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.

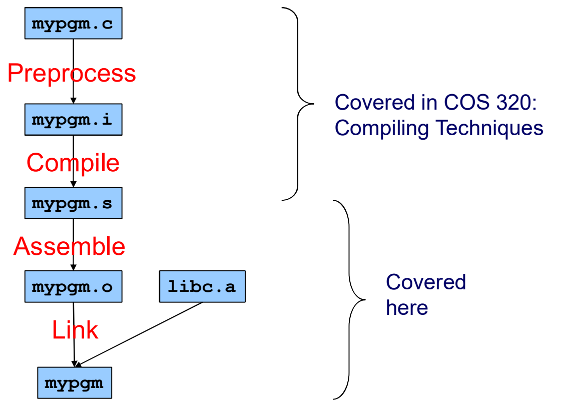
What is your name?
[fill in something here]
A is your grade, Susan.

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



Instruction Set Architecture (ISA)

There are many kinds of computer chips out there:

Intel x86 series

IBM PowerPC

ARM

RISC-V

MIPS

(and, in the old days, dozens more)

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

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

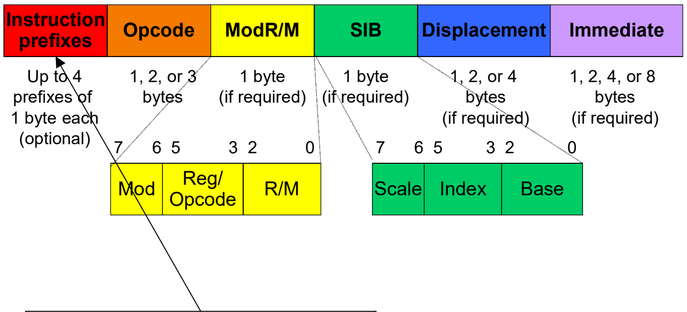
x86-64 Machine Language after Linking

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 prefixes | Opcode | ModR/M | SIB | Displacement | Immediate

Up to 4 prefixes of 1 byte each (optional)

1, 2, or 3 bytes

1 byte (if required)

1 byte (if required)

1, 2, or 4 bytes (if required)

1, 2, 4, or 8 bytes (if required)

7 6 5 3 2 0

Mod | Reg/Opcode | R/M

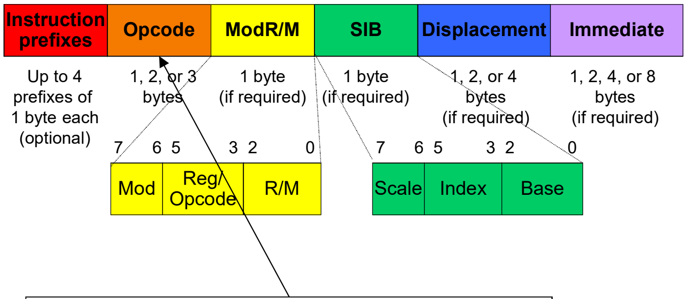
7 6 5 3 2 0

Scale | Index | Base

Instruction prefix

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

x86-64 Instruction Format (cont.)



Instruction prefixes | Opcode | ModR/M | SIB | Displacement | Immediate

Up to 4 prefixes of 1 byte each (optional)

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1 byte (if required)

1, 2, or 4 bytes (if required)

1, 2, 4, or 8 bytes (if required)

7 6 5 3 2 0

Mod | Reg/Opcode | R/M

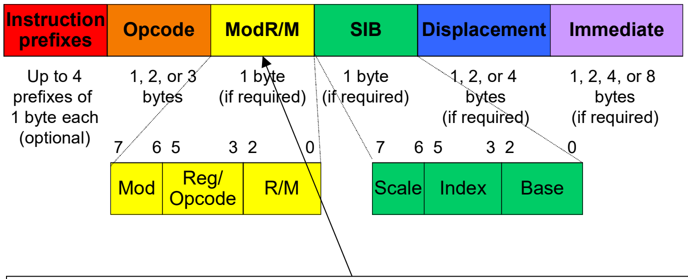
7 6 5 3 2 0

Scale | Index | Base

Opcode

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

x86-64 Instruction Format (cont.)



Instruction prefixes | Opcode | ModR/M | SIB | Displacement | Immediate

Up to 4 prefixes of 1 byte each (optional)

1, 2, or 3 bytes

1 byte (if required)

1 byte (if required)

1, 2, or 4 bytes (if required)

1, 2, 4, or 8 bytes (if required)

7 6 5 3 2 0

Mod | Reg/Opcode | R/M

7 6 5 3 2 0

Scale | Index | Base

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.)

