18-600: Recitation #8

Oct 17th, 2017

Linking & Loading

Reminders

- Shell Lab is out! You should've started poking around fork/exec/signal handlers.
- Remember to watch out for race conditions and signal delivery/reception/masking.
- Remember to follow style guidelines (don't lose out on points :D): http://www.ece.cmu.edu/~ece600/codestyle.html
- We will be conducting a mock midterm exam next week. Be prepared!

Today

- **Linking**
  - What is it and how does it work?
  - Symbol resolution
  - Dynamic v/s Static linking
  - Loading

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

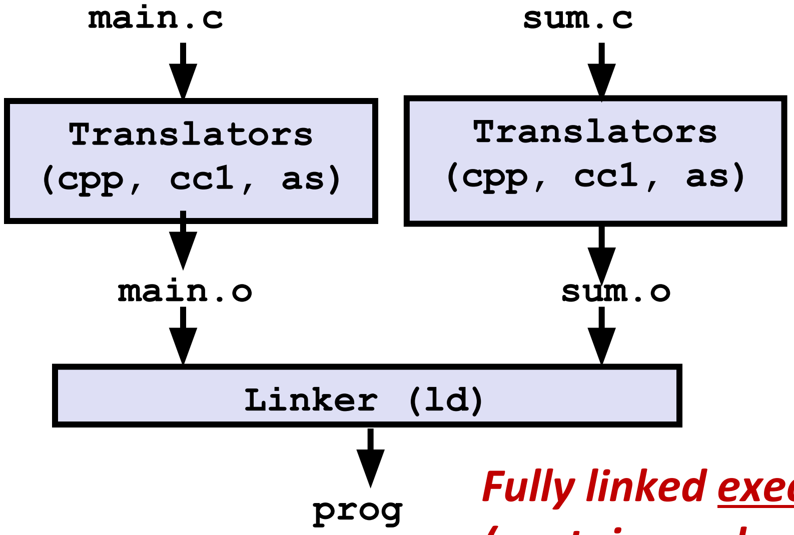
```c
int sum(int *a, int n)
{
    int i, s = 0;

    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`



Source files

Separately compiled <u>relocatable</u> object files

Fully linked <u>executable</u> object file (contains code and data for all functions defined in `main.c` and `sum.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.

- **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)

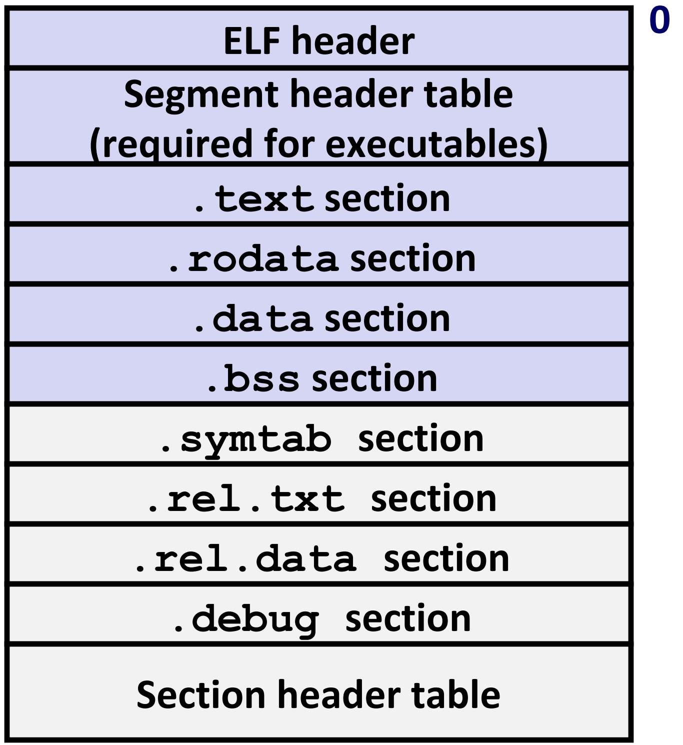
- **Relocatable object file (`.o` file)**
  - Contains code and data in a form that can be combined with other relocatable object files to form executable object file.
    - Each `.o` file is produced from exactly one source (`.c`) file
- **Executable object file (`a.out` file)**
  - Contains code and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

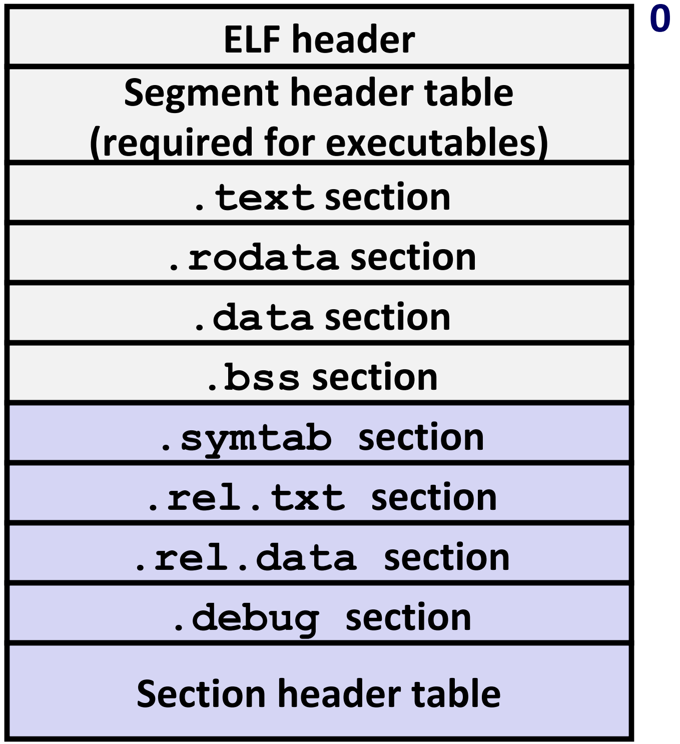
ELF Object File Format

- **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: constant strings, 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

Why do we need symbol tables in the first place?

- **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

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

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

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

main.c

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

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

sum.c

- Referencing a global… (`sum` in `int val = sum(array, 2);`) …that's defined here (`int sum(int *a, int n)` in sum.c)
- Referencing a global… (`array` in `sum(array, 2)`) …that's defined here (`int array[2] = {1, 2};`)
- Defining a global (`main`)
- Linker knows nothing of `val`
- Linker knows nothing of `i` or `s`

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() {`

