

Linking

15-213/14-513/15-513: Introduction to Computer Systems
16th Lecture, October 26, 2023

Final Exam Stuff

- **The scheduled date / time is available on the HUB**
 - Tuesday morning (12/12 at 8:30am)
- **If you have accommodations**
 - You will take the exam with ODR
- **If you have a conflict (see CMU's exam policy)**
 - A makeup exam will be on the exam conflict day, 12/18
- **We will have a Piazza post + google form to collect the details about these cases**
 - If something happens, we can always do a makeup exam or issue an incomplete, even retroactively

Today

■ Linking

- Motivation
- What it does
- How it works

■ Activity

Example C Program

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

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

int main(int argc, char** argv)
{
    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];
    }

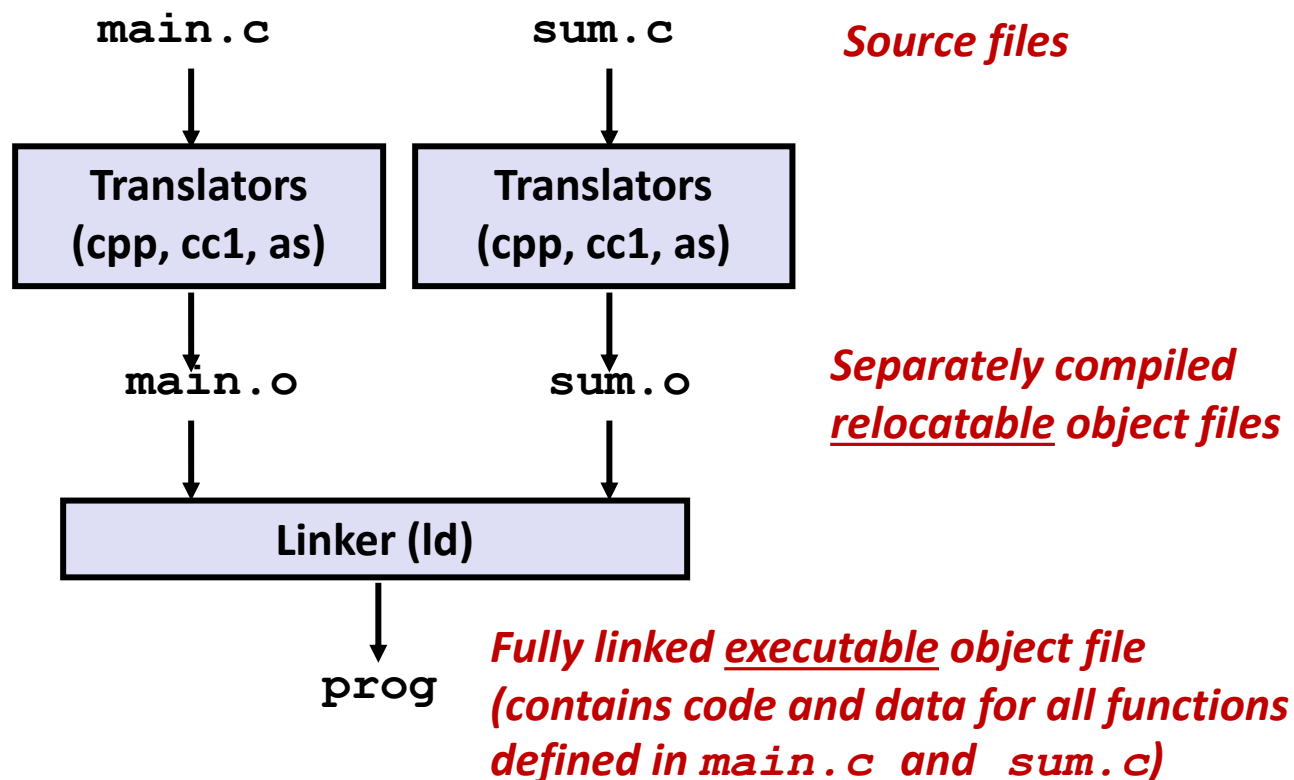
    return s;
}
```

sum.c

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
 - 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.
 - Can compile multiple files concurrently.
- Space: Libraries
 - Common functions can be aggregated into a single file...
 - **Option 1: *Static Linking***
 - Executable files and running memory images contain only the library code they actually use
 - **Option 2: *Dynamic linking***
 - Executable files contain no library code
 - During execution, single copy of library code can be shared across all executing processes

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 entries
 - Each entry includes name, size, and location of symbol.
- **During symbol resolution step, the linker associates each symbol reference with exactly one symbol definition.**

Symbols in Example C Program

Definitions

```
int sum(int *a, int n);  
int array[2] = {1, 2};  
int main(int argc, char** argv)  
{  
    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

Reference

What Do Linkers Do? (cont'd)

■ 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 address memory segments (sections), segment sizes.

