# Linking

Chapter 7

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# Today

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

# Example C Program

```c
int sum(int *a, int n);

int array[2] = {1, 2};

int main()
{
    int val = sum(array, 2);
    return val;
}
```

*main.c*

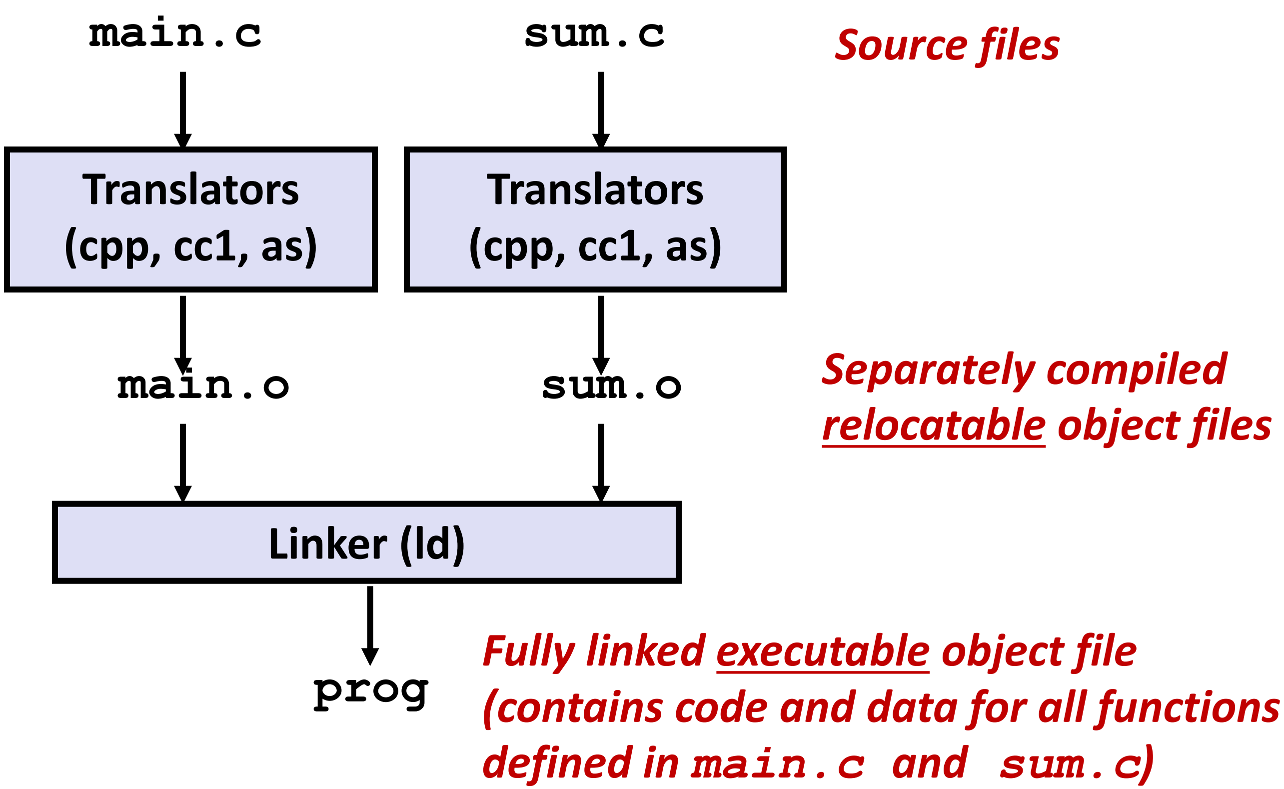
```c
int sum(int *a, int n)
{
    int i, s = 0;

    for (i = 0; i < n; i++) {
        s += a[i];
    }
    return s;
}
```

*sum.c*

# Static Linking

- **Programs are translated and linked using a *compiler driver*:**
  - `linux> gcc -Og -o prog main.c sum.c`
  - `linux> ./prog`



# 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 `struct`s
    - Each entry includes name, size, and location of symbol.
  - **During symbol resolution step, the 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)

