Code optimization & linking

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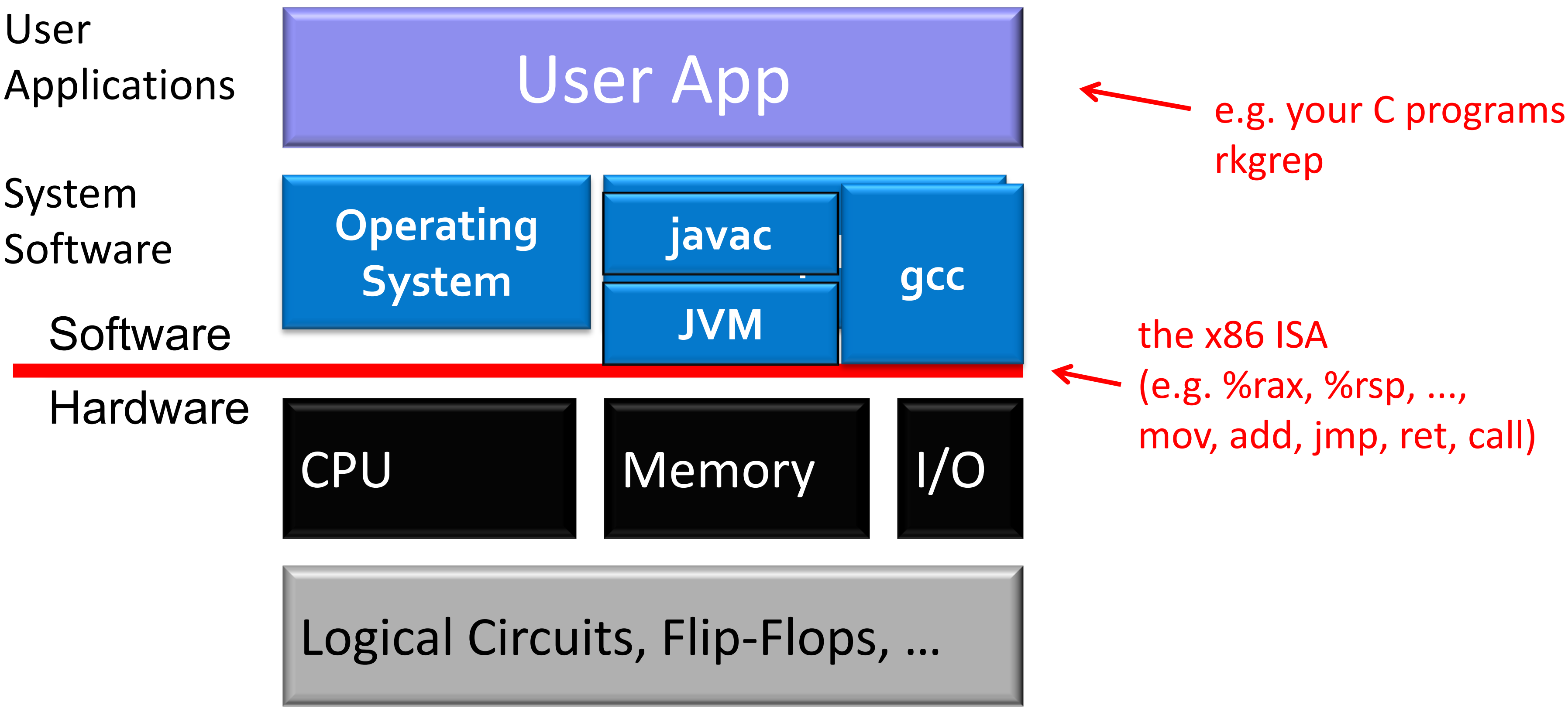
Slides adapted from Jinyang Li, Bryant and O'Hallaron

What we've learnt so far



Today’s plan

- Code optimization (done by the compiler)
  - common optimization techniques
  - what prevents optimization
- C linker

Optimizing Compilers

- Goal: generate efficient, correct machine code
  - allocate registers, choose instructions, ...
- Optimization limitation: must be conservative → do not change program behavior under any scenario
  - analysis is based on static information (no runtime information)
  - most analysis done within a procedure

