CS 33

File Systems; Linkers

Disks Are Important

- Cheap
  - cost/byte much less than SSDs
- (fairly) Reliable
  - data written to a disk is likely to be there next year
- Sometimes fast
  - data in consecutive sectors on a track can be read quickly
- Sometimes slow
  - data in randomly scattered sectors takes a long time to read

Abstraction to the Rescue

- Programs don't deal with sectors, tracks, and cylinders
- Programs deal with *files*
  - maze.c rather than an ordered collection of sectors
  - OS provides the implementation

Implementation Problems

- Speed
  - use the hierarchy
    - » copy files into RAM, copy back when done
  - optimize layout
    - » put sectors of a file in consecutive locations
  - use parallelism
    - » spread file over multiple disks
    - » read multiple sectors at once

Implementation Problems

- Reliability
  - computer crashes
    - » what you thought was safely written to the file never made it to the disk — it's still in RAM, which is lost
    - » worse yet, some parts made it back to disk, some didn't
      - you don't know which is which
      - on-disk data structures might be totally trashed
  - disk crashes
    - » you had backed it up … yesterday
  - you screw up
    - » you accidentally delete the entire directory containing your shell 1 solution

Implementation Problems

- Reliability solutions
  - – computer crashes
    - » transaction-oriented file systems
    - » on-disk data structures always in well defined states
  - – disk crashes
    - » files stored redundantly on multiple disks
  - – you screw up
    - » file system automatically keeps "snapshots" of previous versions of files

gcc Steps

1) Compile
   - to start here, supply .c file
   - to stop here: `gcc -S` (produces .s file)
   - if not stopping here, gcc compiles directly into a .o file, bypassing the assembler
2) Assemble
   - to start here, supply .s file
   - to stop here: `gcc -c` (produces .o file)
3) Link
   - to start here, supply .o file

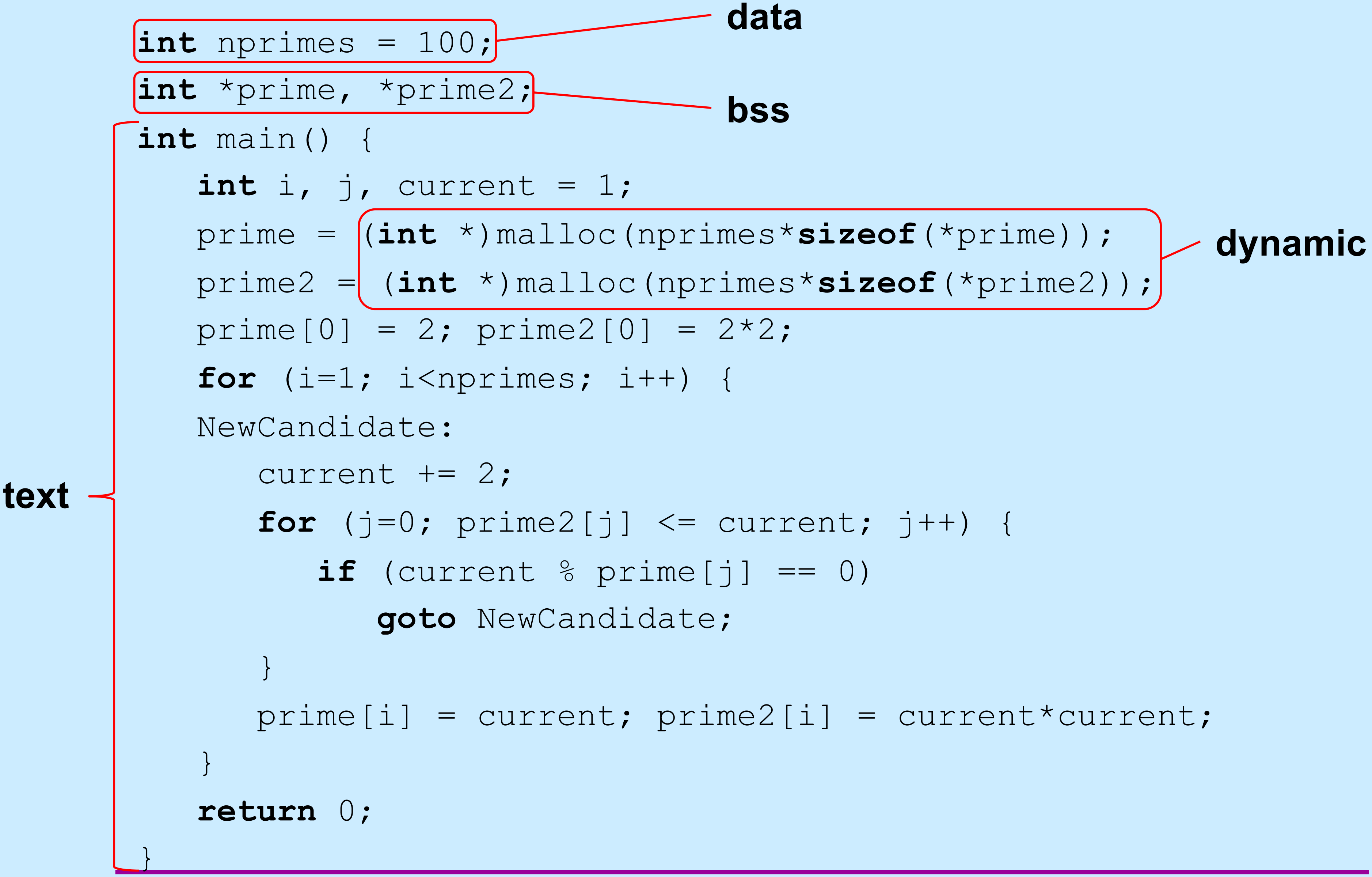
The Linker

- An executable program is one that is ready to be loaded into memory
- The linker (known as ld: /usr/bin/ld) creates such executables from:
  - object files produced by the compiler/assembler
  - collections of object files (known as libraries or archives)
  - and more we'll get to soon ...