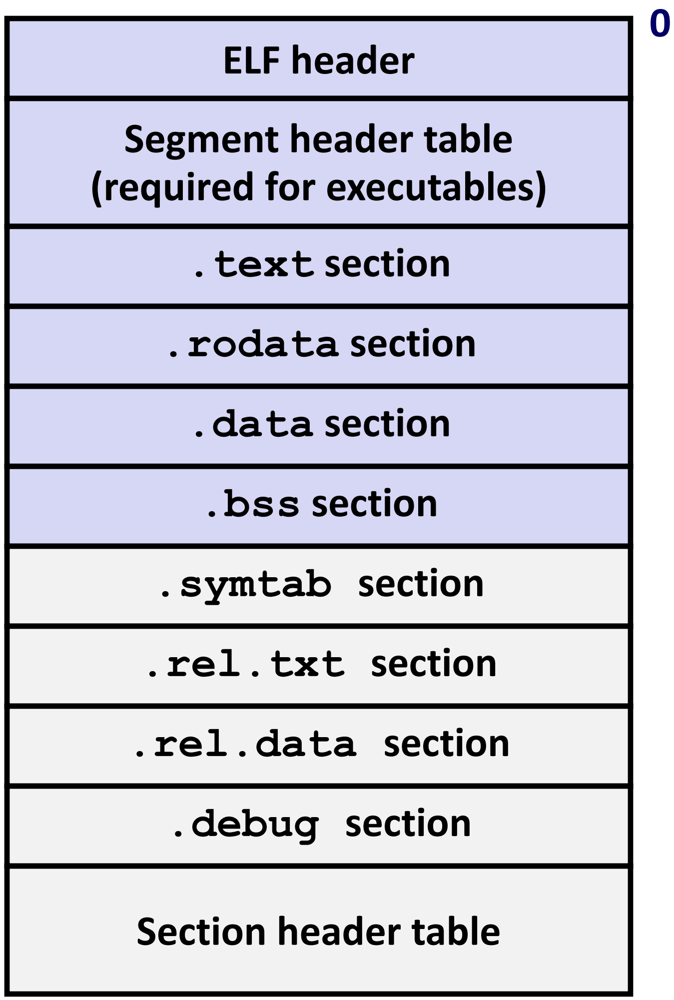
- **Standard binary format for object files**

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

- **Generic name: ELF binaries**

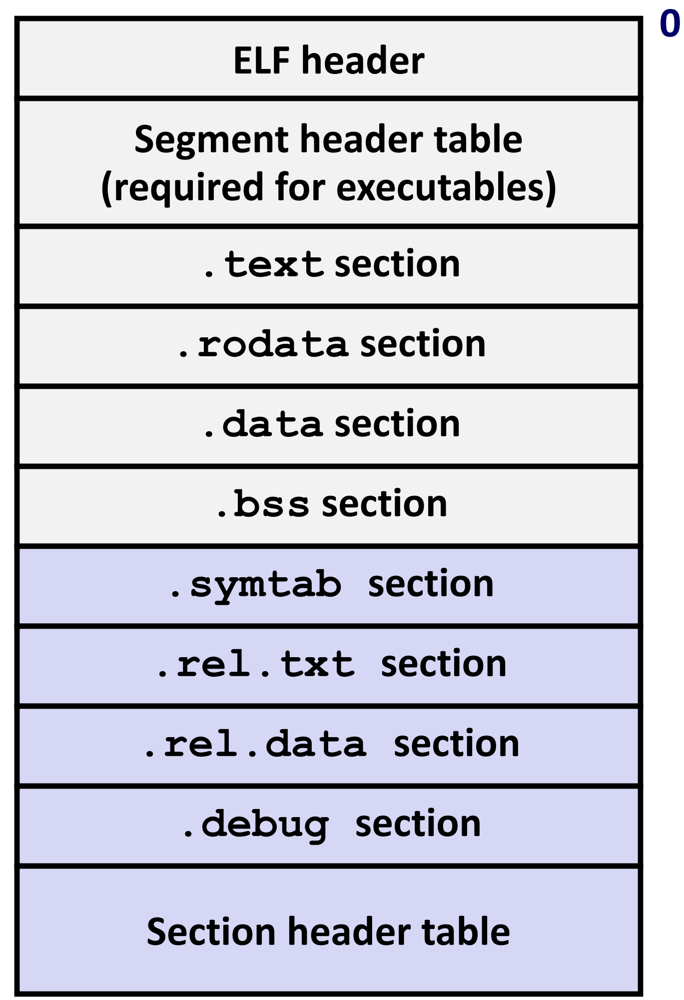
# ELF Object File Format

- **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

Referencing a global…

…that's defined here

```c
int sum(int *a, int n);

int array[2] = {1, 2};

int main()
{
    int val = sum(array, 2);
    return val;
}
```

*main.c*

```c
int sum(int *a, int n)
{
    int i, s = 0;

    for (i = 0; i < n; i++) {
        s += a[i];
    }
    return s;
}
```

