Princeton University

Computer Science 217: Introduction to Programming Systems

Machine Language

A paradox

grader.c

```
enum {BUFSIZE = 48};

char grade = 'D';
char name[BUFSIZE];

/* Read a string into s */
void readString(char *s) {
 char buf[BUFSIZE];
 int i = 0;  int c;

 /* Read string into buf[] */
 for (;;) {
   c = fgetc(stdin);
   if (c == EOF || c == '\n')
      break;
   buf[i] = c;
   i++;
 }
 /* Copy buf[] to s[] */
 buf[i] = '\0';
 for (i = 0; i < BUFSIZE; i++)
   s[i] = buf[i];
}
```

```
int main(void) {
   printf("What is your name?\n");
   readString(name);
   if (strcmp(name, "Andrew") == 0)
      grade = 'B';
   printf("%c is your grade, %s.\n",
          grade, name);
   return 0;
}
```

What is your name?
Bob
D is your grade, Bob.

What is your name?
Andrew
B is your grade, Andrew.

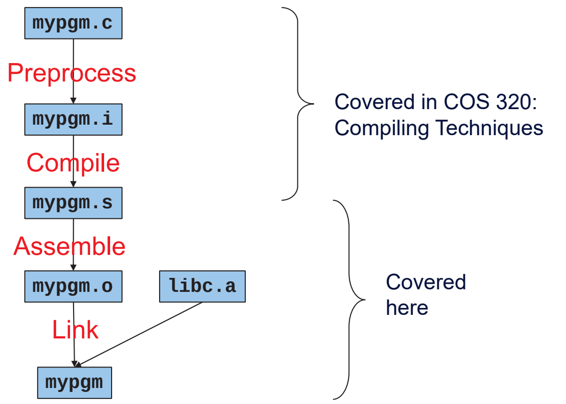
What is your name?
[fill in something here]
A is your grade, Susan.

Machine language

This lecture is about

- machine language (in general)
- x86-64 machine language (in particular)
- The assembly and linking processes
- Amusing and important applications to computer security
  (and therefore, Programming Assignment 5, Buffer Overrun)

The Build Process



Covered in COS 320:
Compiling Techniques

Covered
here

Instruction Set Architecture (ISA)

There are many kinds of computer chips out there:

Intel x86 series
IBM PowerPC
ARM
RISC-V
MIPS

Each of these different "machine architectures" understands a different *machine language*

(and, in the old days, dozens more)

CISC and RISC styles of machine language

CISC	RISC
Complex, powerful instructions	**Simple** do-only-one-thing instructions
Many memory addressing modes (direct, indirect, base+displacement, indexed, scaled indexed)	**Few** memory addressing modes (typically only base+displacement)
Hardware interpretation is **complex**	Hardware interpretation is **simple**
Need relatively **few** instructions to accomplish a given job	Need **more** instructions to accomplish a given job
Example: x86-64	Examples: ARM, PowerPC

Energy efficient; battery lasts longer!

Agenda

x86-64 Machine Language

Buffer overrun vulnerabilities

x86-64 Machine Language after Assembly

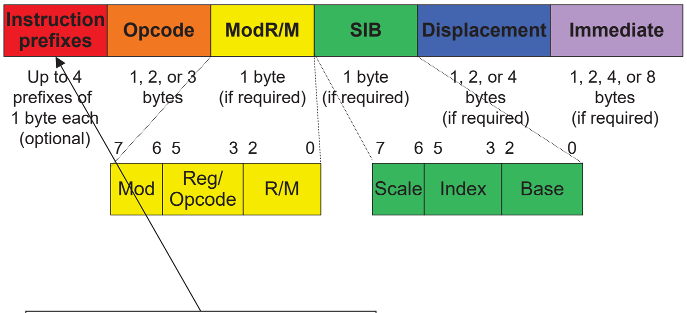
x86-64 Machine Language after Linking

Assembly Language: `addq %rax, %rbx`

Machine Language: `01001000 00000001 11000011`

x86-64 Instruction Format

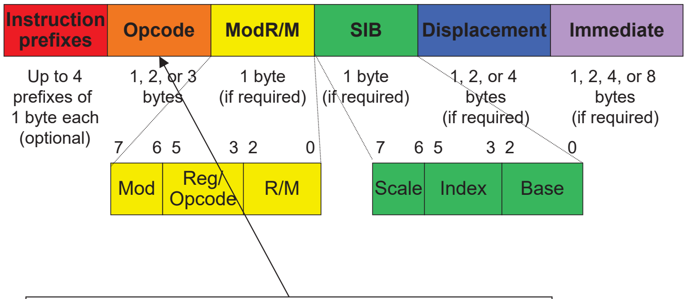
Difficult to generalize about x86-64 instruction format; many instructions use this format



Instruction prefix

- Sometimes a repeat count
- Rarely used; don't be concerned

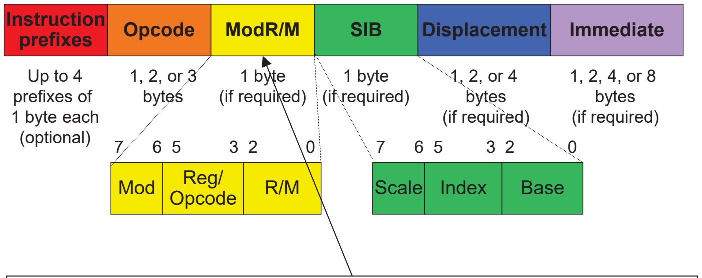
x86-64 Instruction Format (cont.)



Opcode

- Specifies which operation should be performed
  - Add, move, call, etc.
- Sometimes specifies additional (or less) information

x86-64 Instruction Format (cont.)



ModR/M (register mode, register/opcode, register/memory)

- Specifies types of operands (immediate, register, memory)
- Specifies sizes of operands (byte, word, long)
- Sometimes contains an extension of the opcode

x86-64 Instruction Format (cont.)

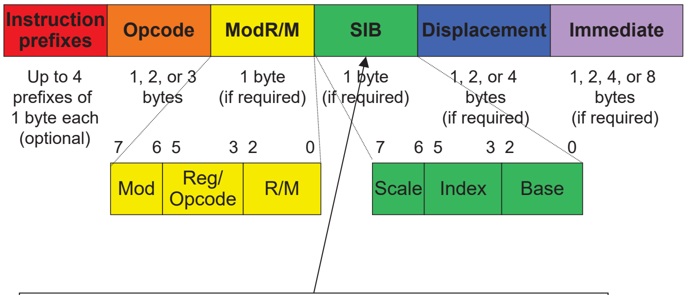
Sometimes 3 bits in ModR/M byte, along with extra bit in another field, specify a register

- For 8-byte registers:

Extra	ModR/M	Register
0	000	RAX
0	001	RCX
0	010	RDX
0	011	RBX
0	100	RSP
0	101	RBP
0	110	RSI
0	111	RDI
1	000	R8
1	001	R9
1	010	R10
1	011	R11
1	100	R12
1	101	R13
1	110	R14
1	111	R15

Similar mappings exist for 4-byte, 2-byte and 1-byte registers

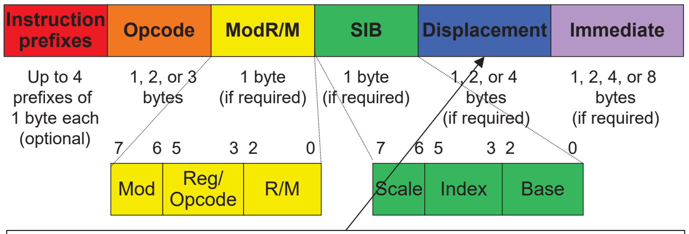
x86-64 Instruction Format (cont.)