Linker's Job

- Piece together components of program
  - arrange within address space
    - » code (and read-only data) goes into text region
    - » initialized data goes into data region
    - » uninitialized data goes into bss region
- Modify address references, as necessary

A Program



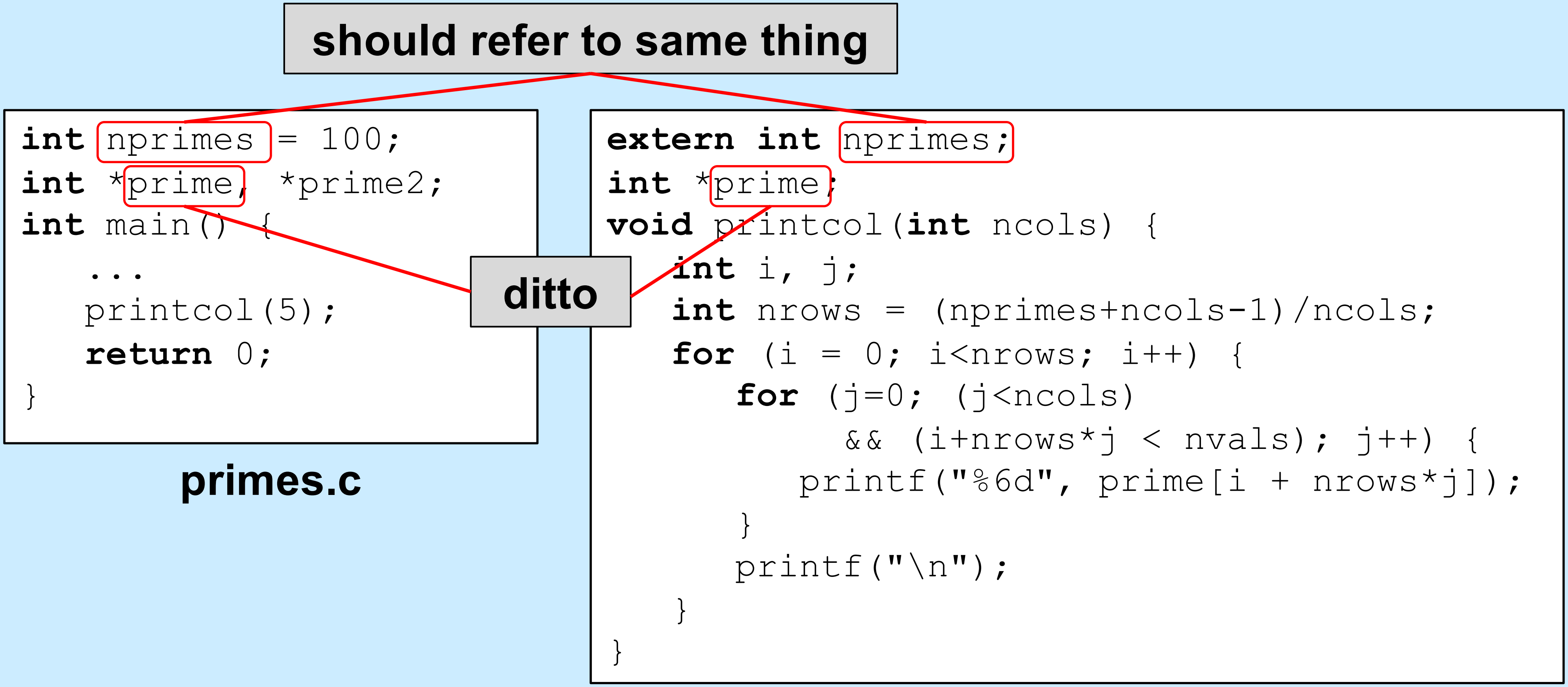
```
int nprimes = 100;
int *prime, *prime2;
int main() {
   int i, j, current = 1;
   prime = (int *)malloc(nprimes*sizeof(*prime));
   prime2 = (int *)malloc(nprimes*sizeof(*prime2));
   prime[0] = 2; prime2[0] = 2*2;
   for (i=1; i<nprimes; i++) {
   NewCandidate:
      current += 2;
      for (j=0; prime2[j] <= current; j++) {
         if (current % prime[j] == 0)
            goto NewCandidate;
      }
      prime[i] = current; prime2[i] = current*current;
   }
   return 0;
}
```

... with Output

```
int nprimes = 100;
int *prime, *prime2;
int main() {
   ...
   printcol(5);
   return 0;
}

void printcol(int ncols) {
   int i, j;
   int nrows = (nprimes+ncols-1)/ncols;
   for (i = 0; i<nrows; i++) {
      for (j=0; (j<ncols) && (i+nrows*j < nvals); j++) {
         printf("%6d", prime[i + nrows*j]);
      }
      printf("\n");
   }
}
```