*sum.c*

Defining a global

Linker knows nothing of `val`

Referencing a global…

…that's defined here

Linker knows nothing of `i` or `s`

# Local Symbols

- **Local non-static C variables vs. local static C variables**
  - local non-static C variables: stored on the stack
  - local static C variables: stored in either `.bss`, or `.data`

```
int f()
{
    static int x = 0;
    return x;
}

int g()
{
    static int x = 1;
    return x;
}
```

**Compiler allocates space in `.data` for each definition of `x`**

**Creates local symbols in the symbol table with unique names, e.g., `x.1` and `x.2`.**

# How Linker Resolves Duplicate Symbol Definitions

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

**p1.c**

strong → `int foo=5;`

strong → 
```
p1() {
}
```

**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 symbols, 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;`<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.**

# Example 1

For example, suppose we attempt to compile and link the following two C modules:

```c
/* foo1.c */
int main()
{
    return 0;
}
```

```c
/* bar1.c */
int main()
{
    return 0;
}
```

In this case, the linker will generate an error message because the strong symbol `main` is defined multiple times (rule 1):

```
unix> gcc foo1.c bar1.c
/tmp/cca015022.o: In function ‘main':
/tmp/cca015022.o(.text+0x0): multiple definition of ‘main'
/tmp/cca015021.o(.text+0x0): first defined here
```

# Example 2

Similarly, the linker will generate an error message for the following modules because the strong symbol x is defined twice (rule 1):

```c
/* foo2.c */
int x = 15213;

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

```c
/* bar2.c */
int x = 15213;

void f()
{
}
```

# Example 3

However, if x is uninitialized in one module, then the linker will quietly choose the strong symbol defined in the other (rule 2):

```c
/* foo3.c */
#include <stdio.h>
void f(void);

int x = 15213;

int main()
{
    f();
    printf("x = %d\n", x);
    return 0;
}
```

```c
/* bar3.c */
int x;

void f()
{
    x = 15212;
}
```

At run time, function `f` changes the value of `x` from 15213 to 15212, which might come as an unwelcome surprise to the author of function `main`! Notice that the linker normally gives no indication that it has detected multiple definitions of `x`:

```
unix> gcc -o foobar3 foo3.c bar3.c
unix> ./foobar3
x = 15212
```

# Example 4

The same thing can happen if there are two weak definitions of x (rule 3):

```c
/* foo4.c */
#include <stdio.h>
void f(void);

int x;

int main()
{
    x = 15213;
    f();
    printf("x = %d\n", x);
    return 0;
}
```

```c
/* bar4.c */
int x;

void f()
{
    x = 15212;
}
```

# Example 5

```
1    /* foo5.c */
2    #include <stdio.h>
3    void f(void);
4
5    int x = 15213;
6    int y = 15212;
7
8    int main()
9    {
10       f();
11       printf("x = 0x%x y = 0x%x \n",
12              x, y);
13       return 0;
14   }
```