Optimization: code motion

- Reduce frequency with which computation performed
  - If it will always produce same result

```
void set_row(long *matrix,
 long i, long n)
{
  for (long j = 0; j < n; j++)
    matrix[n*i+j] = 0;
}
```

```
set_row:
 testq  %rcx, %rcx              # Test n
 jle  .L1                       # If 0, goto done
 imulq %rcx, %rdx               # ni = n*i
 leaq   (%rdi,%rdx,8), %rdx     # rowp = A + ni*8
 movq  $0, %rax                 # j = 0
.L3:
 movq  $0, (%rdx,%rax,8)        # M[rowp+8*j] = 0
 addq  $1, %rax                 # j++
 cmpq  %rcx, %rax               # j:n
 jne .L3                        # if !=, goto loop .L3
.L1:
 ret
```

done inside the loop

done outside the loop

Optimization: use simpler instructions

- Replace costly operation with simpler one
  - Shift, add instead of multiply or divide

    ```
    16*x   -->    x << 4
    ```

  - Recognize sequence of products

```
for (long i=0; i<n; i++ {
   for (long j=0; j<n; j++) {
       matrix[n*i+j] = 0;
   }
}
```

```
long ni = 0;
for (long i = 0; i < n; i++) {
  for (long j = 0; j < n; j++) {
    matrix[ni + j] = 0;
  }
  ni += n;
}
```

assembly not shown
this is equivalent C code

Optimization: reuse common subexpressions

```
// Sum neighbors of i,j
up =  val[(i-1)*n + j];
down =  val[(i+1)*n + j];
left =  val[i*n + j-1];
right = val[i*n + j+1];
sum = up + down + left + right;
```

```
long inj = i*n + j;
up =      val[inj - n];
down =  val[inj + n];
left =      val[inj - 1];
right =    val[inj + 1];
sum = up + down + left + right;
```

3 multiplications:
(i-1)*n, (i+1)*n, i*n

1 multiplication:
i*n

assembly not shown
this is equivalent C code

What prevents optimization?

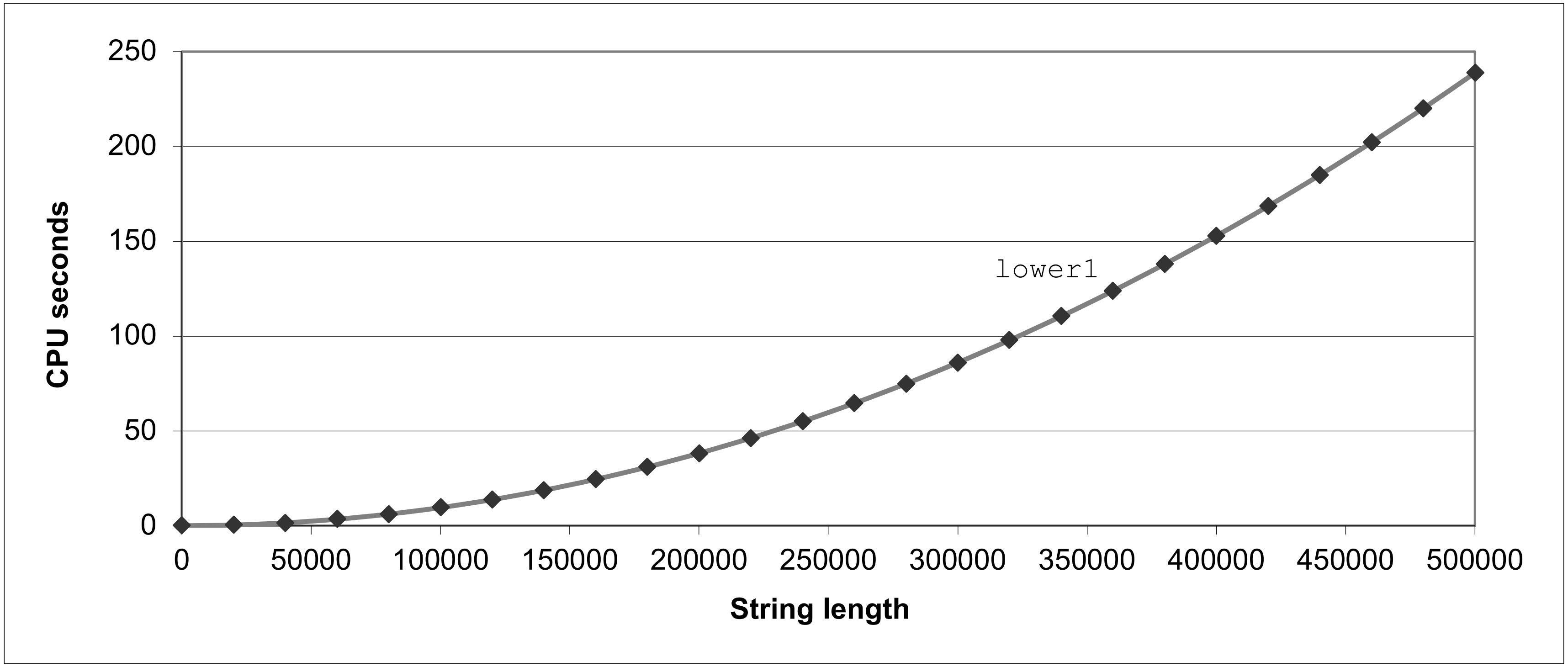
Optimization Blocker #1: Procedure Calls

```
// convert uppercase letters in string to lowercase
void lower(char *s) {
   for (size_t i=0; i<strlen(s); i++) {
      if (s[i] >= 'A' && s[i] <= 'Z') {
         s[i] -= ('A' - 'a');
      }
   }
}
```