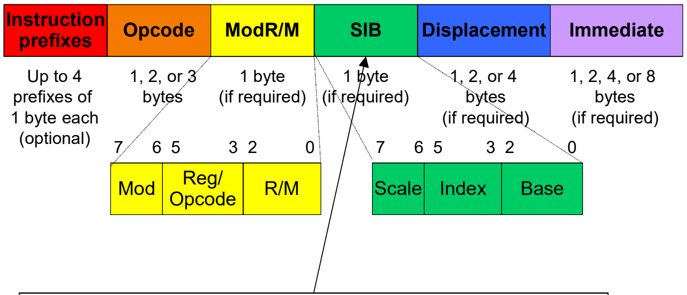
Sometimes 3 bits in ModR/M byte, along with extra bit in another field, specify a register

- 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.)



Instruction prefixes | Opcode | ModR/M | SIB | Displacement | Immediate

Up to 4 prefixes of 1 byte each (optional)

1, 2, or 3 bytes

1 byte (if required)

1 byte (if required)

1, 2, or 4 bytes (if required)

1, 2, 4, or 8 bytes (if required)

7 6 5 3 2 0

Mod | Reg/Opcode | R/M

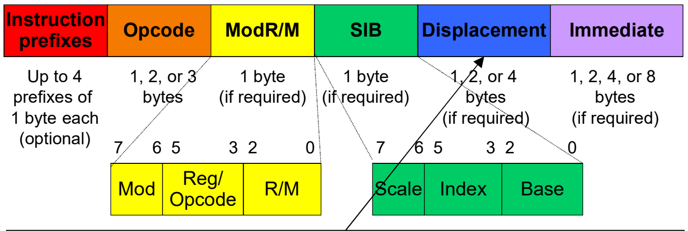
7 6 5 3 2 0

Scale | Index | Base

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.)



Instruction prefixes	Opcode	ModR/M	SIB	Displacement	Immediate
Up to 4 prefixes of 1 byte each (optional)	1, 2, or 3 bytes	1 byte (if required)	1 byte (if required)	1, 2, or 4 bytes (if required)	1, 2, 4, or 8 bytes (if required)

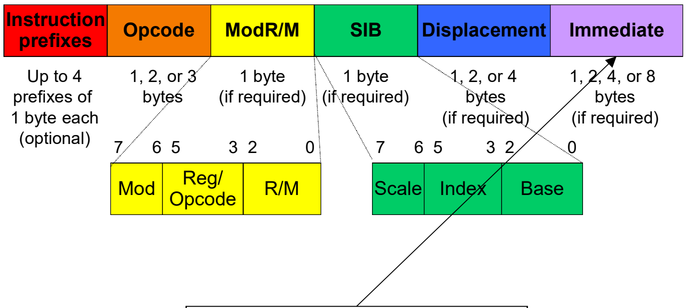
ModR/M: 7 6 5 3 2 0 — Mod | Reg/ Opcode | R/M

SIB: 7 6 5 3 2 0 — Scale | Index | Base

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.)



Instruction prefixes	Opcode	ModR/M	SIB	Displacement	Immediate
Up to 4 prefixes of 1 byte each (optional)	1, 2, or 3 bytes	1 byte (if required)	1 byte (if required)	1, 2, or 4 bytes (if required)	1, 2, 4, or 8 bytes (if required)

ModR/M: 7 6 5 3 2 0 — Mod | Reg/ Opcode | R/M

SIB: 7 6 5 3 2 0 — Scale | Index | Base

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.
%
```

```c
#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?

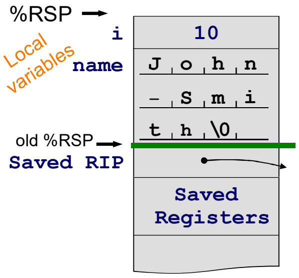
```
% a.out
What is your name?
adsli57asdkhj5jklds;ahj5;klsaduj5klysdukl5aujksd5ukals;5uj;akukla
Segmentation fault
%
```

```c
#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.
%
```