... Compiled Separately



should refer to same thing

ditto

```
int nprimes = 100;
int *prime, *prime2;
int main() {
   ...
   printcol(5);
   return 0;
}
```

primes.c

```
extern int nprimes;
int *prime;
void printcol(int ncols) {
   int i, j;
   int nrows = (nprimes+ncols-1)/ncols;
   for (i = 0; i<nrows; i++) {
      for (j=0; (j<ncols)
           && (i+nrows*j < nvals); j++) {
         printf("%6d", prime[i + nrows*j]);
      }
      printf("\n");
   }
}
```

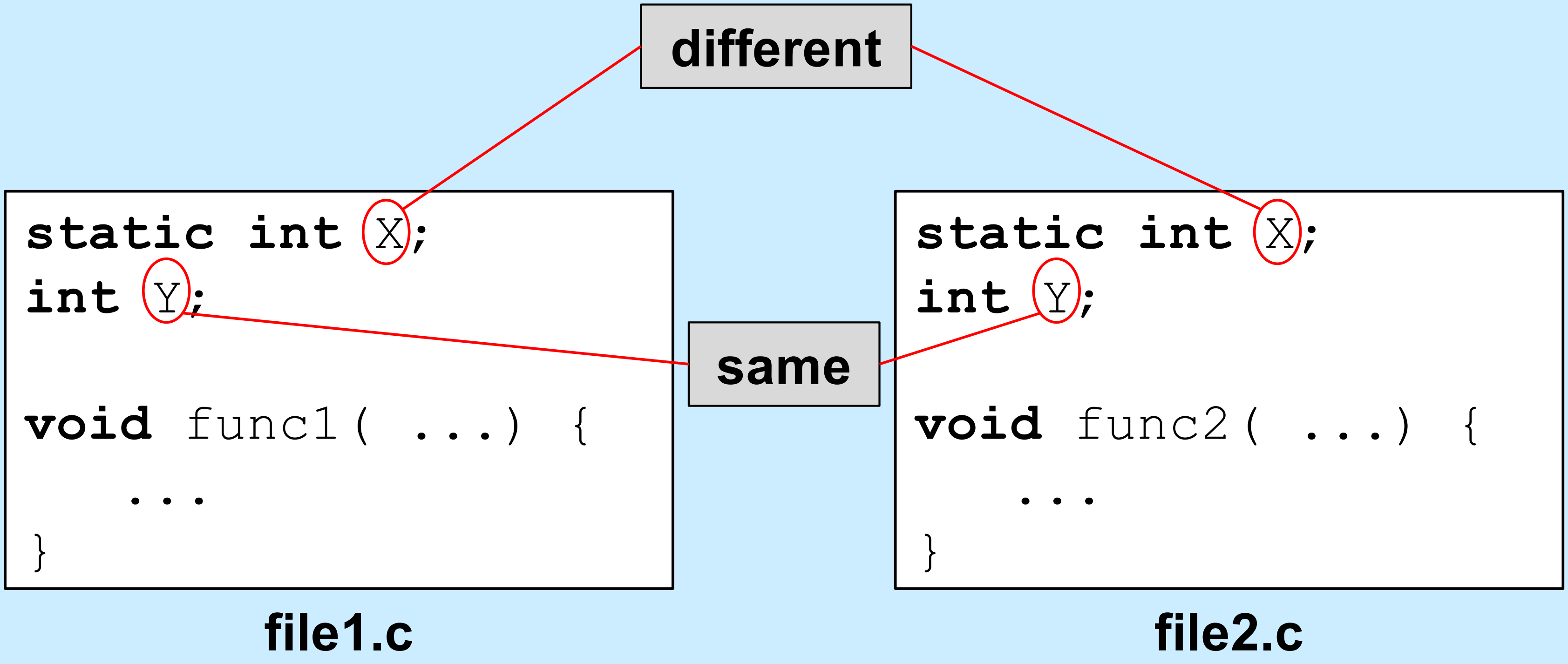
printcol.c

gcc –c primes.c
gcc –c printcol.c
gcc –o primes primes.o printcol.o

Global Variables

- Initialized vs. uninitialized
  - initialized allocated in *data* section
  - uninitialized allocated in *bss* section
    - » implicitly initialized to zero
- File scope vs. program scope
  - *static* global variables known only within file that declares them
    - » two of same name in different files are different
    - » e.g., `static int X;`
  - non-static global variables potentially shared across all files
    - » two of same name in different files are same
    - » e.g., `int X;`