SIB (scale, index, base)

- Used when one of the operands is a memory operand that uses a **s**cale, an **i**ndex register, and/or a **b**ase register

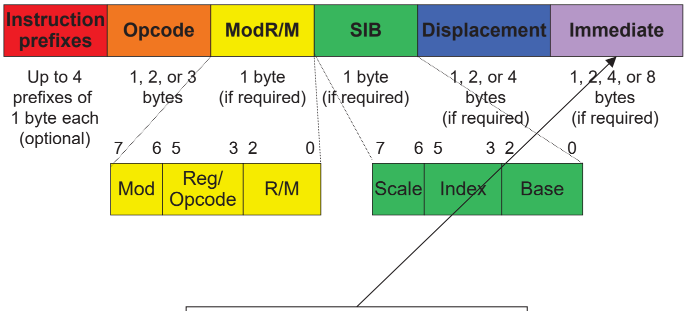
x86-64 Instruction Format (cont.)



Displacement

- Part of memory operand, or…
- In jump and call instructions, indicates the displacement between the destination instruction and the jump/call instruction
  - More precisely, indicates: [addr of destination instr] – [addr of instr following the jump/call]
- Uses little-endian byte order

x86-64 Instruction Format (cont.)



Immediate

- Specifies an immediate operand
- Uses little-endian byte order

Example 1

Assembly lang: `addq %rax, %rbx`
Machine lang: `4801c3`
Explanation:

```
01001000 00000001 11000011

Opcode: This is an add instruction whose src operand is an
8-byte register or memory operand and whose dest operand is
a 8-byte register
                  ModR/M: The M field of the ModR/M byte
                  designates a register
                    ModR/M: The src register is RAX
                       ModR/M: The dest register is RBX
```

Extra	ModR/M	Register
0	000	RAX/EAX
0	001	RCX/ECX
0	010	RDX/EDX
0	011	RBX/EBX
0	100	RSP/ESP
0	101	RBP/EBP
0	110	RSI/ESI
0	111	RDI/EDI

Observation: Sometimes opcode specifies operation (e.g. add) and format(s) of operand(s)

Example 2

Assembly lang: `movl $1, %ebx`
Machine lang: `bb01000000`
Explanation:

```
10111011 00000001 00000000 00000000 00000000

Opcode: This is a mov instruction whose src operand is a 4-byte
immediate
     Opcode: the destination operand is the EBX register
         Immediate: The immediate operand is 1
```

Observation: Sometimes opcode specifies operation and operand(s)
Observation: Immediate operands are in little-endian byte order

Examples 3, 4

Assembly lang: `pushq %rax`
Machine lang: `50`
Explanation:

```
01010000
Opcode: This is a pushq %rax instruction
```

Assembly lang: `pushq %rcx`
Machine lang: `51`
Explanation:

```
01010001
Opcode: This is a pushq %rcx instruction
```

Observation: Sometimes opcode specifies operation and operand(s)
Observation: **pushq** is used often, so is optimized into 1 byte

Example 5

Assembly lang: `movl -8(%eax,%ebx,4), %edx`
Machine lang: `678b5498f8`
Explanation:

```
10100111 10001011 01010100 10011000 11111000

Opcode: This is a mov instruction whose src operand is
a 4-byte register or memory operand and whose dest operand is
a 4-byte register
                  ModR/M: The src operand is a register, the
                  dest operand is of the form disp(base,index,
                  scale), the base and index registers are
                  4-byte registers, and the disp is one-byte
                    ModR/M: The destination register is EDX
                           SIB: The scale is 4
                             SIB: The index register is EBX
                                SIB: The base reg is EAX
                                    Displacement: The disp is -8
```

Observation: Two's complement notation
Observation: Complicated!!!

Agenda

x86-64 Machine Language

Buffer overrun vulnerabilities

x86-64 Machine Language after Assembly

x86-64 Machine Language after Linking

A program

```
% a.out
What is your name?
John Smith
Thank you, John Smith.
%
```

```
#include <stdio.h>
int main(int argc, char **argv) {
  char name[12];  int i;
  printf("What is your name?\n");
  for (i=0; ; i++) {
    int c = getchar();
    if (c=='\n' || c ==EOF) break;
    name[i] = c;
  }
  name[i]='\0';
  printf("Thank you, %s.\n", name);
  return 0;
}
```

Why did this program crash?

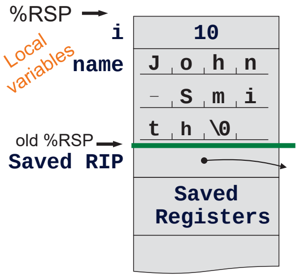
```
% a.out
What is your name?
adsli57asdkhj5jklds;ahj5;klsaduj5klysdukl5aujksd5ukals;5uj;akukla
Segmentation fault
%
```

```
#include <stdio.h>
int main(int argc, char **argv) {
  char name[12];  int i;
  printf("What is your name?\n");
  for (i=0; ; i++) {
    int c = getchar();
    if (c=='\n' || c ==EOF) break;
    name[i] = c;
  }
  name[i]='\0';
  printf("Thank you, %s.\n", name);
  return 0;
}
```

Stack frame layout

```
% a.out
What is your name?
John Smith
Thank you, John Smith.
%
```

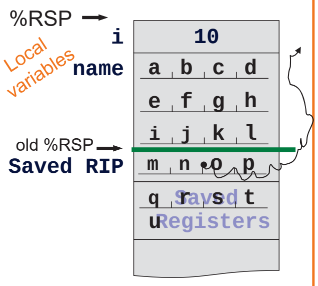
```
#include <stdio.h>
int main(int argc, char **argv) {
  char name[12];  int i;
  printf("What is your name?\n");
  for (i=0; ; i++) {
    int c = getchar();
    if (c=='\n' || c ==EOF) break;
    name[i] = c;
  }
  name[i]='\0';
  printf("Thank you, %s.\n", name);
  return 0;
}
```



Buffer overrun

```
% a.out
What is your name?
abcdefghijklmnopqrstu
Segmentation fault
%
```

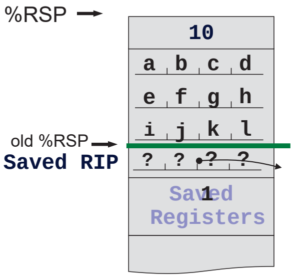
```
#include <stdio.h>
int main(int argc, char **argv) {
  char name[12];  int i;
  printf("What is your name?\n");
  for (i=0; ; i++) {
    int c = getchar();
    if (c=='\n' || c ==EOF) break;
    name[i] = c;
  }
  name[i]='\0';
  printf("Thank you, %s.\n", name);
  return 0;
}
```



Innocuous? buffer overrun

```
% a.out
What is your name?
abcdefghijkl????^A\0\0\0
%
```

```
#include <stdio.h>
int main(int argc, char **argv) {
  char name[12];  int i;
  printf("What is your name?\n");
  for (i=0; ; i++) {
    int c = getchar();
    if (c=='\n' || c ==EOF) break;
    name[i] = c;
  }
  name[i]='\0';
  printf("Thank you, %s.\n", name);
  return 0;
}
```

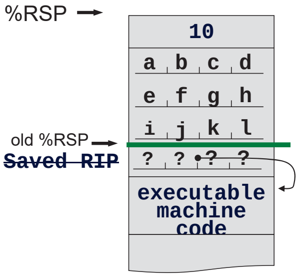


Cleverly malicious?
Maliciously clever?

Buffer overrun

```
% a.out
What is your name?
abcdefghijkl????executable-machine-code...
How may I serve you, master?
%
```

```
#include <stdio.h>
int main(int argc, char **argv) {
  char name[12];  int i;
  printf("What is your name?\n");
  for (i=0; ; i++) {
    int c = getchar();
    if (c=='\n' || c ==EOF) break;
    name[i] = c;
  }
  name[i]='\0';
  printf("Thank you, %s.\n", name);
  return 0;
}
```



NOTE: in the programming assignment, you will not execute machine code directly from the stack, you'll arrange for your injected machine code to be copied to the data segment, and execute it from there.