```
int foo=5;

p1() {
}
```

p2.c

```
int foo;

p2() {
}
```

`int foo;` ← weak

`p2() {` ← strong

Linker's Symbol Rules

- **Rule 1: Multiple strong symbols are not allowed**
  - Each item can be defined only once
  - Otherwise: Linker error
- **Rule 2: Given a strong symbol and multiple weak symbols, choose the strong symbol**
  - References to the weak symbol resolve to the strong symbol
- **Rule 3: If there are multiple weak symbols, 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* (based on which **`x`** is resolved first) 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.

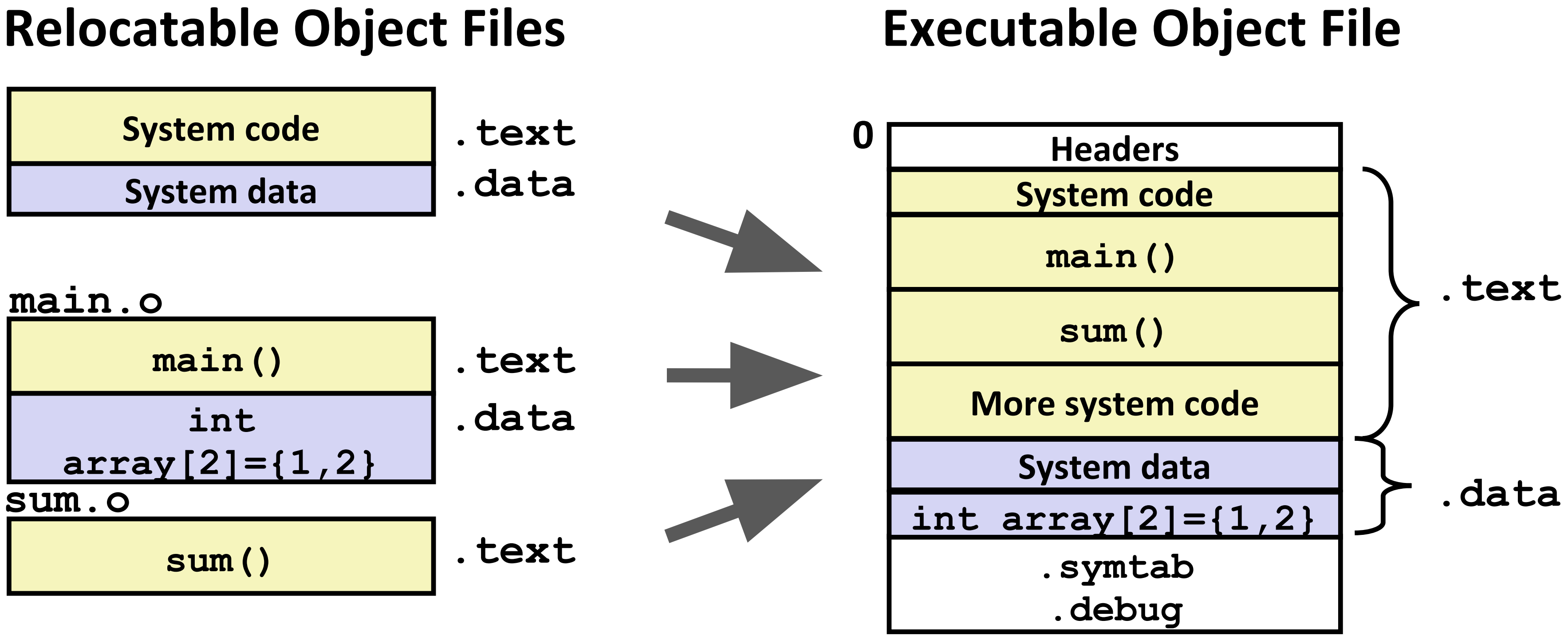
Nightmare scenario: two identical weak structs, compiled by different compilers with different alignment rules.

Global Variables

- **Avoid them, if you can!**

- **Otherwise**
  - Use `static` if you can - hides the symbol from the Linker!
  - Initialize if you define a global variable - make it a strong symbol!
  - Use `extern` if you reference an external global variable - help the Linker out!

Step 2: Relocation



Relocation Entries

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

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

Placeholder values