```
1    /* bar5.c */
2    double x;
3
4    void f()
5    {
6        x = -0.0;
7    }
```

On an IA32/Linux machine, `double`s are 8 bytes and `int`s are 4 bytes. Thus, the assignment `x = -0.0` in line 6 of `bar5.c` will overwrite the memory locations for `x` and `y` (lines 5 and 6 in `foo5.c`) with the double-precision floating-point representation of negative zero!

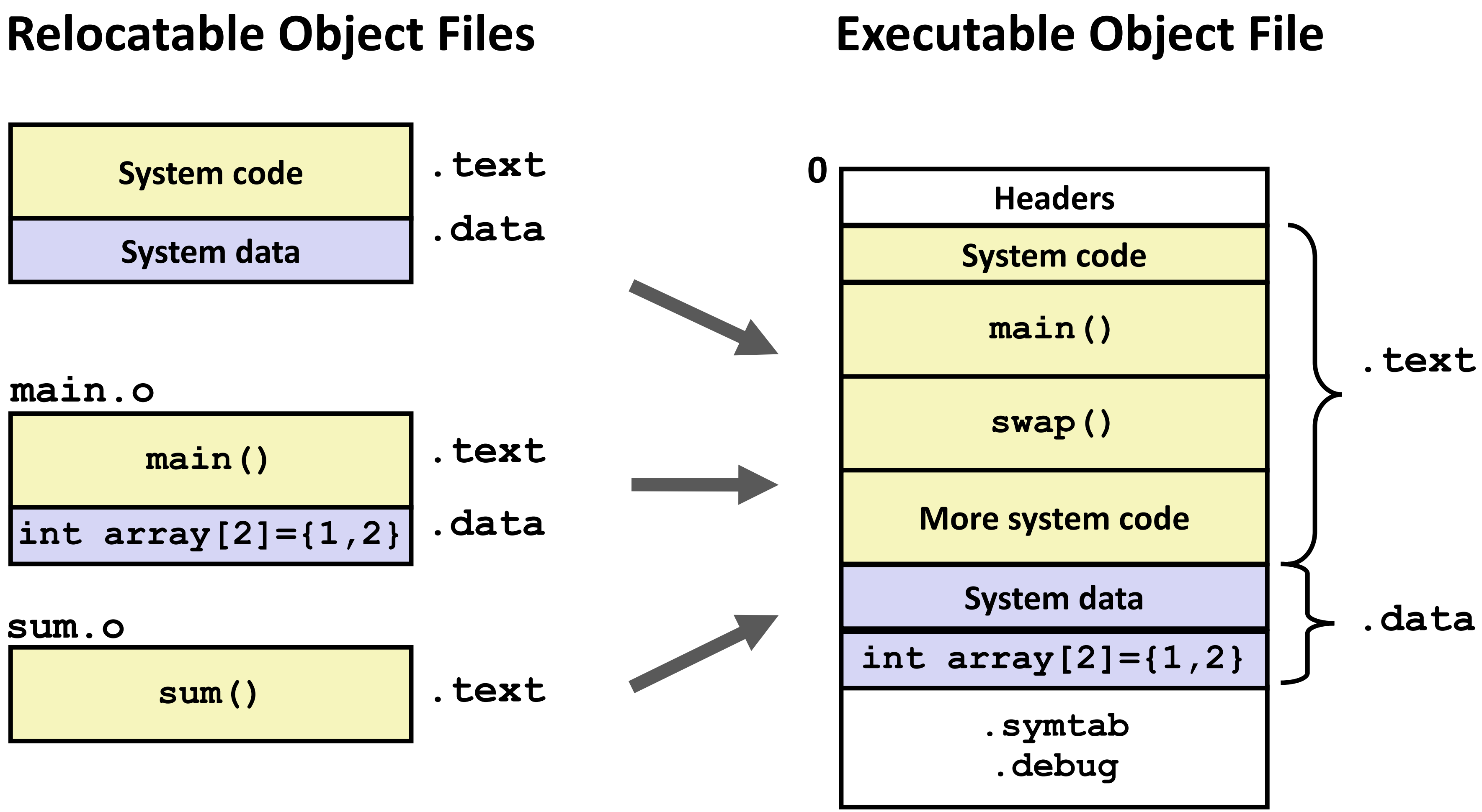
```
linux> gcc -o foobar5 foo5.c bar5.c
linux> ./foobar5
x = 0x0 y = 0x80000000
```

# Global Variables

- **Avoid if you can**

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

# Step 2: Relocation



# Relocation Entries

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

int main()
{
    int val = sum(array, 2);
    return val;
}
```

*main.c*

```
0000000000000000 <main>:
   0:    48 83 ec 08          sub    $0x8,%rsp
   4:    be 02 00 00 00       mov    $0x2,%esi
   9:    bf 00 00 00 00       mov    $0x0,%edi      # %edi = &array
                 a: R_X86_64_32 array              # Relocation entry

   e:    e8 00 00 00 00       callq  13 <main+0x13> # sum()
                 f: R_X86_64_PC32 sum-0x4          # Relocation entry
  13:    48 83 c4 08          add    $0x8,%rsp
  17:    c3                   retq
```