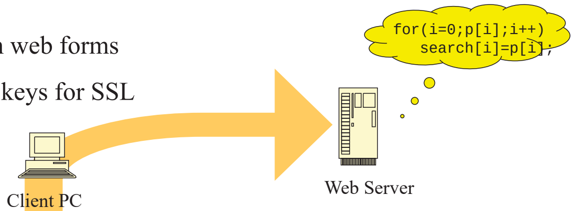
Attacking a web server

URLs

Input in web forms

Crypto keys for SSL

etc.



this is a really long search term that overflows a buffer

Attacking a web browser

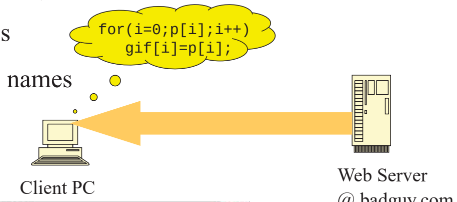
HTML keywords

Images

Image names

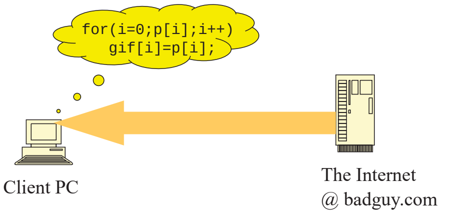
URLs

etc.



Earn $$$ Thousands
working at home!

Attacking everything in sight



E-mail client

PDF viewer

Operating-system kernel

TCP/IP stack

Any application that ever sees input directly from the outside

Defenses against this attack

Best: program in languages that make array-out-of-bounds impossible (Java, C#, ML, python, ...)

None of these would have prevented the "Heartbleed" attack

If you must program in C: use discipline *and software analysis tools* in C programming always to check bounds of array subscripts

Otherwise, stopgap security patches:

- Operating system randomizes initial stack pointer
- "No-execute" memory permission
- "Canaries" at end of stack frames

Your programming assignment: Attack the "grader" program

```
enum {BUFSIZE = 48};

char grade = 'D';
char name[BUFSIZE];

/* Read a string into s */
void readString(char *s) {
 char buf[BUFSIZE];
 int i = 0;  int c;

 /* Read string into buf[] */
 for (;;) {
   c = fgetc(stdin);
   if (c == EOF || c == '\n')
      break;
   buf[i] = c;
   i++;
 }
 /* Copy buf[] to s[] */
 buf[i] = '\0';
 for (i = 0; i < BUFSIZE; i++)
   s[i] = buf[i];
}
```

```
int main(void) {
   printf("What is your name?\n");
   readString(name);
   if (strcmp(name, "Andrew") == 0)
      grade = 'B';
   printf("%c is your grade, %s.\n",
         grade, name);
   return 0;
}
```

What is your name?
Bob
D is your grade, Bob.

What is your name?
Andrew
B is your grade, Andrew.

What is your name?
Susan\0*?!*!????*???!*!%!?!(!*%(*^^?*
A is your grade, Susan.

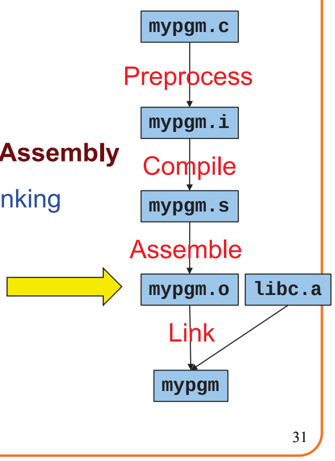
Agenda

x86-64 Machine Language

Buffer overrun vulnerabilities

x86-64 Machine Language after Assembly

x86-64 Machine Language after Linking



An Example Program

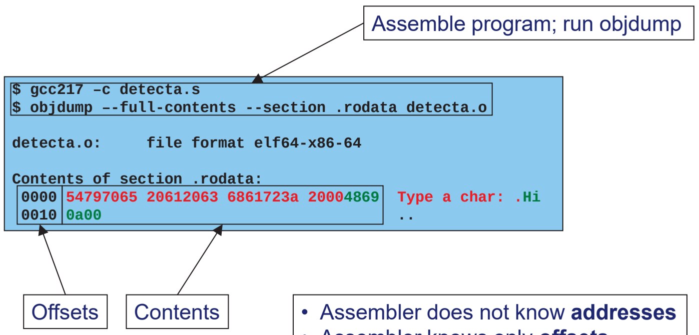
A simple (nonsensical) program:

```
#include <stdio.h>
int main(void)
{  printf("Type a char: ");
   if (getchar() == 'A')
      printf("Hi\n");
   return 0;
}
```

```
        .section ".rodata"
msg1:   .string "Type a char"
msg2:   .string "Hi\n"
        .section ".text"
        .globl  main
main:
        movl    $0, %eax
        movq    $msg1, %rdi
        call    printf
        call    getchar
        cmpl    $'A', %eax
        jne     skip
        movl    $0, %eax
        movq    $msg2, %rdi
        call    printf
skip:
        movl    $0, %eax
        ret
```

Let's consider the machine lang equivalent after assembly…

Examining Machine Lang: RODATA

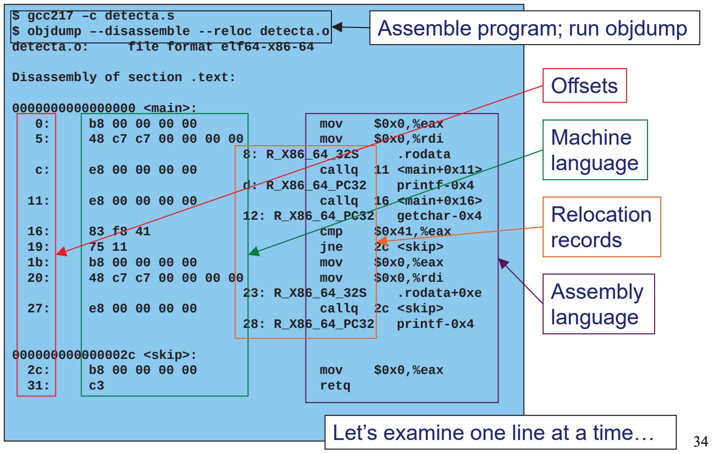


Assemble program; run objdump

```
$ gcc217 –c detecta.s
$ objdump –-full-contents --section .rodata detecta.o

detecta.o:     file format elf64-x86-64

Contents of section .rodata:
 0000 54797065 20612063 6861723a 20004869  Type a char: .Hi
 0010 0a00                                 ..
```

- Assembler does not know **addresses**
- Assembler knows only **offsets**
- **"Type a char"** starts at offset 0
- **"Hi\n"** starts at offset 0e

Examining Machine Lang: TEXT



Assemble program; run objdump

```
$ gcc217 –c detecta.s
$ objdump –-disassemble --reloc detecta.o
detecta.o:     file format elf64-x86-64

Disassembly of section .text:

0000000000000000 <main>:
   0:     b8 00 00 00 00                 mov    $0x0,%eax
   5:     48 c7 c7 00 00 00 00           mov    $0x0,%rdi
                                8: R_X86_64_32S     .rodata
   c:     e8 00 00 00 00                 callq  11 <main+0x11>
                                d: R_X86_64_PC32    printf-0x4
  11:     e8 00 00 00 00                 callq  16 <main+0x16>
                                12: R_X86_64_PC32   getchar-0x4
  16:     83 f8 41                       cmp    $0x41,%eax
  19:     75 11                          jne    2c <skip>
  1b:     b8 00 00 00 00                 mov    $0x0,%eax
  20:     48 c7 c7 00 00 00 00           mov    $0x0,%rdi
                                23: R_X86_64_32S    .rodata+0xe
  27:     e8 00 00 00 00                 callq  2c <skip>
                                28: R_X86_64_PC32   printf-0x4

000000000000002c <skip>:
  2c:     b8 00 00 00 00                 mov    $0x0,%eax
  31:     c3                             retq
```