■ .text section

- Code

■ .rodata section

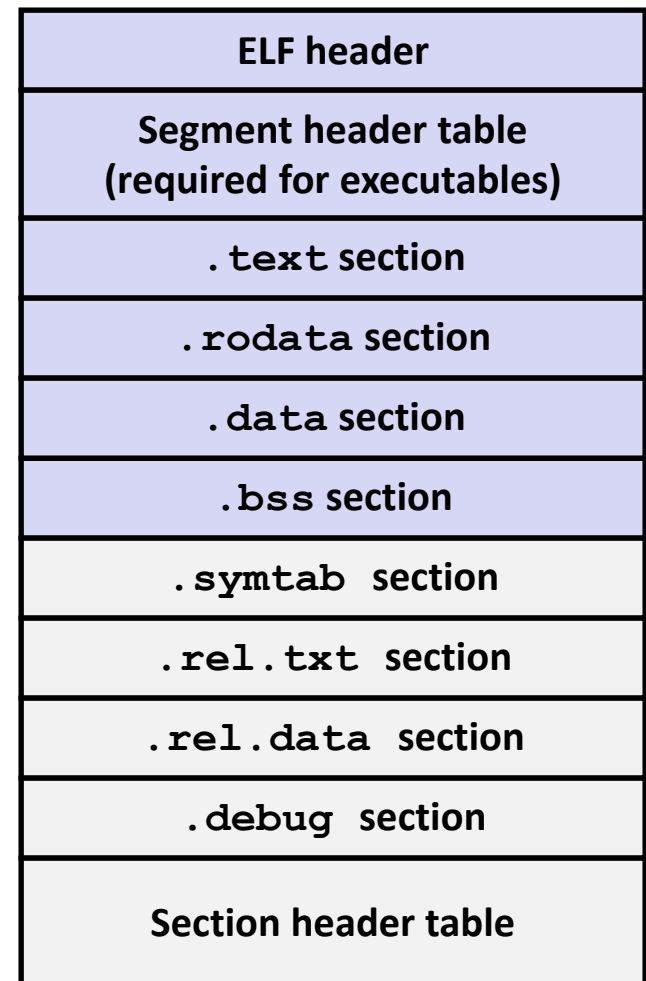
- Read only data: jump tables, string constants, ...