Scope



```
static int X;
int Y;

void func1( ...) {
   ...
}
```

file1.c

```
static int X;
int Y;

void func2( ...) {
   ...
}
```

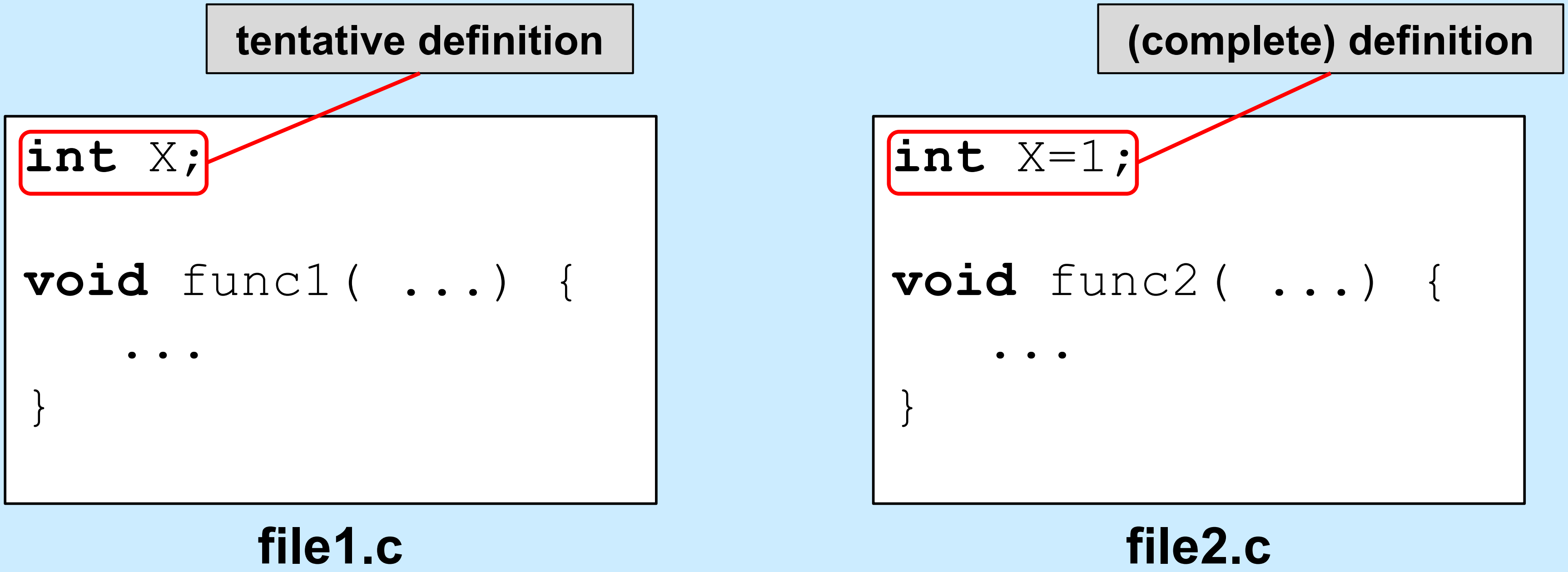
file2.c

Static Local Variables

```
int *sub1() {
  int var = 1;
  …
  return &var;
  /* amazingly illegal */
}
```

```
int *sub2() {
  static int var = 1;
  …
  return &var;
  /* (amazingly) legal */
}
```

Reconciling Program Scope (1)



tentative definition

```
int X;

void func1( ...) {
    ...
}
```

file1.c

(complete) definition

```
int X=1;

void func2( ...) {
    ...
}
```

file2.c

Where does X go?
What's its initial value?

- tentative definitions overridden by compatible (complete) definitions
- if not overridden, then initial value is zero

Reconciling Program Scope (2)

```
int X=2;

void func1( ...) {
   ...
}
```

file1.c

```
int X=1;

void func2( ...) {
   ...
}
```

file2.c

What happens here?

Reconciling Program Scope (3)

```
int X=1;

void func1( ...) {
    ...
}
```

file1.c

```
int X=1;

void func2( ...) {
    ...
}
```

file2.c

Is this ok?

Reconciling Program Scope (4)

```
extern int X;

void func1( ...) {
    ...
}
```

file1.c

```
int X=1;

void func2( ...) {
    ...
}
```

file2.c

What’s the purpose of “extern”?

Default Values (1)

```
float seed = 1.0;

int PrimaryFunc(float arg) {
  ...
  SecondaryFunc(arg + seed);
  ...
}

void SecondaryFunc(float arg) {
  ...
}
```

Default Values (2)

```
float seed = 2.0; /* want a different seed */

int main() {
  ...
  PrimaryFunc(floatingValue);
  ...
}

void SecondaryFunc(float arg) {
  /* would like to override default version */
  ...
}
```

Default Values (3)

```
__attribute__((weak)) float seed = 1.0;

int PrimaryFunc(float arg) {
  ...
  SecondaryFunc(arg + seed);
  ...
}

void __attribute__((weak)) SecondaryFunc(float arg) {
  ...
}
```

Does Location Matter?

```
int main(int argc, char *[]) {
   return(argc);
}
```

```
main:
  pushq %rbp   ; push frame pointer
  movq  %rsp, %rbp     ; set frame pointer to point to new frame
  movl  %edi, %eax     ; put argc into return register (eax)
  movq  %rbp, %rsp     ; restore stack pointer
  popq  %rbp   ; pop stack into frame pointer
  ret          ; return: pops end of stack into rip
```

Location Matters ...

```
int X=6;
int *aX = &X;

int main() {
    void subr(int);
    int y=*aX;
    subr(y);
    return(0);
}

void subr(int i) {
    printf("i = %d\n", i);
}
```

Coping

- Relocation
  - – modify internal references according to where module is loaded in memory
  - – modules needing relocation are said to be *relocatable*
    - » which means they *require* relocation
  - – the compiler/assembler provides instructions to the linker on how to do this