Let's examine one line at a time…

movl $0, %eax

```
$ gcc217 –c detecta.s
$ objdump –-disassemble --reloc detecta.o
detecta.o:     file format elf64-x86-64

Disassembly of section .text:

0000000000000000 <main>:
   0:     b8 00 00 00 00                 mov    $0x0,%eax
   5:     48 c7 c7 00 00 00 00           mov    $0x0,%rdi
                                8: R_X86_64_32S     .rodata
   c:     e8 00 00 00 00                 callq  11 <main+0x11>
                                d: R_X86_64_PC32    printf-0x4
  11:     e8 00 00 00 00                 callq  16 <main+0x16>
                                12: R_X86_64_PC32   getchar-0x4
  16:     83 f8 41                       cmp    $0x41,%eax
  19:     75 11                          jne    2c <skip>
  1b:     b8 00 00 00 00                 mov    $0x0,%eax
  20:     48 c7 c7 00 00 00 00           mov    $0x0,%rdi
                                23: R_X86_64_32S    .rodata+0xe
  27:     e8 00 00 00 00                 callq  2c <skip>
                                28: R_X86_64_PC32   printf-0x4

000000000000002c <skip>:
  2c:     b8 00 00 00 00                 mov    $0x0,%eax
  31:     c3                             retq
```

movl $0, %eax

Assembly lang: `movl $0, %eax`
Machine lang: `b800000000`
Explanation:

```
10111000 00000000 00000000 00000000 00000000

Opcode: This is a mov instruction whose src operand is a 4-byte
immediate
      Opcode: the destination operand is the EAX register
           Immediate: The immediate operand is 0
```

movq $msg1, %rdi

```
$ gcc217 –c detecta.s
$ objdump --disassemble --reloc detecta.o
detecta.o:     file format elf64-x86-64

Disassembly of section .text:

0000000000000000 <main>:
   0:     b8 00 00 00 00                mov    $0x0,%eax
   5:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                         8: R_X86_64_32S     .rodata
   c:     e8 00 00 00 00                callq  11 <main+0x11>
                         d: R_X86_64_PC32    printf-0x4
  11:     e8 00 00 00 00                callq  16 <main+0x16>
                         12: R_X86_64_PC32   getchar-0x4
  16:     83 f8 41                      cmp    $0x41,%eax
  19:     75 11                         jne    2c <skip>
  1b:     b8 00 00 00 00                mov    $0x0,%eax
  20:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                         23: R_X86_64_32S    .rodata+0xe
  27:     e8 00 00 00 00                callq  2c <skip>
                         28: R_X86_64_PC32   printf-0x4

000000000000002c <skip>:
  2c:     b8 00 00 00 00                mov    $0x0,%eax
  31:     c3                            retq
```

movq $msg1, %rdi

Assembly lang: `movq $msg1, %rdi`
Machine lang: `48 C7 C7 00 00 00 00`
Explanation:

```
01001000 11000111 110010111 00000000 00000000 00000000 00000000
Opcode: This is a movq instruction with a 4-byte immediate
source operand and a 8 byte register destination operand
       Opcode: The destination register is RDI
                        Opcode: The destination register is
                        RDI (cont.)
                            Disp: The immediate(memory address)
                            is 0
```

- **movq** must contain an **address**
- Assembler knew **offset** marked by **msg1**
    - **msg1** marks offset 0 relative to beginning of RODATA section
- But assembler did not know address of RODATA section!
- So assembler didn't know **address** marked by **msg1**
- So assembler couldn't generate this instruction completely

Relocation Record 1

```
$ gcc217 –c detecta.s
$ objdump --disassemble --reloc detecta.o
detecta.o:     file format elf64-x86-64

Disassembly of section .text:

0000000000000000 <main>:
   0:     b8 00 00 00 00                mov    $0x0,%eax
   5:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                         8: R_X86_64_32S     .rodata
   c:     e8 00 00 00 00                callq  11 <main+0x11>
                         d: R_X86_64_PC32    printf-0x4
  11:     e8 00 00 00 00                callq  16 <main+0x16>
                         12: R_X86_64_PC32   getchar-0x4
  16:     83 f8 41                      cmp    $0x41,%eax
  19:     75 11                         jne    2c <skip>
  1b:     b8 00 00 00 00                mov    $0x0,%eax
  20:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                         23: R_X86_64_32S    .rodata+0xe
  27:     e8 00 00 00 00                callq  2c <skip>
                         28: R_X86_64_PC32   printf-0x4

000000000000002c <skip>:
  2c:     b8 00 00 00 00                mov    $0x0,%eax
  31:     c3                            retq
```

Relocation Record 1

`8: R_X86_64_32S    .rodata`

This part is always the same,
it's the name of the machine architecture!

Dear Linker,

Please patch the TEXT section at offset 08$_H$. Patch in a <u>32</u>-bit, <u>S</u>igned value. When you determine the addr of the RODATA section, place that address in the TEXT section at the prescribed place.

Sincerely,
Assembler

call printf

```
$ gcc217 –c detecta.s
$ objdump --disassemble --reloc detecta.o
detecta.o:     file format elf64-x86-64

Disassembly of section .text:

0000000000000000 <main>:
   0:     b8 00 00 00 00                mov    $0x0,%eax
   5:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                         8: R_X86_64_32S     .rodata
   c:     e8 00 00 00 00                callq  11 <main+0x11>
                         d: R_X86_64_PC32    printf-0x4
  11:     e8 00 00 00 00                callq  16 <main+0x16>
                         12: R_X86_64_PC32   getchar-0x4
  16:     83 f8 41                      cmp    $0x41,%eax
  19:     75 11                         jne    2c <skip>
  1b:     b8 00 00 00 00                mov    $0x0,%eax
  20:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                         23: R_X86_64_32S    .rodata+0xe
  27:     e8 00 00 00 00                callq  2c <skip>
                         28: R_X86_64_PC32   printf-0x4

000000000000002c <skip>:
  2c:     b8 00 00 00 00                mov    $0x0,%eax
  31:     c3                            retq
```

call printf

Assembly lang: `call printf`
Machine lang: `e8 00 00 00 00`
Explanation:

```
11101000 00000000 00000000 00000000 00000000
Opcode: This is a call instruction with a 4-byte
displacement
            Disp: The displacement is 00000000H (0)
```

- **call** must contain a **displacement**
- Assembler had to generate the displacement:
  [addr of **printf**] – [addr after **call** instr]
- But assembler didn't know addr of **printf**
    - **printf** isn't even present yet!
- So assembler couldn't generate this instruction completely

Relocation Record 2

```
$ gcc217 –c detecta.s
$ objdump --disassemble --reloc detecta.o
detecta.o:     file format elf64-x86-64

Disassembly of section .text:

0000000000000000 <main>:
   0:     b8 00 00 00 00                mov    $0x0,%eax
   5:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                              8: R_X86_64_32S     .rodata
   c:     e8 00 00 00 00                callq  11 <main+0x11>
                              d: R_X86_64_PC32    printf-0x4
  11:     e8 00 00 00 00                callq  16 <main+0x16>
                              12: R_X86_64_PC32   getchar-0x4
  16:     83 f8 41                      cmp    $0x41,%eax
  19:     75 11                         jne    2c <skip>
  1b:     b8 00 00 00 00                mov    $0x0,%eax
  20:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                              23: R_X86_64_32S    .rodata+0xe
  27:     e8 00 00 00 00                callq  2c <skip>
                              28: R_X86_64_PC32   printf-0x4

000000000000002c <skip>:
  2c:     b8 00 00 00 00                mov    $0x0,%eax
  31:     c3                            retq
```

Relocation Record 2

`d: R_X86_64_PC32   printf-0x4`

This part is always the same,
it's the name of the machine architecture!