■ .data section

- Initialized global variables

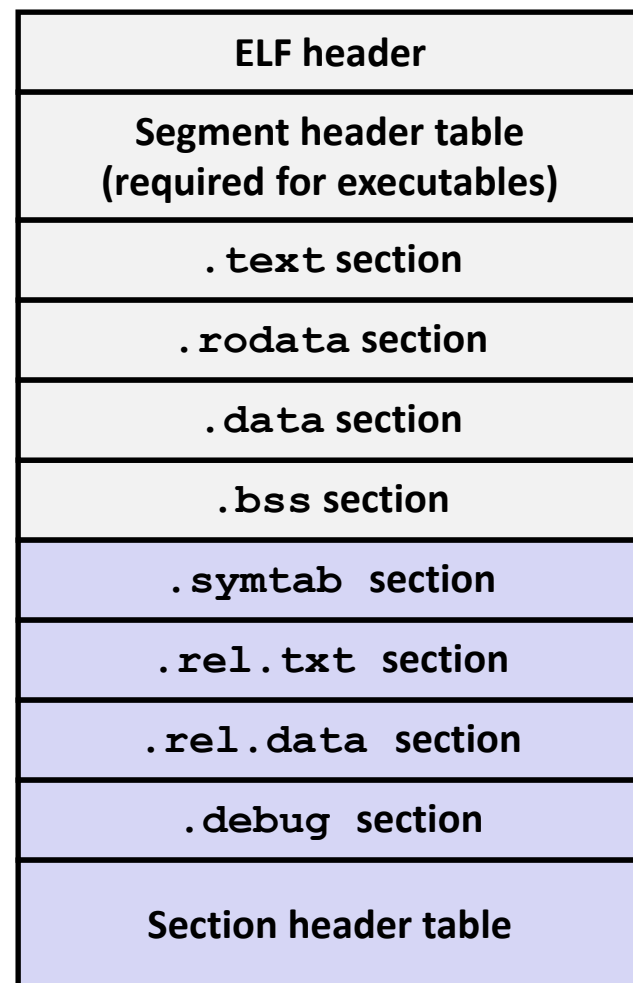
■ .bss section

- 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

...that's defined here

Referencing
a global...

```
int sum(int *a, int n);
int array[2] = {1, 2};
int main(int argc, char **argv)
{
    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
```

Defining
a global

Linker knows
nothing of val

Referencing
a global...

...that's defined here

Linker knows
nothing of i or s

Symbol Identification

Which of the following names will be in the symbol table of `symbols.o`?

`symbols.c`:

```
int incr = 1;
static int foo(int a) {
    int b = a + incr;
    return b;
}

int main(int argc,
         char* argv[]) {
    printf("%d\n", foo(5));
    return 0;
}
```

Names:

- `incr`
- `foo`
- `a`
- `argc`
- `argv`
- `b`
- `main`
- `printf`
- `"%d\n"`

Can find this with `readelf`:

```
linux> readelf -s symbols.o
```

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`

```
static int x = 15;

int f() {
    static int x = 17;
    return x++;
}

int g() {
    static int x = 19;
    return x += 14;
}

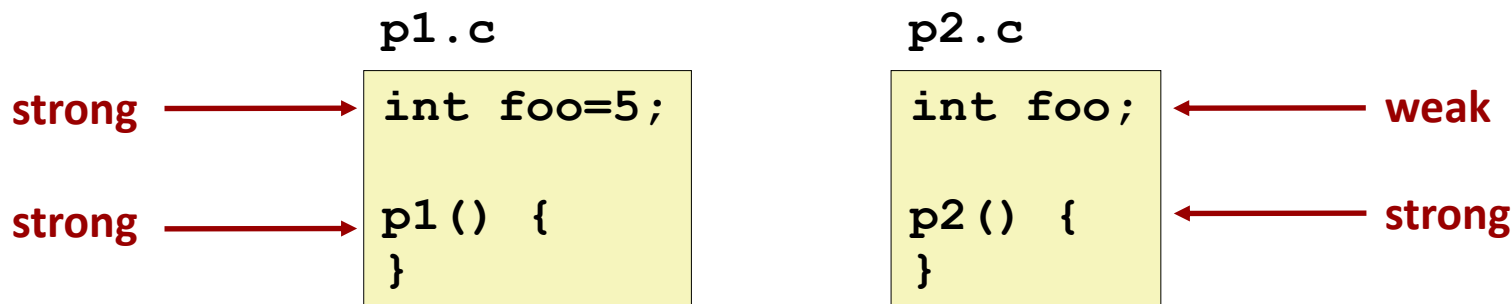
int h() {
    return x += 27;
}
static-local.c
```

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

Creates local symbols in the symbol table with unique names, e.g., `x`, `x.1721` and `x.1724`.

How Linker Resolves Duplicate Symbol Definitions

- Program symbols are either *strong* or *weak*
 - **Strong**: procedures and initialized globals
 - **Weak**: uninitialized globals
 - Or ones declared with specifier **extern**



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`
- **Puzzles on the next slide**

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** might overwrite **y**!
Nasty!

```
int x=7;
p1() {}
```

```
int x;
p2() {}
```

References to **x** will refer to the same initialized variable.

Important: Linker does not do type checking.