A Revised Version of Our Program

```c
extern int X;
int *aX = &X;
int Y = 1;

int main() {
    void subr(int);
    int y = *aX+Y;
    subr(y);
    return(0);
}
```

main.c

```c
#include <stdio.h>
int X;

void subr(int XX) {
    printf("XX = %d\n", XX);
    printf("X = %d\n", X);
}
```

subr.c

```
gcc -o prog -O1 main.c subr.c
```

main.s (1)

```
            .file   "main.c"
0:          .text
0:          .globl  main
0:          .type   main, @function
0: main:
0: .LFB0:
0:          .cfi_startproc
0:          subq    $8, %rsp
4:          .cfi_def_cfa_offset 16
4:          movq    aX(%rip), %rax
11:         movl    (%rax), %edi
13:         addl    Y(%rip), %edi
19:         call    subr
24:         movl    $0, %eax
29:         addq    $8, %rsp
33:         .cfi_def_cfa_offset 8
33:         ret
34:         .cfi_endproc
34:.LFE0:
34:         .size   main, .-main
```

must be replaced with aX's address, expressed as an offset from the next instruction

must be replaced with Y's address, expressed as an offset from the next instruction

must be replaced with subr's address, expressed as an offset from the next instruction

main.s (2)

```
             .globl  Y
0:           .data
0:           .align 4
0:           .type   Y, @object
0:           .size   Y, 4
0:  Y:
0:           .long   1
4:           .globl  aX
8:           .align 8
8:           .type   aX, @object
8:           .size   aX, 8
8:  aX:
8:           .quad   X
8:           .ident  "GCC: (Debian 4.7.2-5) 4.7.2"
0:           .section        .note.GNU-stack,"",@progbits
```

Y should be made known to others

aX should be made known to others

must be replaced with address of X

subr.s (1)

```
           .file   "subr.c"
0:         .section        .rodata.str1.1,"aMS",@progbits,1
0: .LC0:
0:         .string "XX = %d\n"
9: .LC1:
9:         .string "X = %d\n"
```

subr.s (2)

```
0:          .text
0:          .globl  subr
0:          .type   subr, @function
0: subr:
0: .LFB11:
0:          .cfi_startproc
0:          subq    $8, %rsp
4:          .cfi_def_cfa_offset 16
4:          movl    %edi, %esi
6:          movl    $.LC0, %edi
11:         movl    $0, %eax
16:         call    printf
21:         movl    X(%rip), %esi
27:         movl    $.LC1, %edi
32:         movl    $0, %eax
37:         call    printf
42:         addq    $8, %rsp
46:         .cfi_def_cfa_offset 8
46:         ret
47:         .cfi_endproc
47:.LFE11:
47:         .size   subr, .-subr
```

subr should be made known to others

must be replaced with .LC0’s address

must be replaced with .LC1’s address

must be replaced with printf’s address, expressed as an offset from the next instruction

subr.s (3)

reserve 4 bytes of 4-byte aligned storage for X

```
0:         .comm   X,4,4
0:         .ident  "GCC: (Debian 4.7.2-5) 4.7.2"
0:         .section        .note.GNU-stack,"",@progbits
```

Quiz 1

```
int X;
int proc(int arg) {
  static int Y;
  int Z;

  ...

}
```

Which of *X*, *Y*, *Z*, and *arg* would the compiler know the addresses of at compile time?

a) all
b) just *X* and *Y*
c) just *arg* and *Z*
d) none

ELF

- Executable and linking format
  - used on most Unix systems
    - » pretty much all but OS X
  - defines format for:
    - » .o (object) files
    - » .so (shared object) files
    - » executable files

Doing Relocation

- Linker is provided instructions for updating object files
  - lots of ways addresses can appear in machine code
  - three in common use on x86-64
    - 32-bit absolute addresses
      - used for text references
    - 64-bit absolute addresses
      - used for data references
    - 32-bit PC-relative addresses
      - offset from current value of rip
      - used for text and data references

main.o (1)

```
ELF Header:
  Magic:   7f 45 4c 46 02 01 01 00 00 00 00 00 00 00 00 00
  Class:                             ELF64
  Data:                              2's complement, little endian
  Version:                           1 (current)
  OS/ABI:                            UNIX - System V
  ABI Version:                       0
  Type:                              REL (Relocatable file)
  Machine:                           Advanced Micro Devices X86-64
  Version:                           0x1
  Entry point address:               0x0
  Start of program headers:          0 (bytes into file)
  Start of section headers:          296 (bytes into file)
  Flags:                             0x0
  Size of this header:               64 (bytes)
  Size of program headers:           0 (bytes)
  Number of program headers:         0
  Size of section headers:           64 (bytes)
  Number of section headers:         13
  Section header string table index: 10
```

main.o (2)

32-bit, PC-relative address

```
Relocation section '.rela.text' at offset 0x5c0 contains 3 entries:
  Offset          Info           Type           Sym. Value    Sym. Name + Addend
000000000007  000900000002 R_X86_64_PC32     0000000000000008 aX - 4
00000000000f  000a00000002 R_X86_64_PC32     0000000000000000 Y - 4
000000000014  000b00000002 R_X86_64_PC32     0000000000000000 subr - 4

Relocation section '.rela.data' at offset 0x608 contains 1 entries:
  Offset          Info           Type           Sym. Value    Sym. Name + Addend
000000000008  000c00000001 R_X86_64_64       0000000000000000 X + 0
```

64-bit, absolute address

```
   0:    48 83 ec 08               sub    $0x8,%rsp
   4:    48 8b 05 00 00 00 00      mov    0x0(%rip),%rax        # b <main+0xb>
   b:    8b 38                     mov    (%rax),%edi
   d:    03 3d 00 00 00 00         add    0x0(%rip),%edi        # 13 <main+0x13>
  13:    e8 00 00 00 00            callq  18 <main+0x18>
  18:    b8 00 00 00 00            mov    $0x0,%eax
  1d:    48 83 c4 08               add    $0x8,%rsp
  21:    c3                        retq
```