Question: What's the big-O runtime of lower, O(n)?

Lower Case Conversion Performance

– Quadratic performance!



Calling strlen in loop

```
// convert uppercase letters in string to lowercase
void lower(char *s) {

   for (size_t i=0; i<strlen(s); i++) {
      if (s[i] >= 'A' && s[i] <= 'Z') {
         s[i] -= ('A' - 'a');
      }
   }
}
```

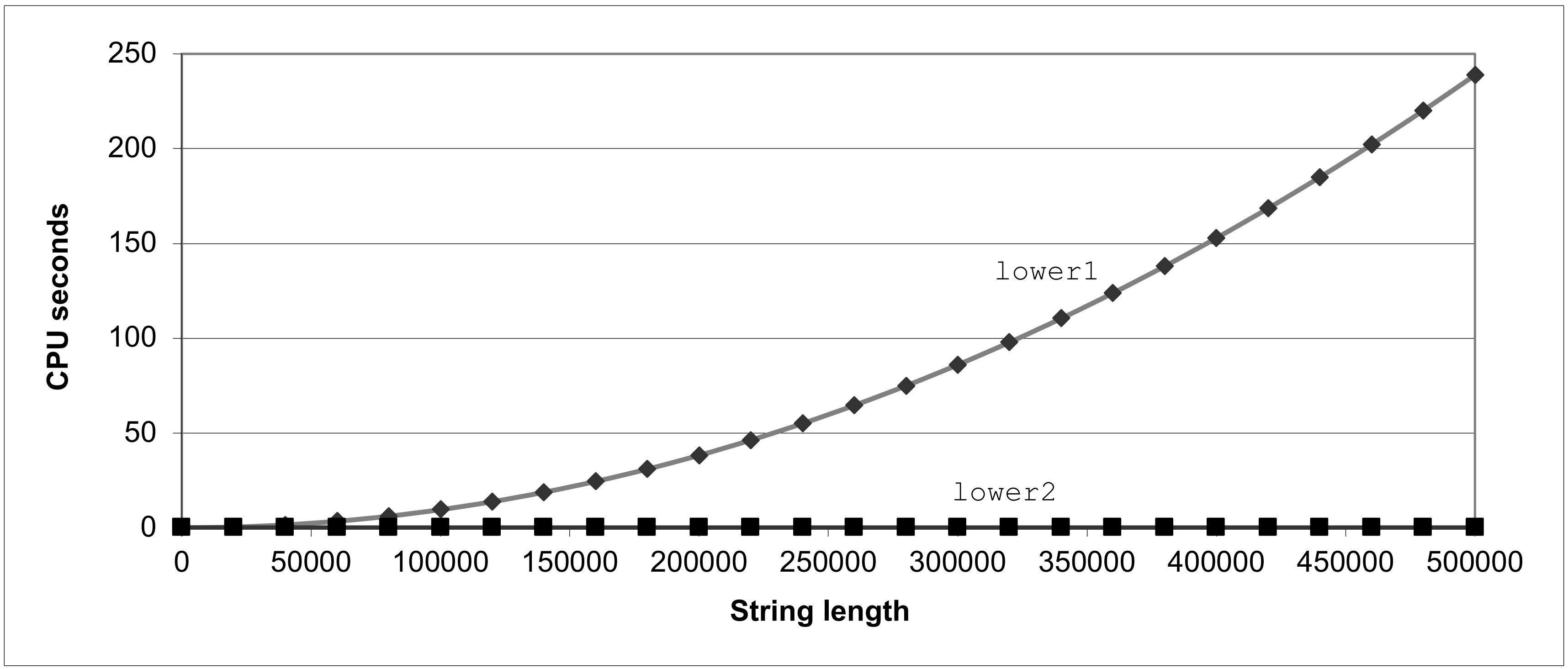
- Strlen takes O(n) to finish
- Strlen is called n times