Type Mismatch Example

```
long int x; /* Weak symbol */
```

```
int main(int argc,  
         char *argv[]) {  
    printf("%ld\n", x);  
    return 0;  
}
```

mismatch-main.c

```
/* Global strong symbol */
```

```
double x = 3.14;
```

mismatch-variable.c

- Compiles without any errors or warnings
- What gets printed?

```
-bash-4.2$ ./mismatch  
4614253070214989087
```

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
 - Treated as weak symbol
 - But also causes linker error if not defined in some file

Use of extern in .h Files (#1)

c1.c

```
#include "global.h"

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

global.h

```
extern int g;
int f();
```

c2.c

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

int g = 0;

int main(int argc, char argv[]) {
    int t = f();
    printf("Calling f yields %d\n", t);
    return 0;
}
```


Linking Example

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

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

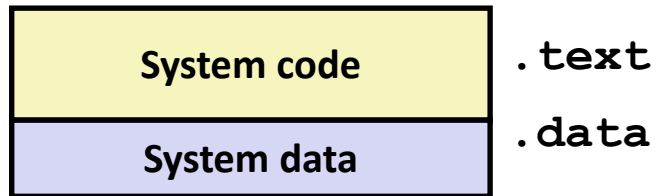
int main(int argc, char **argv)
{
    int val = sum(array, 2);
    return val;
}                                     main.c
```

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

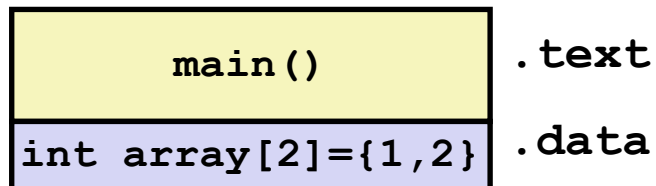
    for (i = 0; i < n; i++) {
        s += a[i];
    }
    return s;
}                                     sum.c
```