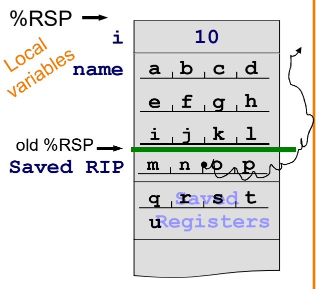
```c
#include <stdio.h>
int main(int argc, char **argv) {
  char name[12];  int i;
  printf("What is your name?\n");
  for (i=0; ; i++) {
    int c = getchar();
    if (c=='\n' || c ==EOF) break;
    name[i] = c;
  }
  name[i]='\0';
  printf("Thank you, %s.\n", name);
  return 0;
}
```



Buffer overrun

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

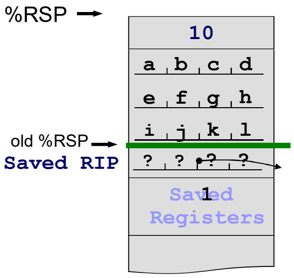
```c
#include <stdio.h>
int main(int argc, char **argv) {
  char name[12];  int i;
  printf("What is your name?\n");
  for (i=0; ; i++) {
    int c = getchar();
    if (c=='\n' || c ==EOF) break;
    name[i] = c;
  }
  name[i]='\0';
  printf("Thank you, %s.\n", name);
  return 0;
}
```



Innocuous? buffer overrun

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

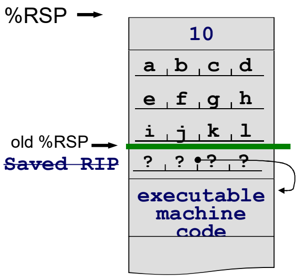
```c
#include <stdio.h>
int main(int argc, char **argv) {
  char name[12];  int i;
  printf("What is your name?\n");
  for (i=0; ; i++) {
    int c = getchar();
    if (c=='\n' || c ==EOF) break;
    name[i] = c;
  }
  name[i]='\0';
  printf("Thank you, %s.\n", name);
  return 0;
}
```



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;
}
```


%RSP

10

a b c d

e f g h

i j k l

old %RSP

~~Saved RIP~~

? ? ? ?

executable machine code

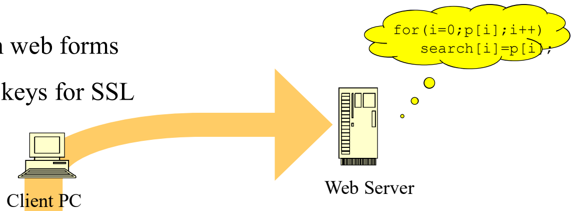
Attacking a web server

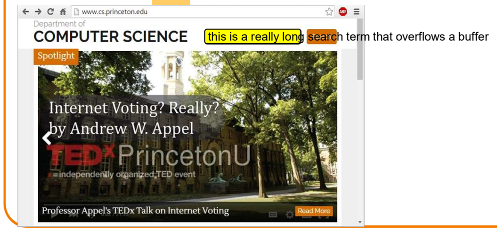
URLs

Input in web forms

Crypto keys for SSL

etc.




www.cs.princeton.edu

Department of COMPUTER SCIENCE

this is a really long search term that overflows a buffer

Spotlight

Internet Voting? Really? by Andrew W. Appel

TEDx PrincetonU
x = independently organized TED event

Professor Appel's TEDx Talk on Internet Voting

Read More

Attacking a web browser

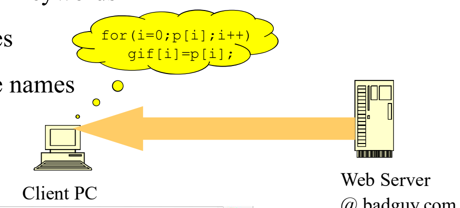
HTML keywords

Images

Image names

URLs

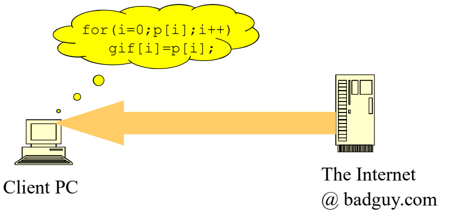
etc.



www.badguy.com

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.

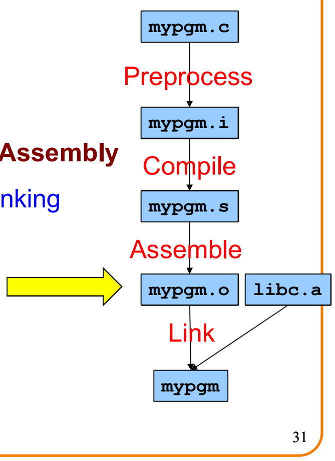
Agenda

x86-64 Machine Language

Buffer overrun vulnerabilities

x86-64 Machine Language after Assembly

x86-64 Machine Language after Linking



An Example Program

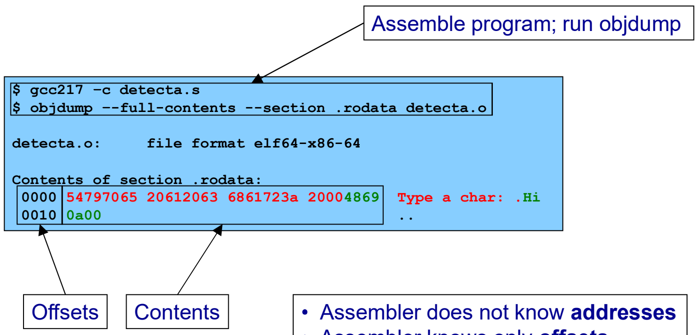
A simple (nonsensical) program:

```
#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…

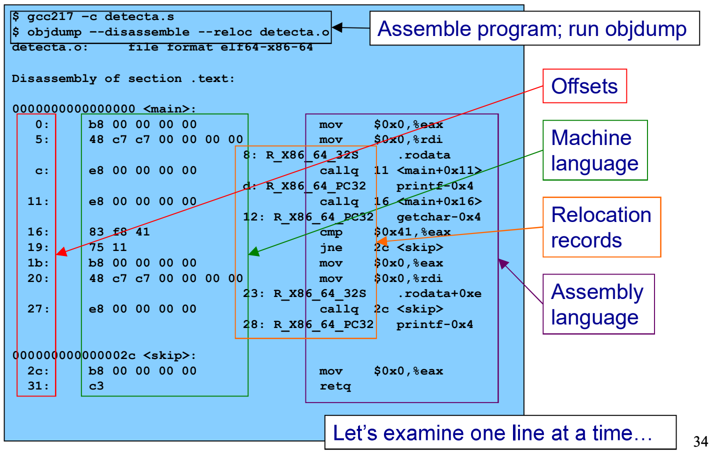
Examining Machine Lang: RODATA


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


```
$ 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 11001011 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

$\underbrace{\texttt{8: R\_X86\_64\_}}_{\text{This part is always the same, it's the name of the machine architecture!}}\texttt{32S}\quad\texttt{.rodata}$

Dear Linker,

Please patch the TEXT section at offset 08$_H$. Patch in a 32-bit, Signed 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
```

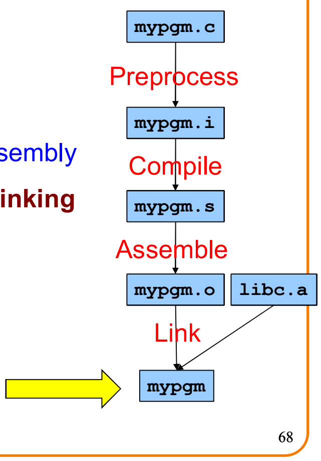
Agenda

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

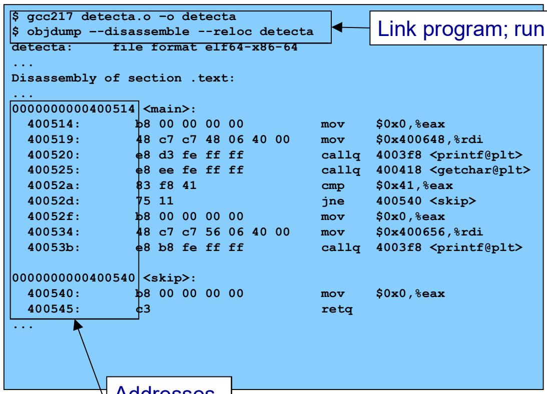
Link program; run objdump

```
$ 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
...
```

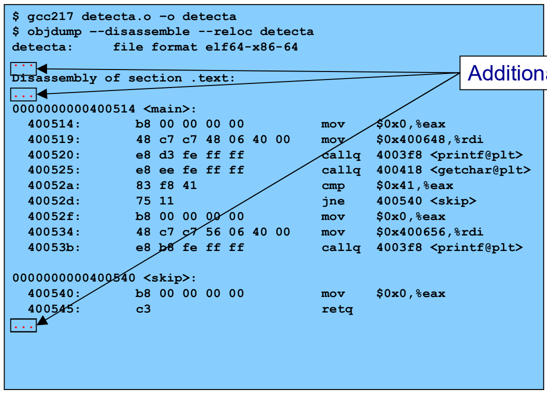
Link program; run objdump

No relocation records!