*main.o*

Source: `objdump -r -d main.o`

# Relocated .text section

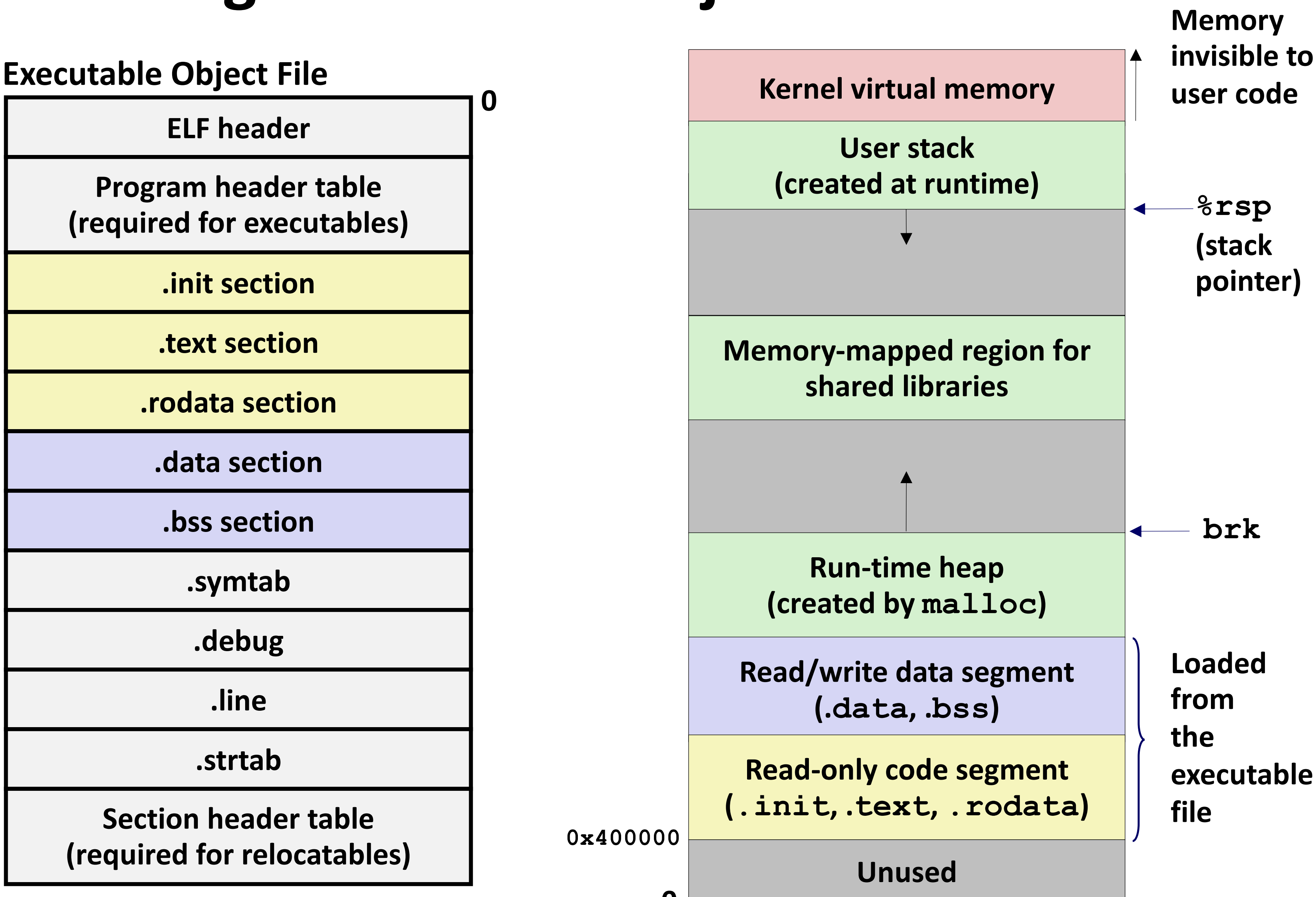
```
00000000004004d0 <main>:
  4004d0:       48 83 ec 08        sub    $0x8,%rsp
  4004d4:       be 02 00 00 00     mov    $0x2,%esi
  4004d9:       bf 18 10 60 00     mov    $0x601018,%edi  # %edi = &array
  4004de:       e8 05 00 00 00     callq  4004e8 <sum>    # sum()
  4004e3:       48 83 c4 08        add    $0x8,%rsp
  4004e7:       c3                 retq

00000000004004e8 <sum>:
  4004e8:       b8 00 00 00 00           mov    $0x0,%eax
  4004ed:       ba 00 00 00 00           mov    $0x0,%edx
  4004f2:       eb 09                    jmp    4004fd <sum+0x15>
  4004f4:       48 63 ca                 movslq %edx,%rcx
  4004f7:       03 04 8f                 add    (%rdi,%rcx,4),%eax
  4004fa:       83 c2 01                 add    $0x1,%edx
  4004fd:       39 f2                    cmp    %esi,%edx
  4004ff:       7c f3                    jl     4004f4 <sum+0xc>
  400501:       f3 c3                    repz retq
```

**Using PC-relative addressing for sum(): 0x4004e8 = 0x4004e3 + 0x5**

`Source: objdump -dx prog`

# 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

    ```
    $ gcc main.c /usr/lib/libc.o
    ```

    - Programmers link big object file into their programs
    - Space and time inefficient

  - **Option 2:** Put each function in a separate source file

    ```
    $ gcc main.c /usr/lib/printf.o /usr/lib/scanf.o …
    ```

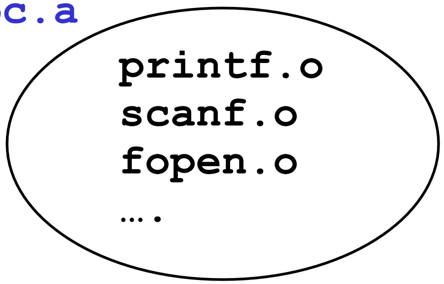
    - Programmers explicitly link appropriate binaries into their programs
    - More efficient, but burdensome on the programmer