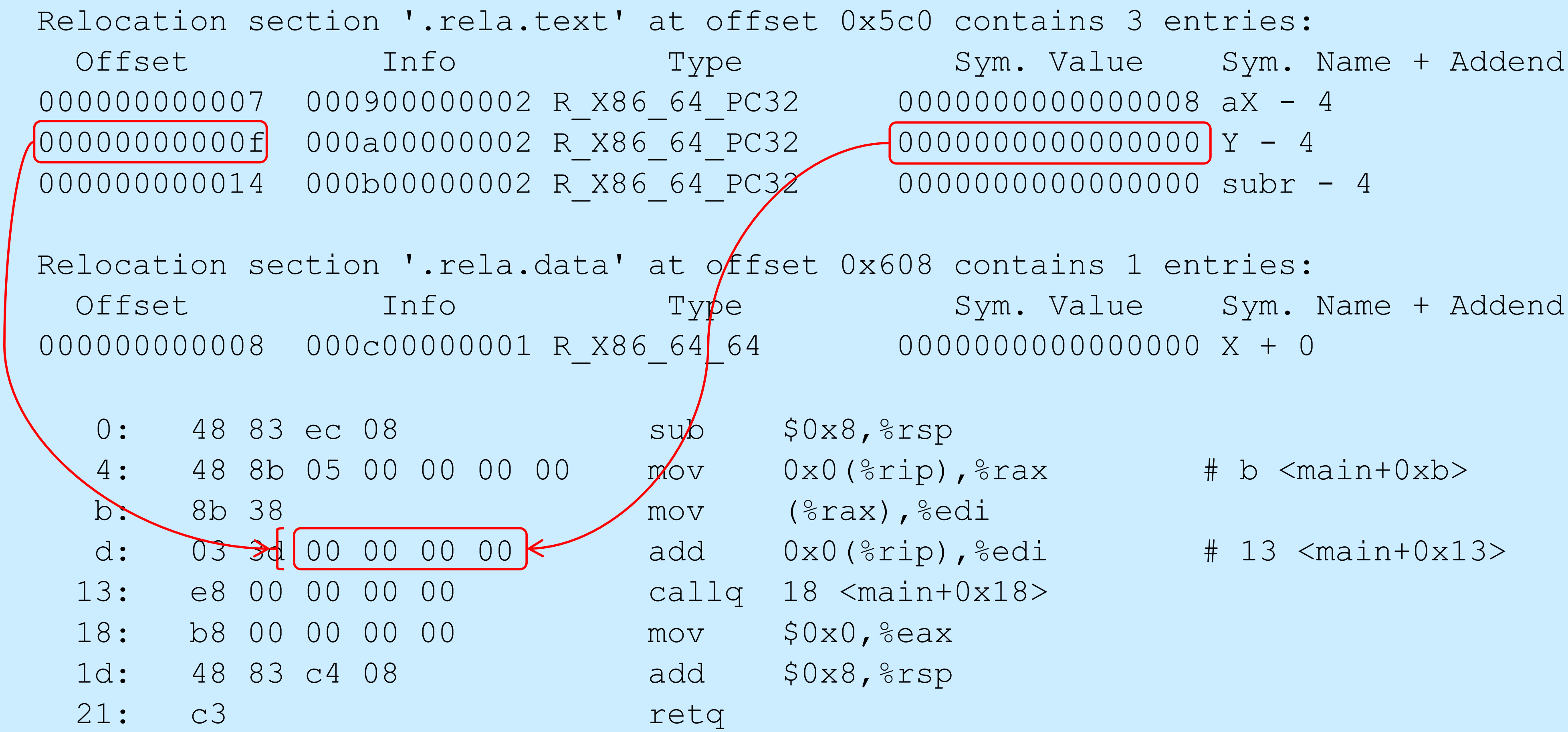
main.o (3)

```
Relocation section '.rela.text' at offset 0x5c0 contains 3 entries:
  Offset          Info           Type           Sym. Value    Sym. Name + Addend
000000000007  000900000002 R_X86_64_PC32     0000000000000008 aX - 4
00000000000f  000a00000002 R_X86_64_PC32     0000000000000000 Y - 4
000000000014  000b00000002 R_X86_64_PC32     0000000000000000 subr - 4

Relocation section '.rela.data' at offset 0x608 contains 1 entries:
  Offset          Info           Type           Sym. Value    Sym. Name + Addend
000000000008  000c00000001 R_X86_64_64       0000000000000000 X + 0
```

```
   0:   48 83 ec 08             sub    $0x8,%rsp
   4:   48 8b 05 00 00 00 00    mov    0x0(%rip),%rax        # b <main+0xb>
   b:   8b 38                   mov    (%rax),%edi
   d:   03 3d 00 00 00 00       add    0x0(%rip),%edi        # 13 <main+0x13>
  13:   e8 00 00 00 00          callq  18 <main+0x18>
  18:   b8 00 00 00 00          mov    $0x0,%eax
  1d:   48 83 c4 08             add    $0x8,%rsp
  21:   c3                      retq
```

main.o (4)