Calling strlen in loop

```
// convert uppercase letters in string to lowercase
void lower(char *s) {
   size_t len = strlen(s);
   for (size_t i=0; i<len; i++) {
      if (s[i] >= 'A' && s[i] <= 'Z') {
         s[i] -= ('A' - 'a');
      }
   }
}
```

Lower Case Conversion Performance

– Now performance is linear w/ length, as expected



Optimization Blocker: Procedure Calls

- Why can't compiler move `strlen` out of inner loop?
  - Procedure may have side effects
    - May alter global state
  - Procedure may not return same value given same arguments
    - May depend on global state
- Compiler optimization is conservative:
  - Treat procedure call as a black box
  - Weak optimizations near them
- Remedies:
  - Do your own code motion

Optimization Blocker 2: Memory aliasing

```
// Sum rows of n X n matrix and store in vector a
void sum_rows(long *matrix, long *a, long n) {
   for (long i = 0; i < n; i++) {
      a[i] = 0;
      for (long j = 0; j < n; j++) {
         a[i] += matrix[i*n + j];
    }
}
```

```
# inner loop
.L4:
   movq    (%rsi,%rax,8), %r9    # %r9 = a[i]
   addq    (%rdi), %r9           # %r9 += matrix[i*n+j]
   movq    %r9, (%rsi,%rax,8)    # a[i] = r9
   addq     $8, %rdi
   cmpq     %rcx, %rdi
   jne      .L4
```

– Code updates `a[i]` on every iteration
– Why not keep sum in register and stores once at the end?

Memory aliasing: different pointers may point to the same location

```
void sum_rows(long *matrix, long *a, long n) {
   for (long i = 0; i < n; i++) {
      a[i] = 0;
      for (long j = 0; j < n; j++) {
         a[i] += matrix[i*n + j];
      }
   }
}

int main() {
   long matrix[3][3] = {
      {1, 1, 1},
      {1, 1, 1},
      {1, 1, 1}};

   long *a;
   a = (&matrix[0][0])+3;

   sum_rows(&matrix[0][0],a,3);
}
```

a[i] aliases some location in matrix
updates to a[i] changes matrix value

Value of a:

```
before loop:  [1, 1, 1]
after i = 0: [3, 1, 1]
after i = 1: [3, 7, 1]
after i = 2: [3, 7, 3]
```

Optimization blocker: memory aliasing

- Compiler cannot optimize due to potential aliasing
- Manual “optimization”

```
void sum_rows(long *matrix, long *a, long n) {
   for (long i = 0; i < n; i++) {
      long sum = 0;
      for (long j = 0; j < n; j++) {
         sum += matrix[i*n + j];
         a[i] = sum;
      }

}
```

compiler will move a[i] = sum out of inner loop

Getting High Performance

- Use compiler optimization flags
- Watch out for:
  - hidden algorithmic inefficiencies
  - Watch out for optimization blockers: procedure calls & memory aliasing
- Profile the program’s performance

Today’s lesson plan

- Common code optimization (done by the compiler)
  - common optimization
  - what prevents optimization
- C linker