```
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

Actual, in-code values

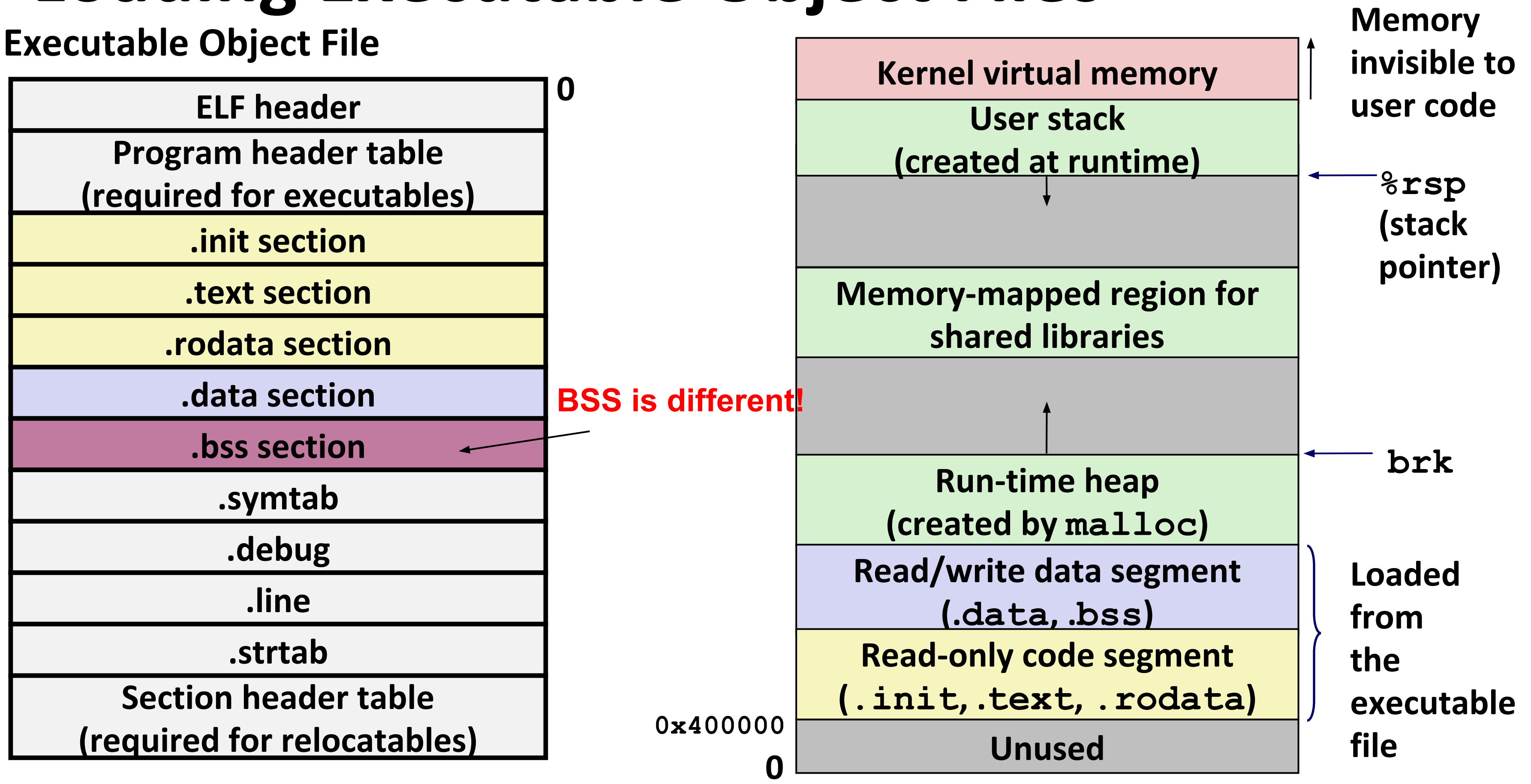
```
00000000004004d0 <main>:
  4004d0:        48 83 ec 08          sub     $0x8,%rsp
  4004d4:        be 02 00 00 00       mov     $0x2,%esi
  4004d9:        bf 18 10 60 00       mov     $0x601018,%edi   # %edi = &array
  4004de:        e8 05 00 00 00       callq   4004e8 <sum>     # sum()