# 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*).

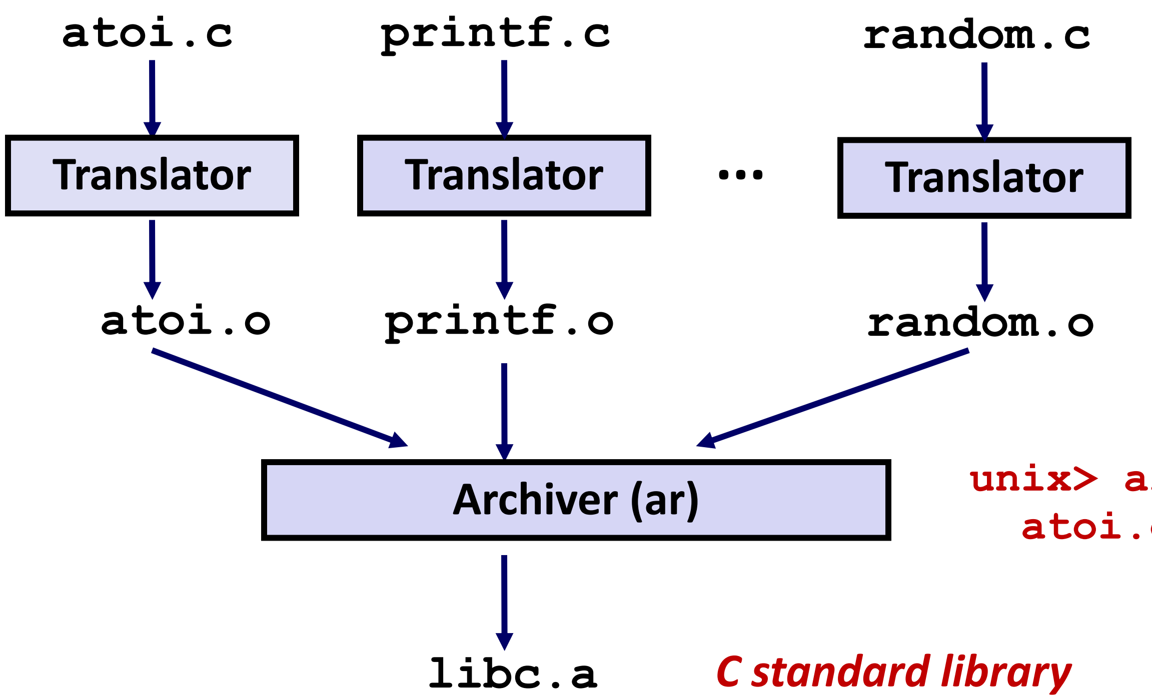
```
$ gcc main.c /usr/src/libc.a
```

**libc.a**




  - 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)

- 4.6 MB archive of 1496 object files.
- I/O, memory allocation, signal handling, string handling, data and time, random numbers, integer math

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

- 2 MB archive of 444 object files.
- floating point math (sin, cos, tan, log, exp, sqrt, …)

```
% ar -t libc.a | sort
…
fork.o
…
fprintf.o
fpu_control.o
fputc.o
freopen.o
fscanf.o
fseek.o
fstab.o
…
```

```
% ar -t 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

libvector.a

```c
#include <stdio.h>
#include "vector.h"

int x[2] = {1, 2};
int y[2] = {3, 4};
int z[2];

int main()
{
    addvec(x, y, z, 2);
    printf("z = [%d %d]\n”,
           z[0], z[1]);
    return 0;
}
```

*main2.c*

```c
void addvec(int *x, int *y,
            int *z, int n) {
    int i;