Dear Linker,

Please patch the TEXT section at offset 0d$_H$. Patch in a 32-bit "PC-relative" value. When you determine the addr of `printf`, compute [addr of `printf`] – [addr after `call`] and place the result at the prescribed place.

Sincerely,
Assembler

call getchar

```
$ gcc217 –c detecta.s
$ objdump --disassemble --reloc detecta.o
detecta.o:     file format elf64-x86-64

Disassembly of section .text:

0000000000000000 <main>:
   0:     b8 00 00 00 00                mov    $0x0,%eax
   5:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                              8: R_X86_64_32S     .rodata
   c:     e8 00 00 00 00                callq  11 <main+0x11>
                              d: R_X86_64_PC32    printf-0x4
  11:     e8 00 00 00 00                callq  16 <main+0x16>
                              12: R_X86_64_PC32   getchar-0x4
  16:     83 f8 41                      cmp    $0x41,%eax
  19:     75 11                         jne    2c <skip>
  1b:     b8 00 00 00 00                mov    $0x0,%eax
  20:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                              23: R_X86_64_32S    .rodata+0xe
  27:     e8 00 00 00 00                callq  2c <skip>
                              28: R_X86_64_PC32   printf-0x4

000000000000002c <skip>:
  2c:     b8 00 00 00 00                mov    $0x0,%eax
  31:     c3                            retq
```

call getchar

Assembly lang: `call getchar`
Machine lang: `e8 00 00 00 00`
Explanation:

```
11101000 00000000 00000000 00000000 00000000
Opcode: This is a call instruction with a 4-byte
displacement
            Disp: The displacement is 00000000H (0)
```

- `call` must contain a **displacement**
- Assembler had to generate the displacement: [addr of `getchar`] – [addr after `call` instr]
- But assembler didn't know addr of `getchar`
  - `getchar` isn't even present yet!
- So assembler couldn't generate this instruction completely

Relocation Record 3

```
$ gcc217 –c detecta.s
$ objdump --disassemble --reloc detecta.o
detecta.o:     file format elf64-x86-64

Disassembly of section .text:

0000000000000000 <main>:
   0:     b8 00 00 00 00                mov    $0x0,%eax
   5:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                              8: R_X86_64_32S     .rodata
   c:     e8 00 00 00 00                callq  11 <main+0x11>
                              d: R_X86_64_PC32    printf-0x4
  11:     e8 00 00 00 00                callq  16 <main+0x16>
                              12: R_X86_64_PC32   getchar-0x4
  16:     83 f8 41                      cmp    $0x41,%eax
  19:     75 11                         jne    2c <skip>
  1b:     b8 00 00 00 00                mov    $0x0,%eax
  20:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                              23: R_X86_64_32S    .rodata+0xe
  27:     e8 00 00 00 00                callq  2c <skip>
                              28: R_X86_64_PC32   printf-0x4

000000000000002c <skip>:
  2c:     b8 00 00 00 00                mov    $0x0,%eax
  31:     c3                            retq
```

Relocation Record 3

`12: R_X86_64_PC32 getchar-0x4`

Dear Linker,

Please patch the TEXT section at offsets 12$_H$. Do a 32-bit PC-relative patch. When you determine the addr of `getchar`, compute [offset of `getchar`] – [addr after `call`] and place the result at the prescribed place.

Sincerely,
Assembler

cmpl $'A', %eax

```
$ gcc217 –c detecta.s
$ objdump --disassemble --reloc detecta.o
detecta.o:     file format elf64-x86-64

Disassembly of section .text:

0000000000000000 <main>:
   0:     b8 00 00 00 00                  mov    $0x0,%eax
   5:     48 c7 c7 00 00 00 00            mov    $0x0,%rdi
                              8: R_X86_64_32S     .rodata
   c:     e8 00 00 00 00                  callq  11 <main+0x11>
                              d: R_X86_64_PC32    printf-0x4
  11:     e8 00 00 00 00                  callq  16 <main+0x16>
                              12: R_X86_64_PC32   getchar-0x4
  16:     83 f8 41                        cmp    $0x41,%eax
  19:     75 11                           jne    2c <skip>
  1b:     b8 00 00 00 00                  mov    $0x0,%eax
  20:     48 c7 c7 00 00 00 00            mov    $0x0,%rdi
                              23: R_X86_64_32S    .rodata+0xe
  27:     e8 00 00 00 00                  callq  2c <skip>
                              28: R_X86_64_PC32   printf-0x4

000000000000002c <skip>:
  2c:     b8 00 00 00 00                  mov    $0x0,%eax
  31:     c3                              retq
```

cmpl $'A', %eax

Assembly lang: `cmpl $'A', %eax`
Machine lang: `83 f8 41`
Explanation:

```
10000011 11111000 01000001
Opcode: This is an instruction whose source operand is a
one-byte immediate and whose destination operand is a
register or memory
            ModR/M: This is a cmpl instruction, and the last
            three bytes of the ModR/M field specify the
            destination register
                  ModR/M: The dest register is EAX
                       The immediate operand is 41H ('A')
```

jne skip

```
$ gcc217 –c detecta.s
$ objdump --disassemble --reloc detecta.o
detecta.o:     file format elf64-x86-64

Disassembly of section .text:

0000000000000000 <main>:
   0:     b8 00 00 00 00                  mov    $0x0,%eax
   5:     48 c7 c7 00 00 00 00            mov    $0x0,%rdi
                              8: R_X86_64_32S     .rodata
   c:     e8 00 00 00 00                  callq  11 <main+0x11>
                              d: R_X86_64_PC32    printf-0x4
  11:     e8 00 00 00 00                  callq  16 <main+0x16>
                              12: R_X86_64_PC32   getchar-0x4
  16:     83 f8 41                        cmp    $0x41,%eax
  19:     75 11                           jne    2c <skip>
  1b:     b8 00 00 00 00                  mov    $0x0,%eax
  20:     48 c7 c7 00 00 00 00            mov    $0x0,%rdi
                              23: R_X86_64_32S    .rodata+0xe
  27:     e8 00 00 00 00                  callq  2c <skip>
                              28: R_X86_64_PC32   printf-0x4

000000000000002c <skip>:
  2c:     b8 00 00 00 00                  mov    $0x0,%eax
  31:     c3                              retq
```

jne skip

Assembly lang: `jne skip`
Machine lang: `75 11`
Explanation:

```
01110101 00010001
Opcode: This is a jne instruction with a one-byte
displacement
            Disp: The displacement is 11H (17D)
```

- **`jne`** must contain a **displacement**
- Assembler had to generate the displacement:
  [addr of **`skip`**] – [addr after **`jne`** instr]
  Assembler **did** know addr of **`skip`**
- So assembler **could** generate this instruction completely
  $2c_H – 1b_H = 11_H = 17_D$

jne skip

Is it clear why jump and call instructions contain displacements instead of addresses?