  4004e3: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

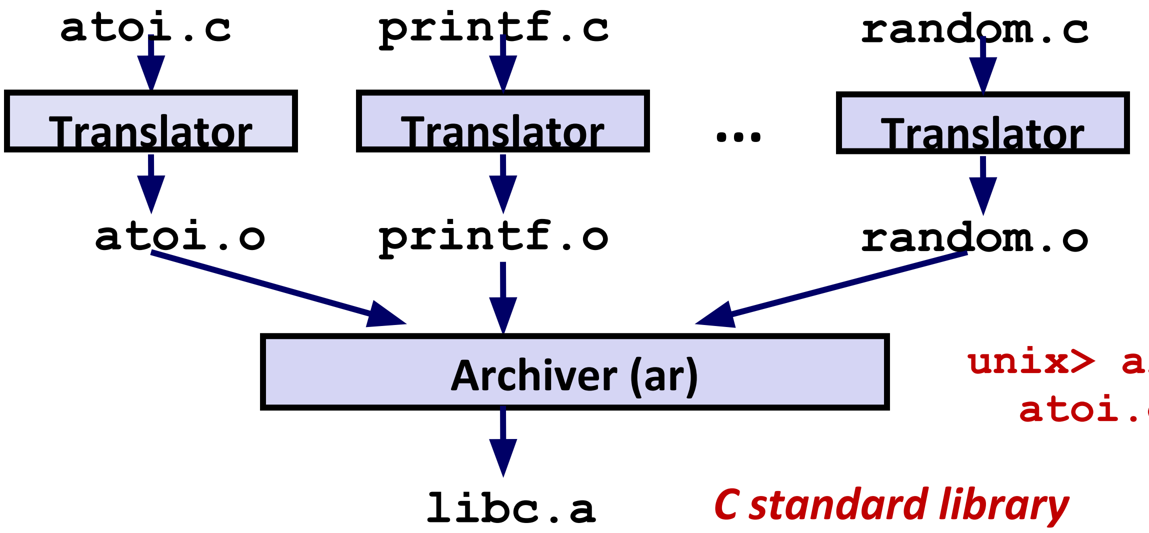
- **How to package functions commonly used by programmers?**
  - Math, I/O, memory management, string manipulation, etc.

- **Awkward, given the linker framework so far:**
  - **Option 1:** Put all functions into a single source file
    - 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.

Linking with Static Libraries