Example C Program

```
#include “sum.h”
int array[2] = {1, 2};

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

main.c

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

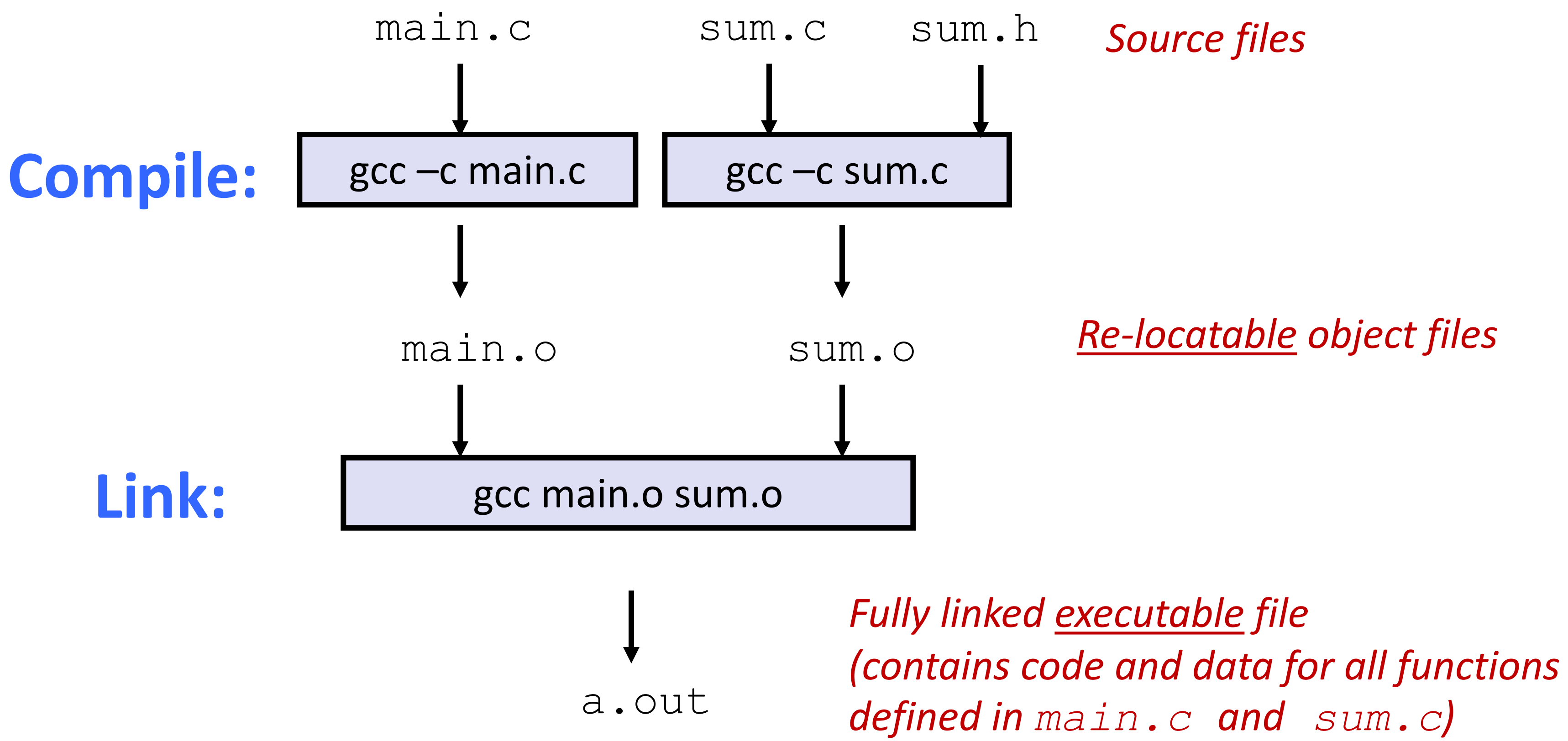
sum.h

```
#include “sum.h”

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

sum.c

Linking


main.c
sum.c
sum.h
Source files
Compile:
gcc –c main.c
gcc –c sum.c
main.o
sum.o
Re-locatable object files
Link:
gcc main.o sum.o
a.out
Fully linked executable file
(contains code and data for all functions
defined in main.c and sum.c)

Why a separate link phase?

- Modula code & efficient compilation
  - Better to structure a program as smaller source files
  - Change of a source file requires only re-compile that file, and then relink.

- Support libraries (no source needed)
  - Build libraries of common functions, other files link against libraries
    - e.g., Math library, standard C library

How does linker merge object files?

- 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 in *symbol table*.
    - Each symbol table entry contains size, and location of symbol.
  - **Linker associates each symbol reference with its symbol definition (i.e. the address of that symbol)**

How does linker merge object files?

- Step 2: Relocation
  - Merge separate object files into one binary executable file
  - Re-locates symbols in the `.o` files to their final absolute memory locations in the executable.