    for (i = 0; i < n; i++)
        z[i] = x[i] + y[i];
}
```

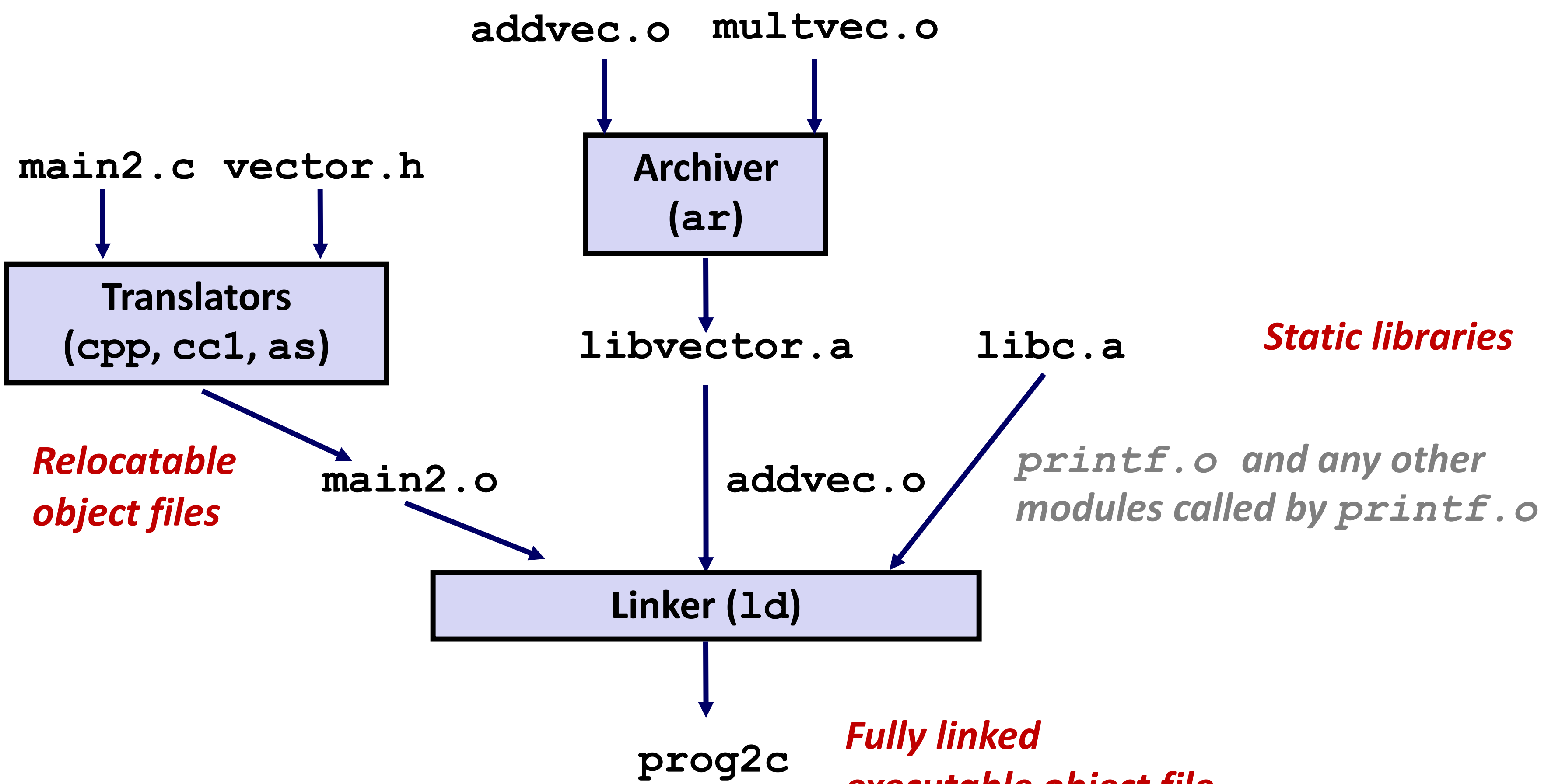
*addvec.c*

```c
void multvec(int *x, int *y,
             int *z, int n)
{
    int i;

    for (i = 0; i < n; i++)
        z[i] = x[i] * y[i];
}
```

*multvec.c*

# Linking with Static Libraries




*"c" for "compile-time"*

# Using Static Libraries

- **Make a static library: libvector.a**

```
unix> gcc -c addvec.c multvec.c
unix> ar rcs libvector.a addvec.o multvec.o
```

- **Compile main2.c**

```
unix> gcc -c main2.c
main2.c:2:19: fatal error: vector.h: No such file or directory
unix> vi vector.h
unix> gcc -c main2.c
unix> gcc -static -o prog2 main2.o ./libvector.a
unix> ./prog2
z = [4 6]
```

# 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'
```