```
#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

libvector.a

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

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

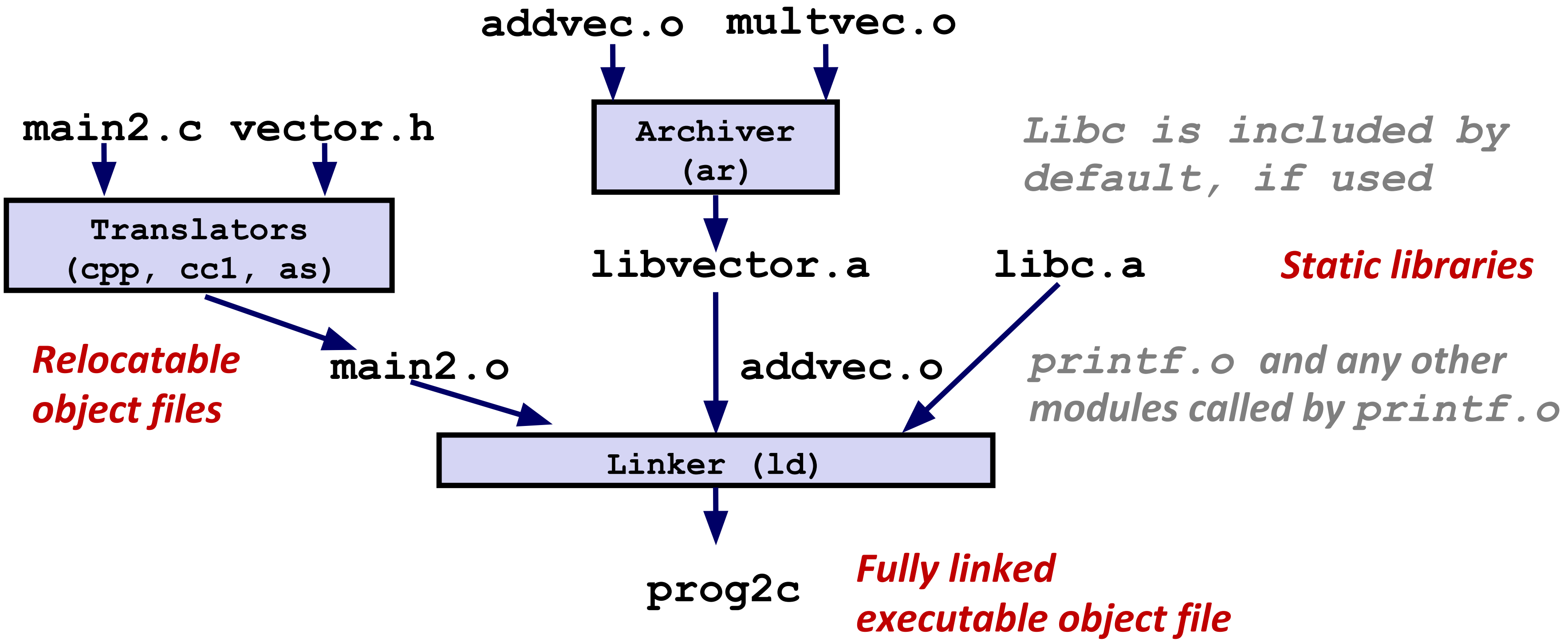
addvec.c

```
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

- **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

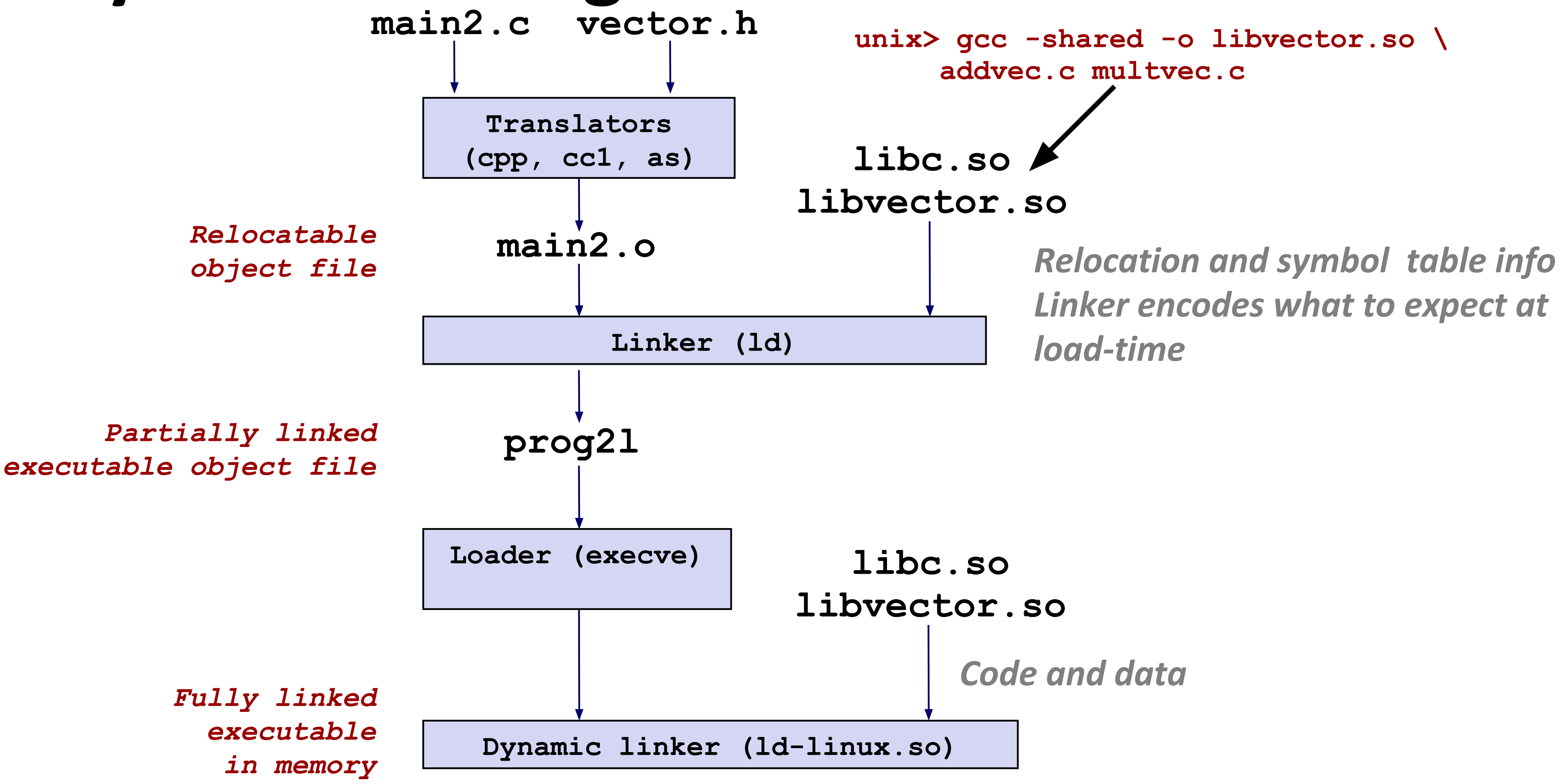
- **Static libraries have the following disadvantages:**
  - Duplication in the stored executables (every function needs libc)
  - Duplication in the running executables
  - Minor bug fixes of system libraries require each application to explicitly relink

- **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);
    }

/* 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

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.**

Shell Lab Discussion / OH