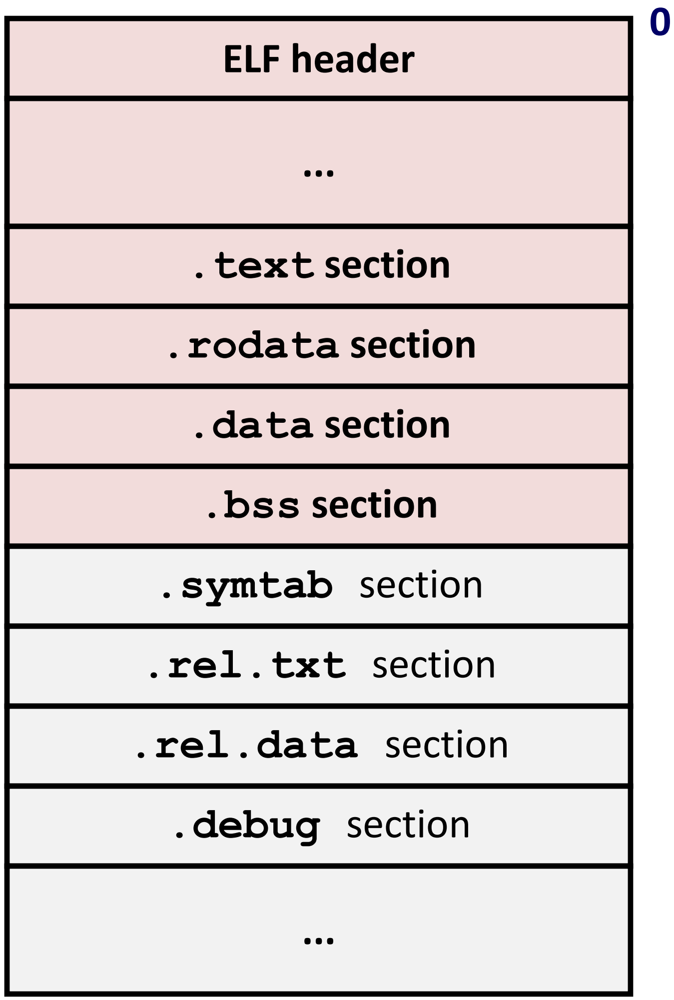
Let's look at these two steps in more detail….

Format of the object files

- ELF is Linux's binary format for object files, including
  - Object files (`.o`),
  - Executable object files (`a.out`)
  - Shared object files, i.e. libraries (`.so`)

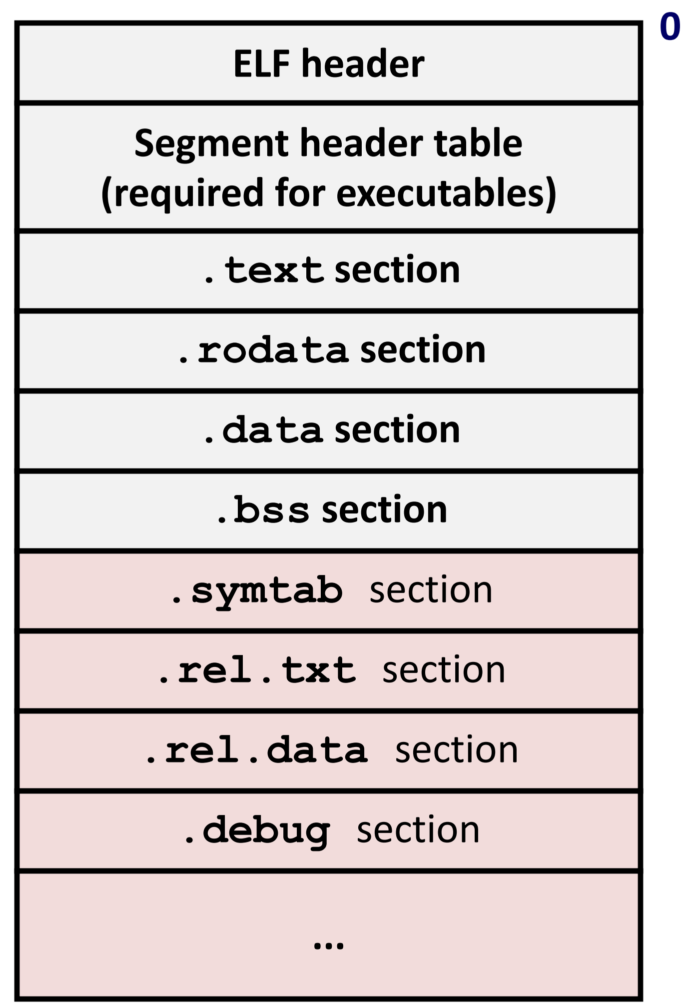
ELF Object File Format

- Elf header
  - file type (.o, exec, .so) ...
- `.text` section
  - Code
- `.rodata` section
  - Read only data
- `.data` section
  - Initialized global variables
- `.bss` section
  - Uninitialized global variables
  - "Better Save Space"
  - Has section header but occupies no space



ELF Object File Format (cont.)

- `.symtab` section
  - Symbol table (symbol name, type, address)
- `.rel.text` section
  - Relocation info for **`.text`** section
  - Addresses of instructions that will need to be modified in the executable
- `.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`**)



Linker Symbols

- Global symbols
  - Symbols that can be referenced by other object files
  - E.g. non-`static` functions & global variables.

