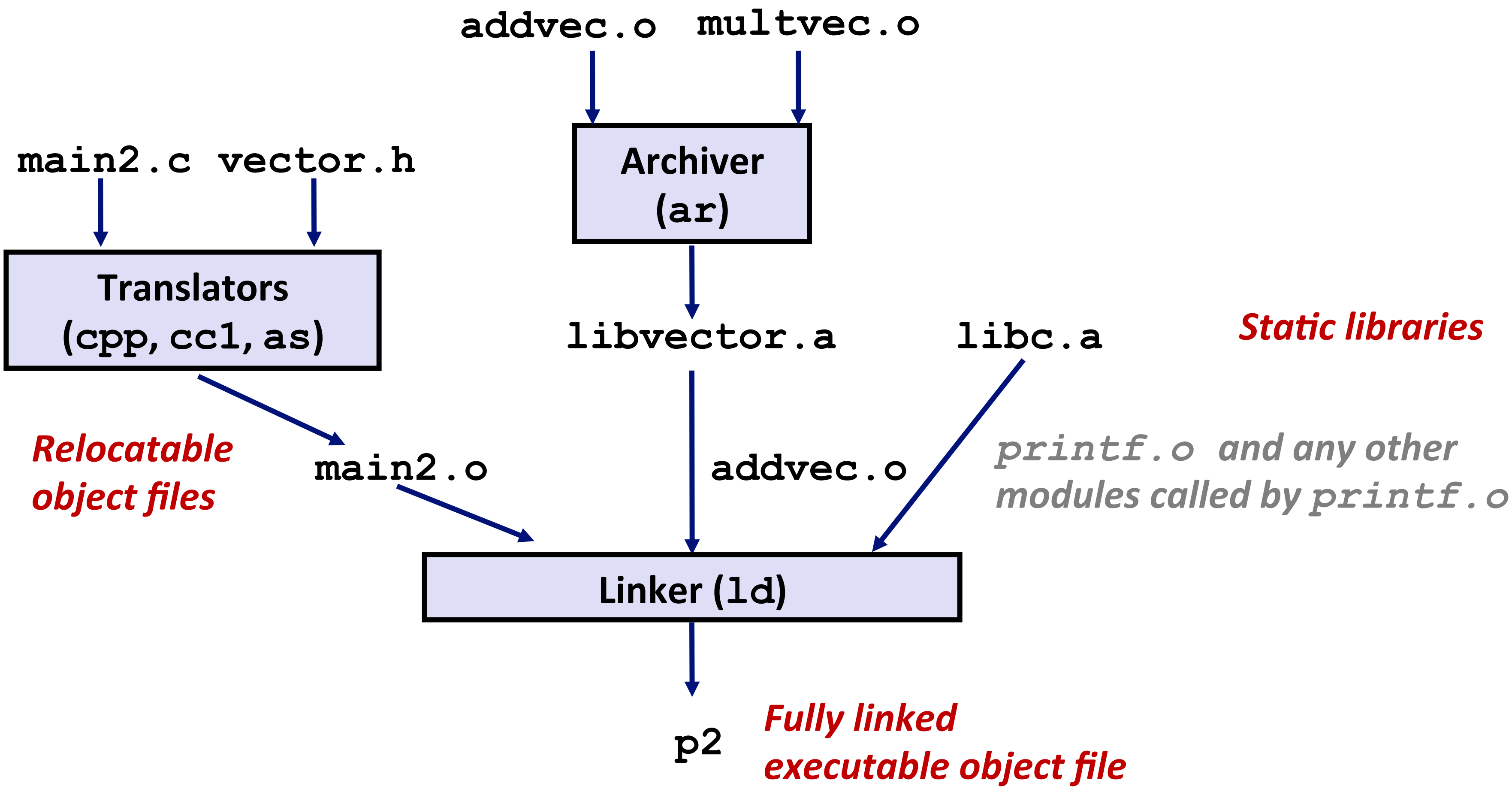
## `libm.a` (the C math library)