# Modern Solution: 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

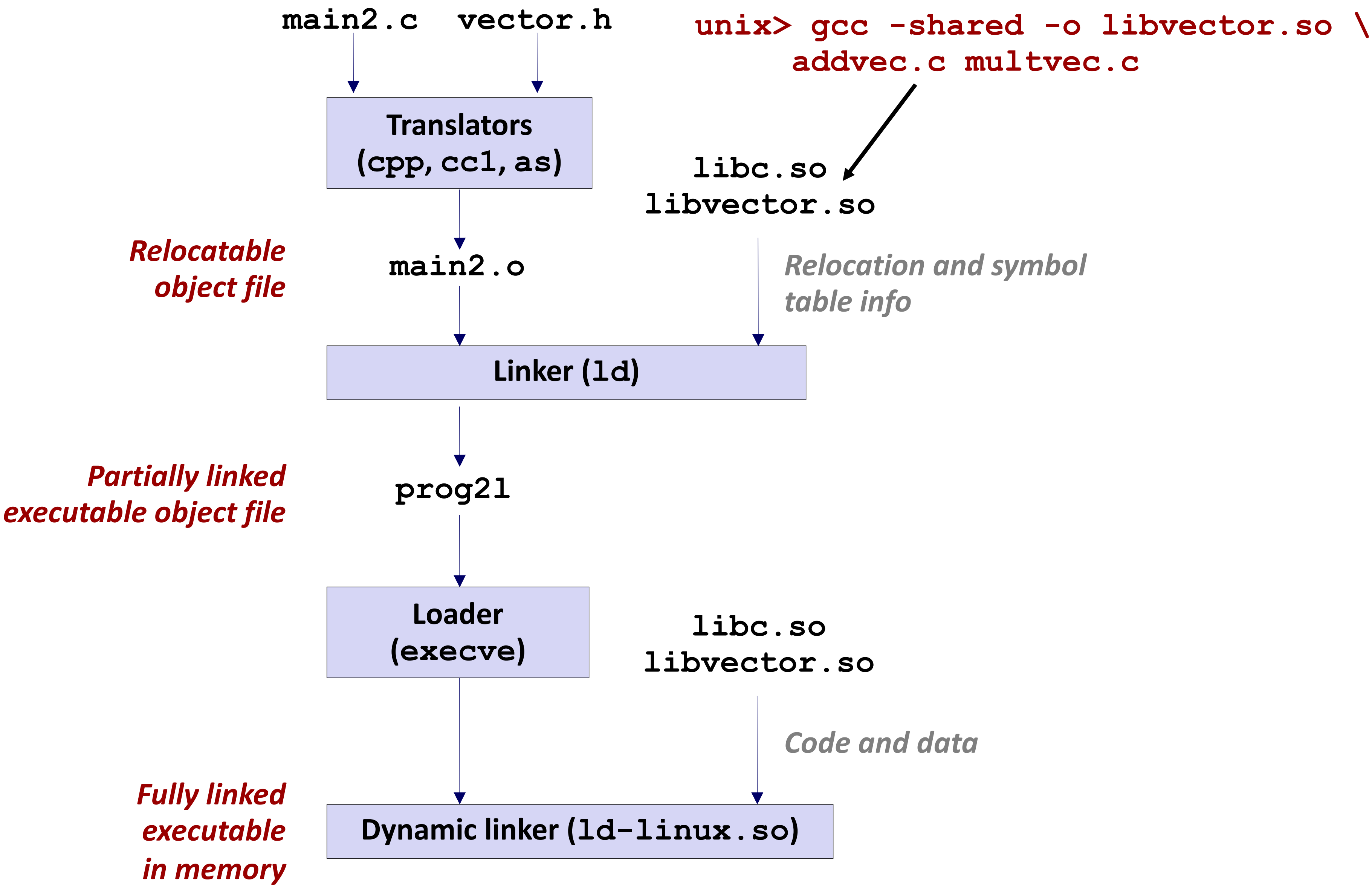
# Shared Libraries (cont.)

- **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 <stdlib.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 library that contains addvec() */
    handle = dlopen("./libvector.so", RTLD_LAZY);
    if (!handle) {
        fprintf(stderr, "%s\n", dlerror());
        exit(1);
    }
```

dll.c

# 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;
}
```

dll.c

# Dynamic Linking at Run-time

- **Make a dynamic library: libvector.so**

```
unix> gcc -shared -o libvector.so \
      addvec.c multvec.c
```

- **Compile**

```
unix> gcc -o dll dll.c -ldl
mydll.cc:22:16: error: invalid conversion from 'void*' to
'void (*)(int*, int*, int*, int)' [-fpermissive]
  addvec = dlsym(handle, "addvec");
```

```
addvec = dlsym(handle, "addvec");
➔ addvec = (void(*)(int*, int*, int*, int)) dlsym(handle, "addvec");
```

```
unix> gcc -o dll dll.c -ldl
unix> ./dll
unix> z = [4 6]
```

# 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

```c
#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
```

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# 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"); /* Get 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;
}
```

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# 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"); /* Get address of libc free */
    if ((error = dlerror()) != NULL) {
        fputs(error, stderr);
        exit(1);
    }
    freep(ptr); /* Call libc free */
    printf("free(%p)\n", ptr);
}
#endif
```

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# 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