movl $0, %eax

```
$ gcc217 –c detecta.s
$ objdump --disassemble --reloc detecta.o
detecta.o:     file format elf64-x86-64

Disassembly of section .text:

0000000000000000 <main>:
   0:     b8 00 00 00 00                  mov    $0x0,%eax
   5:     48 c7 c7 00 00 00 00            mov    $0x0,%rdi
                              8: R_X86_64_32S     .rodata
   c:     e8 00 00 00 00                  callq  11 <main+0x11>
                              d: R_X86_64_PC32    printf-0x4
  11:     e8 00 00 00 00                  callq  16 <main+0x16>
                              12: R_X86_64_PC32   getchar-0x4
  16:     83 f8 41                        cmp    $0x41,%eax
  19:     75 11                           jne    2c <skip>
  1b:     b8 00 00 00 00                  mov    $0x0,%eax
  20:     48 c7 c7 00 00 00 00            mov    $0x0,%rdi
                              23: R_X86_64_32S    .rodata+0xe
  27:     e8 00 00 00 00                  callq  2c <skip>
                              28: R_X86_64_PC32   printf-0x4

000000000000002c <skip>:
  2c:     b8 00 00 00 00                  mov    $0x0,%eax
  31:     c3                              retq
```

movl $0, %eax

Assembly lang: `movl $0, %eax`
Machine lang: `b800000000`
Explanation:

```
10111000 00000001 00000000 00000000 00000000

Opcode: This is a mov instruction whose src operand is a 4-byte
immediate
      Opcode: the destination operand is the EAX register
           Immediate: The immediate operand is 0
```

movq $msg2, %rdi

```
$ gcc217 –c detecta.s
$ objdump --disassemble --reloc detecta.o
detecta.o:     file format elf64-x86-64

Disassembly of section .text:

0000000000000000 <main>:
   0:     b8 00 00 00 00                mov    $0x0,%eax
   5:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                              8: R_X86_64_32S     .rodata
   c:     e8 00 00 00 00                callq  11 <main+0x11>
                              d: R_X86_64_PC32    printf-0x4
  11:     e8 00 00 00 00                callq  16 <main+0x16>
                              12: R_X86_64_PC32   getchar-0x4
  16:     83 f8 41                      cmp    $0x41,%eax
  19:     75 11                         jne    2c <skip>
  1b:     b8 00 00 00 00                mov    $0x0,%eax
  20:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                              23: R_X86_64_32S    .rodata+0xe
  27:     e8 00 00 00 00                callq  2c <skip>
                              28: R_X86_64_PC32   printf-0x4

000000000000002c <skip>:
  2c:     b8 00 00 00 00                mov    $0x0,%eax
  31:     c3                            retq
```

movq $msg2, %rdi

Assembly lang: `movq $msg2, %rdi`
Machine lang: `48 C7 C7 00 00 00 00`
Explanation:

```
01001000 11000111 110010111 00000000 00000000 00000000 00000000
Opcode: This is a movq instruction with a 4-byte immediate
source operand and a 8 byte register destination operand
       Opcode: The destination register is RDI
                        Opcode: The destination register is
                        RDI (cont.)
                            Disp: The immediate(memory address)
                            is 0
```

- **`movq`** must contain an **address**
- Assembler knew **offset** marked by **`msg2`**
    - **`msg2`** marks offset $0e_H$ relative to beginning of RODATA section
- But assembler did not know address of RODATA section!
- So assembler didn't know **address** marked by **`msg2`**
- So assembler couldn't generate this instruction completely

Relocation Record 4

```
$ gcc217 –c detecta.s
$ objdump --disassemble --reloc detecta.o
detecta.o:     file format elf64-x86-64

Disassembly of section .text:

0000000000000000 <main>:
   0:     b8 00 00 00 00                mov    $0x0,%eax
   5:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                              8: R_X86_64_32S     .rodata
   c:     e8 00 00 00 00                callq  11 <main+0x11>
                              d: R_X86_64_PC32    printf-0x4
  11:     e8 00 00 00 00                callq  16 <main+0x16>
                              12: R_X86_64_PC32   getchar-0x4
  16:     83 f8 41                      cmp    $0x41,%eax
  19:     75 11                         jne    2c <skip>
  1b:     b8 00 00 00 00                mov    $0x0,%eax
  20:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                              23: R_X86_64_32S    .rodata+0xe
  27:     e8 00 00 00 00                callq  2c <skip>
                              28: R_X86_64_PC32   printf-0x4

000000000000002c <skip>:
  2c:     b8 00 00 00 00                mov    $0x0,%eax
  31:     c3                            retq
```

Relocation Record 4

```
23: R_X86_64_32S  .rodata+0xe
```

Dear Linker,

Please patch the TEXT section at offset 23_H. Patch in a 32-bit Signed value. When you determine the addr of the RODATA section, add $0e_H$ to that address, and place the result in the TEXT section at the prescribed place.

Sincerely,
Assembler

call printf

```
$ gcc217 –c detecta.s
$ objdump --disassemble --reloc detecta.o
detecta.o:     file format elf64-x86-64

Disassembly of section .text:

0000000000000000 <main>:
   0:     b8 00 00 00 00                mov    $0x0,%eax
   5:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                              8: R_X86_64_32S     .rodata
   c:     e8 00 00 00 00                callq  11 <main+0x11>
                              d: R_X86_64_PC32    printf-0x4
  11:     e8 00 00 00 00                callq  16 <main+0x16>
                              12: R_X86_64_PC32   getchar-0x4
  16:     83 f8 41                      cmp    $0x41,%eax
  19:     75 11                         jne    2c <skip>
  1b:     b8 00 00 00 00                mov    $0x0,%eax
  20:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                              23: R_X86_64_32S    .rodata+0xe
  27:     e8 00 00 00 00                callq  2c <skip>
                              28: R_X86_64_PC32   printf-0x4

000000000000002c <skip>:
  2c:     b8 00 00 00 00                mov    $0x0,%eax
  31:     c3                            retq
```

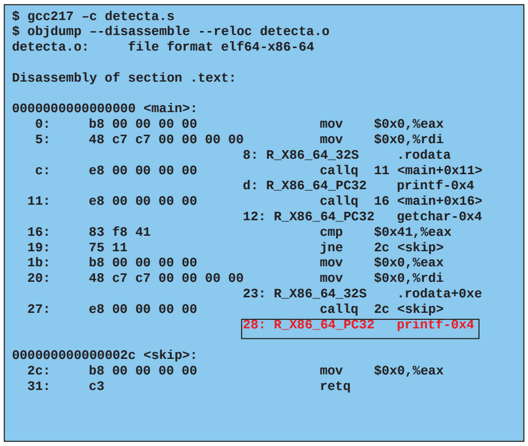
call printf

Assembly lang: `call printf`
Machine lang: `e8 00 00 00 00`
Explanation:

11101000 00000000 00000000 00000000 00000000
Opcode: This is a call instruction with a 4-byte displacement
Disp: The displacement is 00000000$_H$ (0)

- **call** must contain a **displacement**
- Assembler must generate the displacement: [addr of **printf**] – [addr after **call** instr]
- But assembler didn't know addr of **printf**
  - **printf** isn't even present yet!
- So assembler couldn't generate this instruction completely

Relocation Record 5



```
$ gcc217 –c detecta.s
$ objdump --disassemble --reloc detecta.o
detecta.o:     file format elf64-x86-64

Disassembly of section .text:

0000000000000000 <main>:
   0:     b8 00 00 00 00                mov    $0x0,%eax
   5:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                              8: R_X86_64_32S     .rodata
   c:     e8 00 00 00 00                callq  11 <main+0x11>
                              d: R_X86_64_PC32    printf-0x4
  11:     e8 00 00 00 00                callq  16 <main+0x16>
                              12: R_X86_64_PC32   getchar-0x4
  16:     83 f8 41                      cmp    $0x41,%eax
  19:     75 11                         jne    2c <skip>
  1b:     b8 00 00 00 00                mov    $0x0,%eax
  20:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                              23: R_X86_64_32S    .rodata+0xe
  27:     e8 00 00 00 00                callq  2c <skip>
                              28: R_X86_64_PC32   printf-0x4

000000000000002c <skip>:
  2c:     b8 00 00 00 00                mov    $0x0,%eax
  31:     c3                            retq
```

Relocation Record 5

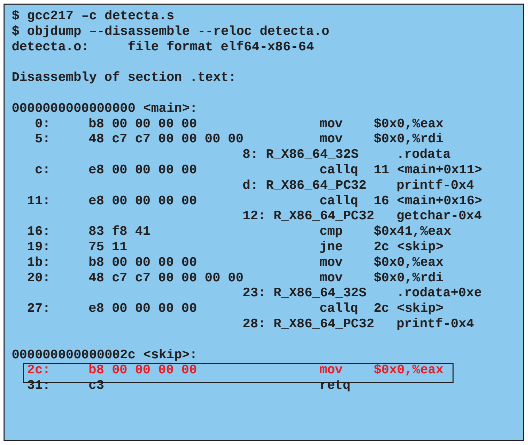
`28: R_X86_64_PC32 printf-0x4`

Dear Linker,

Please patch the TEXT section at offset 28$_H$. Patch in a 32-bit PC-relative address. When you determine the addr of printf, compute [addr of printf] – [addr after call] and place the result at the prescribed place.