- 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'
```

# Shared Libraries

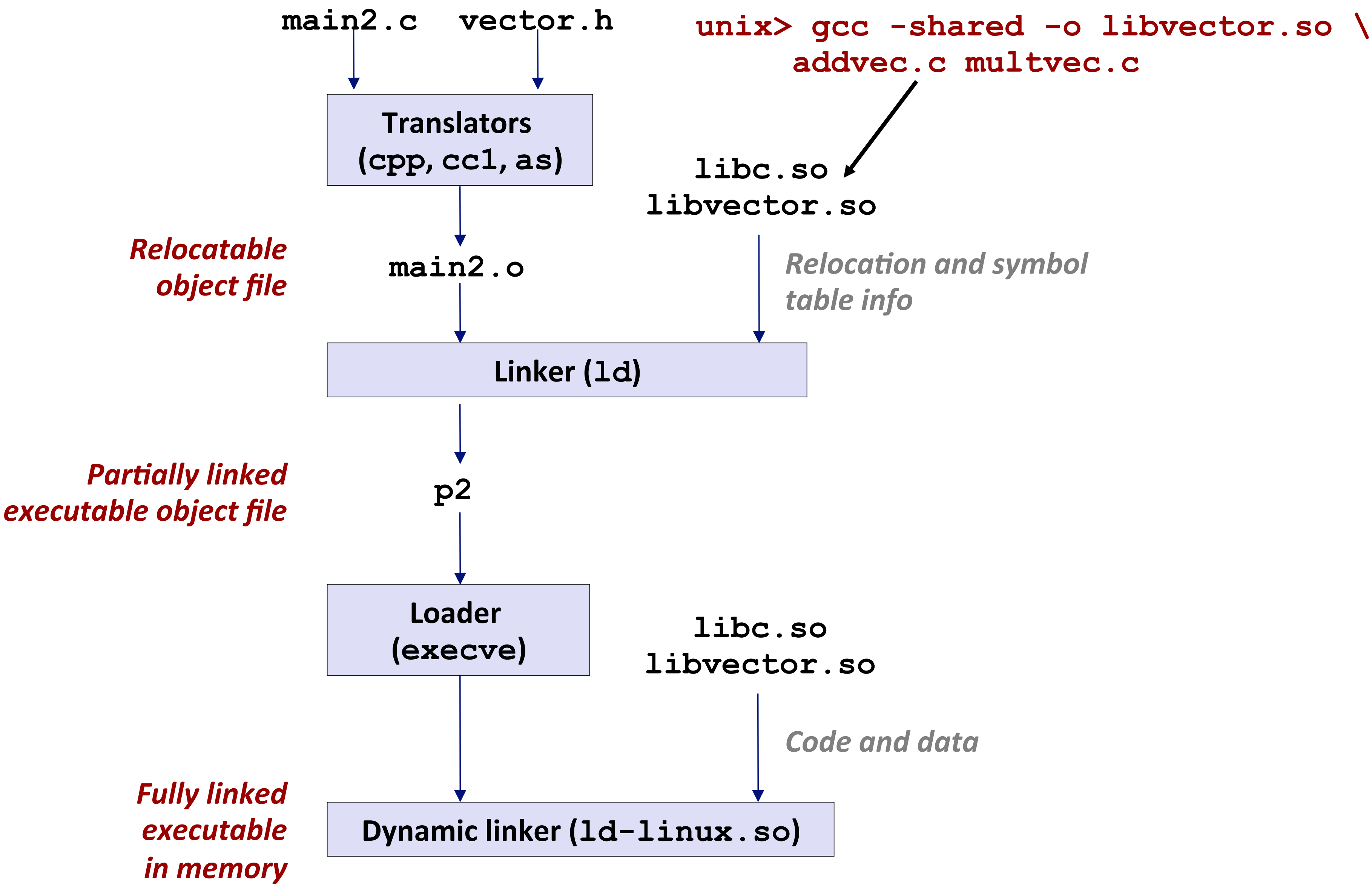
- **Static libraries have the following disadvantages:**
  - Duplication in the stored executables (every function needs libc)
  - Duplication in the running executables
  - Minor bug fixes of system libraries require each application to explicitly relink

- **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)
  - 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**

# Example program

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

int main()
{
    int *p = malloc(32);
    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 `lib` `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
malloc(32)=0x1edc010
free(0x1edc010)
linux>
```

# 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
malloc(32) = 0x1aa0010
free(0x1aa0010)
linux>
```

- 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

```
#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"); /* 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"); /* Addr 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)
malloc(32) = 0xe60010
free(0xe60010)
linux>
```

- **The `LD_PRELOAD` environment variable tells the dynamic linker to resolve unresolved refs (e.g., to `malloc`) by looking in `mymalloc.so` first.**

# 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

# Supplemental slides

# 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
```

**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
```

# 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)