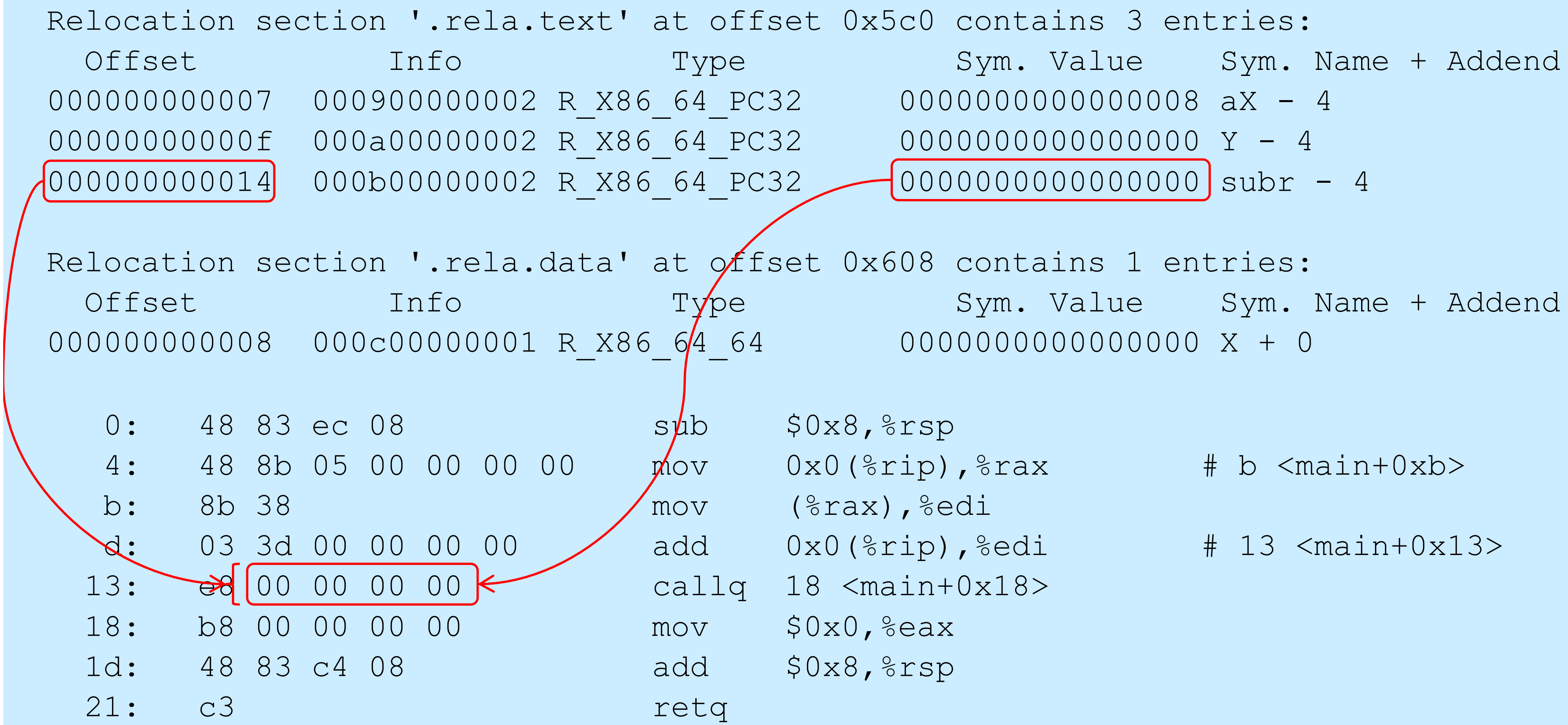


```
Relocation section '.rela.text' at offset 0x5c0 contains 3 entries:
  Offset          Info           Type           Sym. Value    Sym. Name + Addend
000000000007  000900000002 R_X86_64_PC32     0000000000000008 aX - 4
00000000000f  000a00000002 R_X86_64_PC32     0000000000000000 Y - 4
000000000014  000b00000002 R_X86_64_PC32     0000000000000000 subr - 4

Relocation section '.rela.data' at offset 0x608 contains 1 entries:
  Offset          Info           Type           Sym. Value    Sym. Name + Addend
000000000008  000c00000001 R_X86_64_64       0000000000000000 X + 0

   0:   48 83 ec 08             sub    $0x8,%rsp
   4:   48 8b 05 00 00 00 00    mov    0x0(%rip),%rax        # b <main+0xb>
   b:   8b 38                   mov    (%rax),%edi
   d:   03 3d 00 00 00 00       add    0x0(%rip),%edi        # 13 <main+0x13>
  13:   e8 00 00 00 00          callq  18 <main+0x18>
  18:   b8 00 00 00 00          mov    $0x0,%eax
  1d:   48 83 c4 08             add    $0x8,%rsp
  21:   c3                      retq
```

main.o (5)



```
Relocation section '.rela.text' at offset 0x5c0 contains 3 entries:
  Offset          Info           Type           Sym. Value    Sym. Name + Addend
000000000007  000900000002 R_X86_64_PC32     0000000000000008 aX - 4
00000000000f  000a00000002 R_X86_64_PC32     0000000000000000 Y - 4
000000000014  000b00000002 R_X86_64_PC32     0000000000000000 subr - 4

Relocation section '.rela.data' at offset 0x608 contains 1 entries:
  Offset          Info           Type           Sym. Value    Sym. Name + Addend
000000000008  000c00000001 R_X86_64_64       0000000000000000 X + 0

   0:   48 83 ec 08             sub    $0x8,%rsp
   4:   48 8b 05 00 00 00 00    mov    0x0(%rip),%rax        # b <main+0xb>
   b:   8b 38                   mov    (%rax),%edi
   d:   03 3d 00 00 00 00       add    0x0(%rip),%edi        # 13 <main+0x13>
  13:   e8 00 00 00 00          callq  18 <main+0x18>
  18:   b8 00 00 00 00          mov    $0x0,%eax
  1d:   48 83 c4 08             add    $0x8,%rsp
  21:   c3                      retq
```