Sincerely,
Assembler

movl $0, %eax



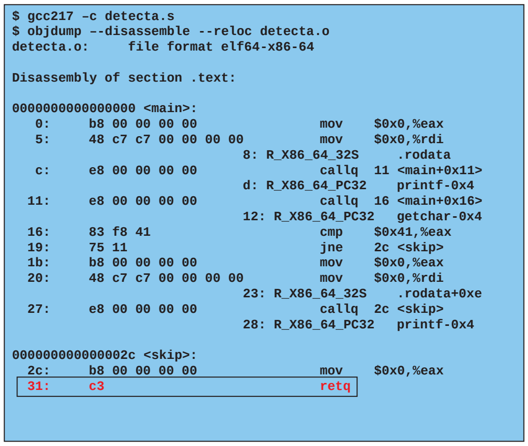
```
$ gcc217 –c detecta.s
$ objdump --disassemble --reloc detecta.o
detecta.o:     file format elf64-x86-64

Disassembly of section .text:

0000000000000000 <main>:
   0:     b8 00 00 00 00                mov    $0x0,%eax
   5:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                              8: R_X86_64_32S     .rodata
   c:     e8 00 00 00 00                callq  11 <main+0x11>
                              d: R_X86_64_PC32    printf-0x4
  11:     e8 00 00 00 00                callq  16 <main+0x16>
                              12: R_X86_64_PC32   getchar-0x4
  16:     83 f8 41                      cmp    $0x41,%eax
  19:     75 11                         jne    2c <skip>
  1b:     b8 00 00 00 00                mov    $0x0,%eax
  20:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                              23: R_X86_64_32S    .rodata+0xe
  27:     e8 00 00 00 00                callq  2c <skip>
                              28: R_X86_64_PC32   printf-0x4

000000000000002c <skip>:
  2c:     b8 00 00 00 00                mov    $0x0,%eax
  31:     c3                            retq
```

movl $0, %eax

Assembly lang: `movl $0, %eax`
Machine lang: `b8 00 00 00 00`
Explanation:

10111000 00000000 00000000 00000000 00000000
Opcode: This is a mov instruction whose source operand is a four-byte immediate and whose destination is EAX
The immediate operand is 0

ret



```
$ gcc217 –c detecta.s
$ objdump --disassemble --reloc detecta.o
detecta.o:     file format elf64-x86-64

Disassembly of section .text:

0000000000000000 <main>:
   0:     b8 00 00 00 00                mov    $0x0,%eax
   5:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                              8: R_X86_64_32S     .rodata
   c:     e8 00 00 00 00                callq  11 <main+0x11>
                              d: R_X86_64_PC32    printf-0x4
  11:     e8 00 00 00 00                callq  16 <main+0x16>
                              12: R_X86_64_PC32   getchar-0x4
  16:     83 f8 41                      cmp    $0x41,%eax
  19:     75 11                         jne    2c <skip>
  1b:     b8 00 00 00 00                mov    $0x0,%eax
  20:     48 c7 c7 00 00 00 00          mov    $0x0,%rdi
                              23: R_X86_64_32S    .rodata+0xe
  27:     e8 00 00 00 00                callq  2c <skip>
                              28: R_X86_64_PC32   printf-0x4

000000000000002c <skip>:
  2c:     b8 00 00 00 00                mov    $0x0,%eax
  31:     c3                            retq
```

ret

Assembly lang: `ret`
Machine lang: `c3`
Explanation:

```
11000011
Opcode: This is a ret (alias retq) instruction
```

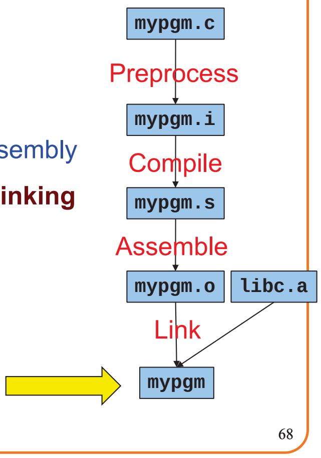
Agenda

x86-64 Machine Language

Buffer overrun vulnerabilities

x86-64 Machine Language after Assembly

x86-64 Machine Language after Linking



From Assembler to Linker

Assembler writes its data structures to .o file

Linker:

- Reads .o file
- Writes executable binary file
- Works in two phases: **resolution** and **relocation**

Linker Resolution

Resolution

- Linker resolves references

For this program, linker:

- Notes that labels **`getchar`** and **`printf`** are unresolved
- Fetches machine language code defining **`getchar`** and **`printf`** from libc.a
- Adds that code to TEXT section
- Adds more code (e.g. definition of _**`start`**) to TEXT section too
- Adds code to other sections too

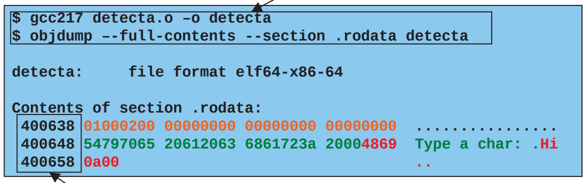
Linker Relocation

Relocation

- Linker patches (“relocates”) code
- Linker traverses relocation records, patching code as specified

Examining Machine Lang: RODATA

Link program; run objdump



```
$ gcc217 detecta.o –o detecta
$ objdump –-full-contents --section .rodata detecta

detecta:     file format elf64-x86-64

Contents of section .rodata:
 400638 01000200 00000000 00000000 00000000  ................
 400648 54797065 20612063 6861723a 20004869  Type a char: .Hi
 400658 0a00                                 ..
```

(Partial) addresses, not offsets

RODATA is at …**00400638**$_H$
Starts with some header info
Real start of RODATA is at …**00400648**$_H$
"Type a char: " starts at …**00400648**$_H$
"Hi\n" starts at …**00400656**$_H$

Examining Machine Lang: TEXT

```
$ gcc217 detecta.o –o detecta
$ objdump --disassemble --reloc detecta
detecta:     file format elf64-x86-64
...
Disassembly of section .text:
...
0000000000400514 <main>:
  400514:       b8 00 00 00 00          mov    $0x0,%eax
  400519:       48 c7 c7 48 06 40 00    mov    $0x400648,%rdi
  400520:       e8 d3 fe ff ff          callq  4003f8 <printf@plt>
  400525:       e8 ee fe ff ff          callq  400418 <getchar@plt>
  40052a:       83 f8 41                cmp    $0x41,%eax
  40052d:       75 11                   jne    400540 <skip>
  40052f:       b8 00 00 00 00          mov    $0x0,%eax
  400534:       48 c7 c7 56 06 40 00    mov    $0x400656,%rdi
  40053b:       e8 b8 fe ff ff          callq  4003f8 <printf@plt>

0000000000400540 <skip>:
  400540:       b8 00 00 00 00          mov    $0x0,%eax
  400545:       c3                      retq
...
```

Link program; run objdump

No relocation records!