- Local symbols
  - Symbols that can only be referenced by this object file.
  - E.g. static functions & global variables

- External symbols ← needs to be resolved
  - Symbols referenced by this object file but defined in other object files.

Step 1: Symbol Resolution

Referencing
a global…

…that's defined here

```c
#include "sum.h"

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`

C linker quirks: it allows symbol name collision!

- 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() {
}
```

`int foo;` ← weak

`p2() {` ← strong

Symbol resolution in the face of name collision

- Rule 1: Multiple strong symbols are not allowed
  - Otherwise: Linker error
- Rule 2: If there’s a strong symbol and multiple weak symbols, they all 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!

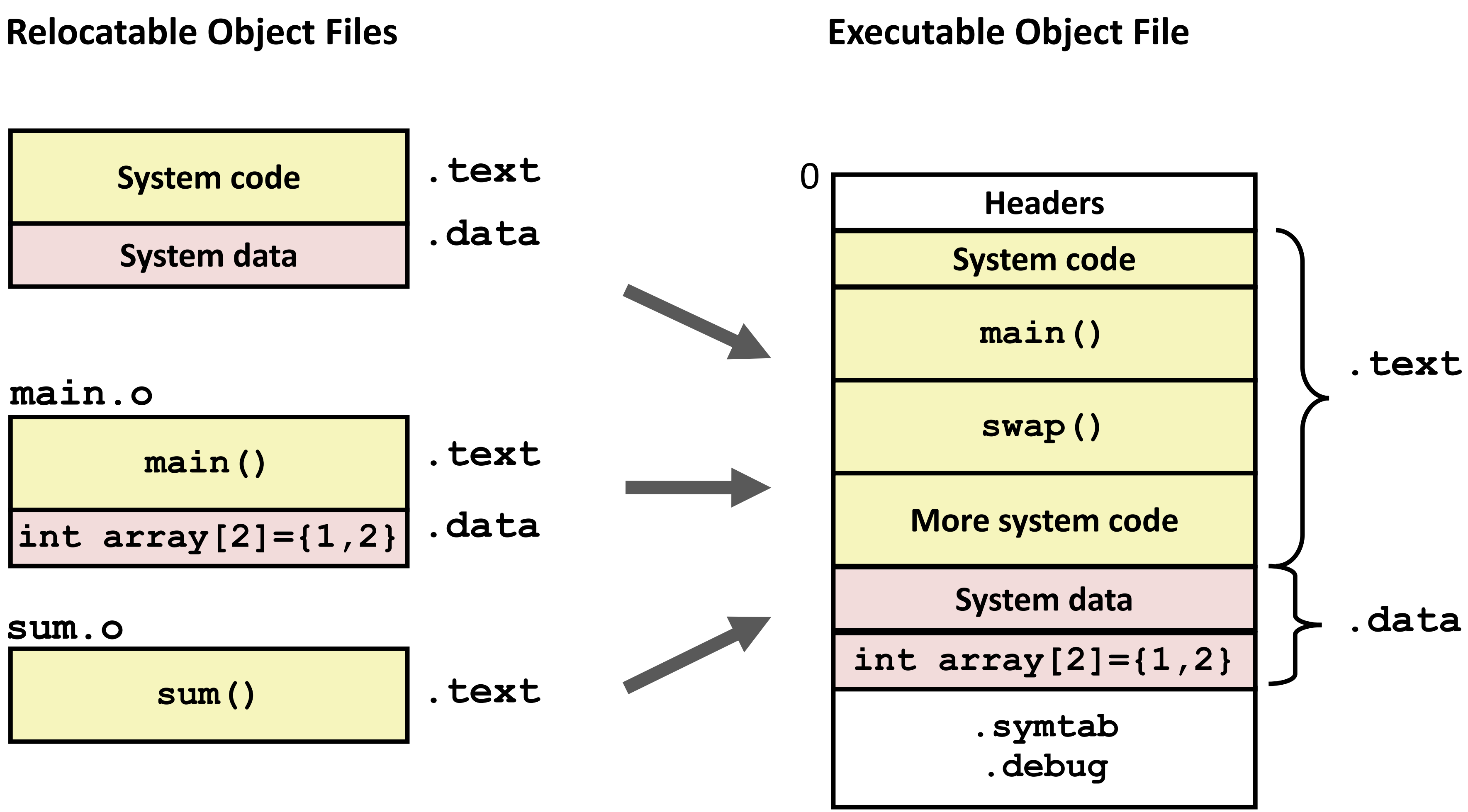
`int x=7;`
`int y=5;`
`p1() {}`
	`double x;`
	`p2() {}`
		Writes to `x` in `p2` will overwrite `y`!
		Nasty!