main.o (6)

```
Relocation section '.rela.text' at offset 0x5c0 contains 3 entries:
  Offset          Info           Type           Sym. Value    Sym. Name + Addend
000000000007  000900000002 R_X86_64_PC32     0000000000000008 aX - 4
00000000000f  000a00000002 R_X86_64_PC32     0000000000000000 Y - 4
000000000014  000b00000002 R_X86_64_PC32     0000000000000000 subr - 4

Relocation section '.rela.data' at offset 0x608 contains 1 entries:
  Offset          Info           Type           Sym. Value    Sym. Name + Addend
000000000008  000c00000001 R_X86_64_64       0000000000000000 X + 0

   0:   48 83 ec 08             sub    $0x8,%rsp
   4:   48 8b 05 00 00 00 00    mov    0x0(%rip),%rax        # b <main+0xb>
   b:   8b 38                   mov    (%rax),%edi
   d:   03 3d 00 00 00 00       add    0x0(%rip),%edi        # 13 <main+0x13>
  13:   e8 00 00 00 00          callq  18 <main+0x18>
  18:   b8 00 00 00 00          mov    $0x0,%eax
  1d:   48 83 c4 08             add    $0x8,%rsp
  21:   c3                      retq
```

subr.o (1)

```
ELF Header:
  Magic:   7f 45 4c 46 02 01 01 00 00 00 00 00 00 00 00 00
  Class:                             ELF64
  Data:                              2's complement, little endian
  Version:                           1 (current)
  OS/ABI:                            UNIX - System V
  ABI Version:                       0
  Type:                              REL (Relocatable file)
  Machine:                           Advanced Micro Devices X86-64
  Version:                           0x1
  Entry point address:               0x0
  Start of program headers:          0 (bytes into file)
  Start of section headers:          312 (bytes into file)
  Flags:                             0x0
  Size of this header:               64 (bytes)
  Size of program headers:           0 (bytes)
  Number of program headers:         0
  Size of section headers:           64 (bytes)
  Number of section headers:         13
  Section header string table index: 10
```

subr.o (2)

```
Relocation section '.rela.text' at offset 0x5b0 contains 5 entries:
  Offset          Info           Type           Sym. Value    Sym. Name + Addend
000000000007  00050000000a R_X86_64_32       0000000000000000 .rodata.str1.1 + 0
000000000011  000a00000002 R_X86_64_PC32     0000000000000000 printf - 4
000000000017  000b00000002 R_X86_64_PC32     0000000000000004 X - 4
00000000001c  00050000000a R_X86_64_32       0000000000000000 .rodata.str1.1 + 9
000000000026  000a00000002 R_X86_64_PC32     0000000000000000 printf - 4
```

```
.rodata.str1.1:
XX = %d\n\0X = %d\n\0
```

```
   0:   48 83 ec 08             sub    $0x8,%rsp
   4:   89 fe                   mov    %edi,%esi
   6:   bf 00 00 00 00          mov    $0x0,%edi
   b:   b8 00 00 00 00          mov    $0x0,%eax
  10:   e8 00 00 00 00          callq  15 <subr+0x15>
  15:   8b 35 00 00 00 00       mov    0x0(%rip),%esi        # 1b <subr+0x1b>
  1b:   bf 00 00 00 00          mov    $0x0,%edi
  20:   b8 00 00 00 00          mov    $0x0,%eax
  25:   e8 00 00 00 00          callq  2a <subr+0x2a>
  2a:   48 83 c4 08             add    $0x8,%rsp
  2e:   c3                      retq
```

Quiz 2

Consider the following 5-byte instruction:

```
ea 00 00 00 00
```

`ea` is the opcode for the call instruction with a 32-bit PC-relative operand.

Suppose this instruction is at location 0x1000. To what location would control be transferred if the instruction were executed as is?

a) 0

b) 0x1000

c) 0x1001

d) 0x1005

printf.o

```
Relocation section '.rela.text' at offset 0x5c0 contains 3 entries:
  Offset          Info           Type           Sym. Value    Sym. Name + Addend
0000000002d3  000b00000002 R_X86_64_PC32     0000000000000000 write - 4

Relocation section '.rela.data' at offset 0x608 contains 1 entries:
  Offset          Info           Type           Sym. Value    Sym. Name + Addend
0000000000d3  000c00000001 R_X86_64_64       0000000000000000 StandardFiles + 0
```

prog

```
ELF Header:
  Magic:   7f 45 4c 46 02 01 01 00 00 00 00 00 00 00 00 00
  Class:                             ELF64
  Data:                              2's complement, little endian
  Version:                           1 (current)
  OS/ABI:                            UNIX - System V
  ABI Version:                       0
  Type:                              EXEC (Executable file)
  Machine:                           Advanced Micro Devices X86-64
  Version:                           0x1
  Entry point address:               0x400400
  Start of program headers:          64 (bytes into file)
  Start of section headers:          2704 (bytes into file)
  Flags:                             0x0
  Size of this header:               64 (bytes)
  Size of program headers:           56 (bytes)
  Number of program headers:         8
  Size of section headers:           64 (bytes)
  Number of section headers:         31
  Section header string table index: 28
```

Final Result

Symbol	Value	Size	
_start	0x400400	0x60	text
main	0x400460	0x3f	
subr	0x4004a0	0x30	
printf	0x4004d0	0x12000	
write	0x4124d0	0x30	
.rodata	0x412500	0x9	
aX	0x413000	0x8	data
Y	0x413008	0x8	
StandardFiles	0x413010	0x1000	
X	0x414010	0x8	bss