Addresses, not offsets

Let's examine one line at a time…

Additional Code

```
$ gcc217 detecta.o –o detecta
$ objdump --disassemble --reloc detecta
detecta:     file format elf64-x86-64
...
Disassembly of section .text:
...
0000000000400514 <main>:
  400514:       b8 00 00 00 00          mov    $0x0,%eax
  400519:       48 c7 c7 48 06 40 00    mov    $0x400648,%rdi
  400520:       e8 d3 fe ff ff          callq  4003f8 <printf@plt>
  400525:       e8 ee fe ff ff          callq  400418 <getchar@plt>
  40052a:       83 f8 41                cmp    $0x41,%eax
  40052d:       75 11                   jne    400540 <skip>
  40052f:       b8 00 00 00 00          mov    $0x0,%eax
  400534:       48 c7 c7 56 06 40 00    mov    $0x400656,%rdi
  40053b:       e8 b8 fe ff ff          callq  4003f8 <printf@plt>

0000000000400540 <skip>:
  400540:       b8 00 00 00 00          mov    $0x0,%eax
  400545:       c3                      retq
...
```

Additional code

movq $msg1, %rdi

```
$ gcc217 detecta.o –o detecta
$ objdump --disassemble --reloc detecta
detecta:     file format elf64-x86-64
...
Disassembly of section .text:
...
0000000000400514 <main>:
  400514:       b8 00 00 00 00          mov    $0x0,%eax
  400519:       48 c7 c7 48 06 40 00    mov    $0x400648,%rdi
  400520:       e8 d3 fe ff ff          callq  4003f8 <printf@plt>
  400525:       e8 ee fe ff ff          callq  400418 <getchar@plt>
  40052a:       83 f8 41                cmp
  40052d:       75 11                   jne
  40052f:       b8 00 00 00 00          mov
  400534:       48 c7 c7 56 06 40 00    mov
  40053b:       e8 b8 fe ff ff          call

0000000000400540 <skip>:
  400540:       b8 00 00 00 00          mov
  400545:       c3                      retq
...
```

Recall: Real addr of RODATA = **…00400648**$_H$

Linker replaced **00000000**$_H$ with real addr of RODATA + 0
= **…00400648H + 0**
= **…00400648**$_H$
= addr denoted by **msg1**

call printf

```
$ gcc217 detecta.o –o detecta
$ objdump --disassemble --reloc detecta
detecta:     file format elf64-x86-64
...
Disassembly of section .text:
...
0000000000400514 <main>:
  400514:       b8 00 00 00 00          mov    $0x0,%eax
  400519:       48 c7 c7 48 06 40 00    mov    $0x400648,%rdi
  400520:       e8 d3 fe ff ff          callq  4003f8 <printf@plt>
  400525:       e8 ee fe ff ff          callq  400418 <getchar@plt>
  40052a:       83 f8 41                cmp    $0x41,%eax
  40052d:       75 11                   jne    400540 <skip>
  40052f:       b8 00 00 00 00
  400534:       48 c7 c7 56 06 40 00
  40053b:       e8 b8 fe ff ff

0000000000400540 <skip>:
  400540:       b8 00 00 00 00
  400545:       c3
...
```

Addr of **printf** = **…004003f8**$_H$

Linker replaced **00000000**$_H$ with [addr of **printf**] **-** [addr after **call**]
= **…004003f8**$_H$ **–** **…00400525**$_H$
= **…fffffed3**$_H$
= **-301**$_D$

call getchar

```
$ gcc217 detecta.o –o detecta
$ objdump --disassemble --reloc detecta
detecta:     file format elf64-x86-64
...
Disassembly of section .text:
...
0000000000400514 <main>:
  400514:       b8 00 00 00 00          mov    $0x0,%eax
  400519:       48 c7 c7 48 06 40 00    mov    $0x400648,%rdi
  400520:       e8 d3 fe ff ff          callq  4003f8 <printf@plt>
  400525:       e8 ee fe ff ff          callq  400418 <getchar@plt>
  40052a:       83 f8 41                cmp    $0x41,%eax
  40052d:       75 11                   jne    400540 <skip>
  40052f:       b8 00 00 00 00
  400534:       48 c7 c7 56 06 40 00
  40053b:       e8 b8 fe ff ff

0000000000400540 <skip>:
  400540:       b8 00 00 00 00
  400545:       c3
...
```

Addr of **getchar** = **…00400418**$_H$

Linker replaced **00000000**$_H$ with [addr of **getchar**] **-** [addr after **call**]
= **…00400418**$_H$ **–** **…0040052a**$_H$
= **…fffffeee**$_H$
= **-274**$_D$

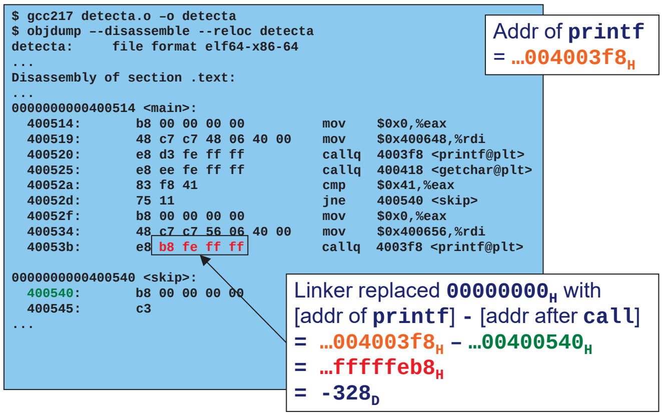
movq $msg2, %rdi

```
$ gcc217 detecta.o –o detecta
$ objdump --disassemble --reloc detecta
detecta:     file format elf64-x86-64
...
Disassembly of section .text:
...
0000000000400514 <main>:
  400514:       b8 00 00 00 00          mov    $0x0,%eax
  400519:       48 c7 c7 48 06 40 00    mov    $0x400648,%rdi
  400520:       e8 d3 fe ff ff          callq  4003f8 <printf@plt>
  400525:       e8 ee fe ff ff          callq  400418 <getchar@plt>
  40052a:       83 f8 41                cmp    $0x41,%eax
  40052d:       75 11                   jne    400540 <skip>
  40052f:       b8 00 00 00 00          mov    $0x0,%eax
  400534:       48 c7 c7 56 06 40 00    mov    $0x400656,%rdi
  40053b:       e8 b8 fe ff ff          callq  4003f8 <printf@plt>

0000000000400540 <skip>:
  400540:       b8 00 00 00 00          mov
  400545:       c3                      retq
...
```

Recall: Real addr of RODATA = **…00400648**$_H$

Linker replaced **00000000**$_H$ with real addr of RODATA + **e**$_H$
= **…00400648H + e**$_H$
= **…00400656**$_H$
= addr denoted by **msg2**

call printf



```
$ gcc217 detecta.o –o detecta
$ objdump --disassemble --reloc detecta
detecta:     file format elf64-x86-64
...
Disassembly of section .text:
...
0000000000400514 <main>:
  400514:       b8 00 00 00 00          mov    $0x0,%eax
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  400520:       e8 d3 fe ff ff          callq  4003f8 <printf@plt>
  400525:       e8 ee fe ff ff          callq  400418 <getchar@plt>
  40052a:       83 f8 41                cmp    $0x41,%eax
  40052d:       75 11                   jne    400540 <skip>
  40052f:       b8 00 00 00 00          mov    $0x0,%eax
  400534:       48 c7 c7 56 06 40 00    mov    $0x400656,%rdi
  40053b:       e8 b8 fe ff ff          callq  4003f8 <printf@plt>

0000000000400540 <skip>:
  400540:       b8 00 00 00 00
  400545:       c3
...
```

Addr of **`printf`**
= …$004003f8_H$

Linker replaced $\mathbf{00000000}_H$ with
[addr of **`printf`**] **-** [addr after **`call`**]
= …$004003f8_H$ – …00400540_H
= …$fffffeb8_H$
= -328_D

Summary

x86-64 Machine Language

- CISC: many instructions, complex format
- Fields: prefix, opcode, modR/M, SIB, displacement, immediate

Assembler

- Reads assembly language file
- Generates TEXT, RODATA, DATA, BSS sections
    - Containing machine language code
- Generates **relocation records**
- Writes object (.o) file

Linker

- Reads object (.o) file(s)
- Does **resolution**: resolves references to make code complete
- Does **relocation**: traverses relocation records to patch code
- Writes executable binary file