`int x=7;` `p1() {}`	`int x;` `p2() {}`	References to `x` will refer to the same initialized variable.

How to avoid symbol resolution confusion

- Avoid global variables 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`

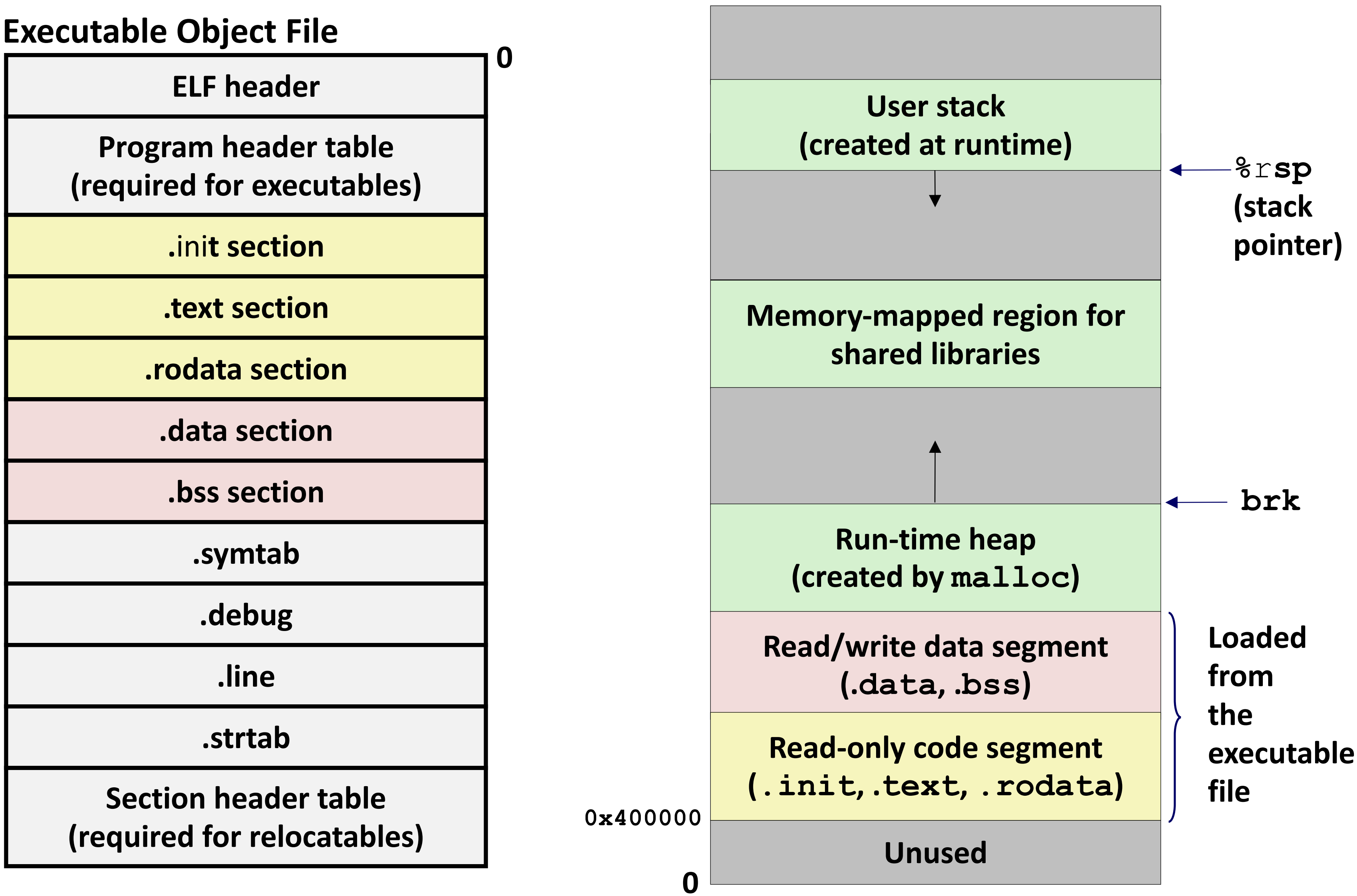
Relocated .text section

```
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:       c3                         retq
```

objdump -d a.out

Loading Executable Object Files



Dynamic linking: Shared Libraries

- 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.

- Shared library routines can be shared by multiple processes.
  - More on this when we learn about virtual memory

Dynamic Linking at Load-time