Step 2: Relocation

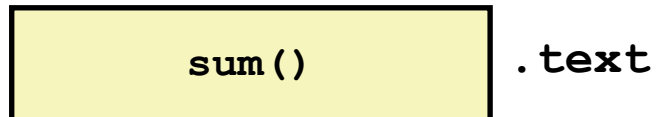
Relocatable Object Files



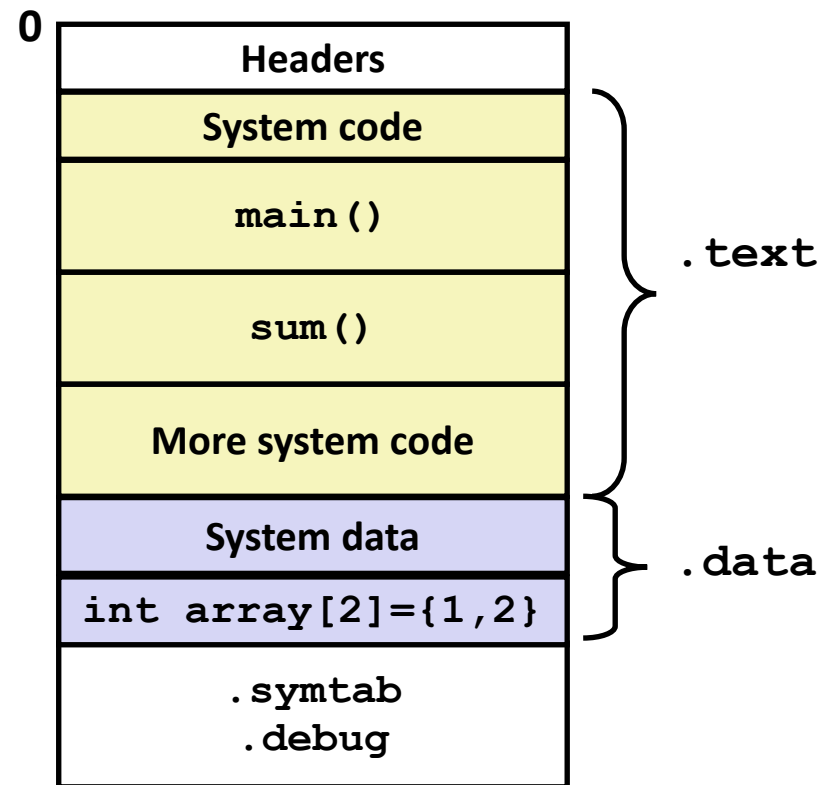
main.o



sum.o



Executable Object File



Relocation Entries

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

int main(int argc, char**
argv)
{
    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
```

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

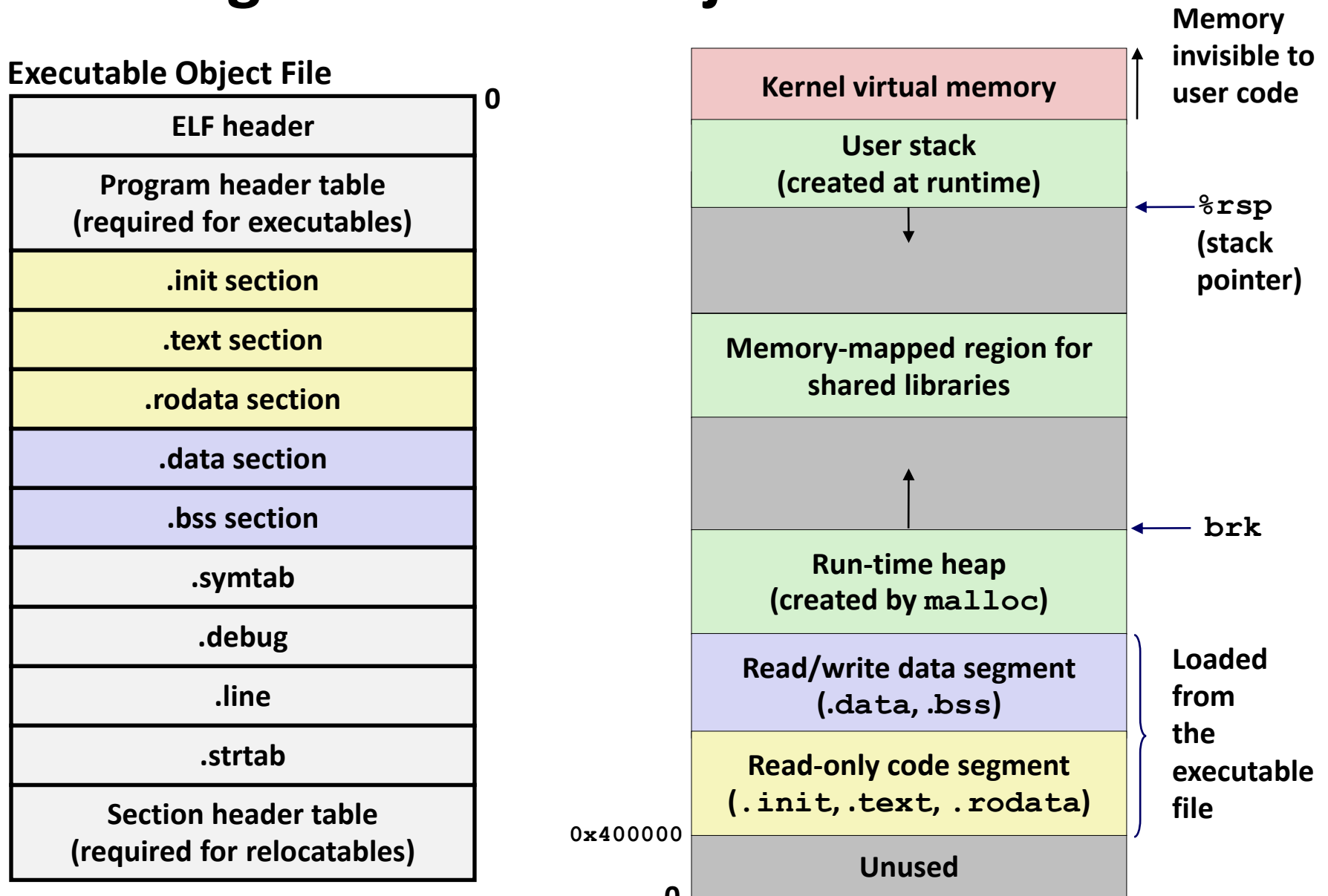
```

`callq` instruction uses PC-relative addressing for `sum()`:

$$0x4004e8 = 0x4004e3 + 0x5$$

Source: `objdump -d prog`

Loading Executable Object Files



Quiz

<https://canvas.cmu.edu/courses/37116/quizzes/109922>

Activity

■ Get the activity

- Go to Canvas → Assignments

- Or here is a direct link:

<https://www.cs.cmu.edu/~213/activities/linking.pdf>

■ Form groups of 2

- One person runs the activity on a shark machine
- The other person fills in the answers

Linking Recap

- **Usually: Just happens, no big deal**
- **Sometimes: Strange errors**