Addresses, not offsets

Let's examine one line at a time…

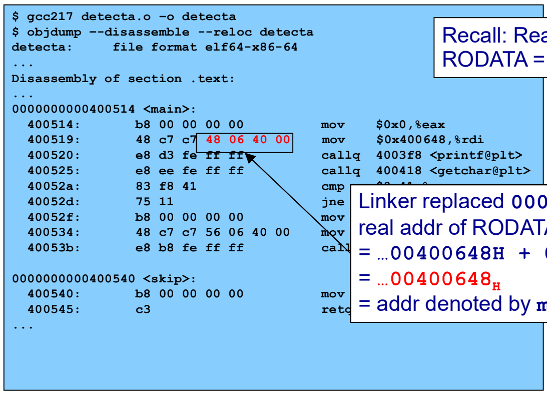
Additional Code



```
$ 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

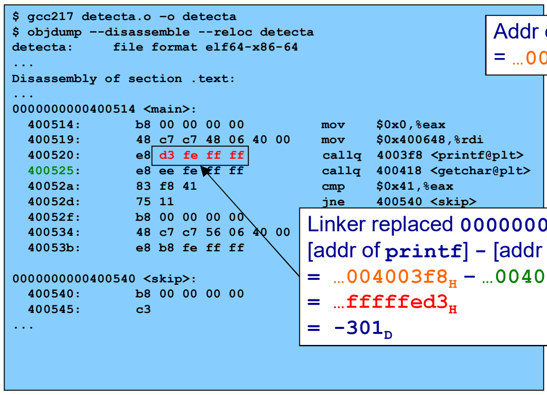


```
$ gcc217 detecta.o –o detecta
$ objdump --disassemble --reloc detecta
detecta:     file format elf64-x86-64
...
Disassembly of section .text:
...
0000000000400514 <main>:
  400514:       b8 00 00 00 00          mov    $0x0,%eax
  400519:       48 c7 c7 48 06 40 00    mov    $0x400648,%rdi
  400520:       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                      ret
...
```

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

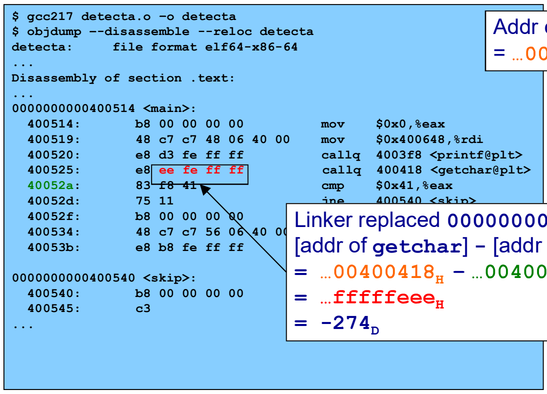


```
$ gcc217 detecta.o –o detecta
$ objdump --disassemble --reloc detecta
detecta:     file format elf64-x86-64
...
Disassembly of section .text:
...
0000000000400514 <main>:
  400514:       b8 00 00 00 00          mov    $0x0,%eax
  400519:       48 c7 c7 48 06 40 00    mov    $0x400648,%rdi
  400520:       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

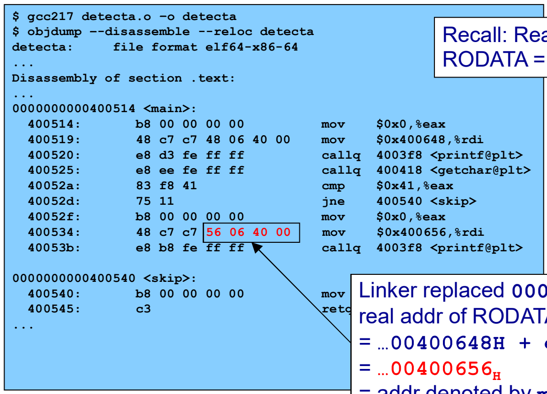


```
$ gcc217 detecta.o –o detecta
$ objdump --disassemble --reloc detecta
detecta:     file format elf64-x86-64
...
Disassembly of section .text:
...
0000000000400514 <main>:
  400514:       b8 00 00 00 00          mov    $0x0,%eax
  400519:       48 c7 c7 48 06 40 00    mov    $0x400648,%rdi
  400520:       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$_H$
= …ffffeee$_H$
= -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                      ret
...
```

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
  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
  400545:       c3
...
```

Addr of `printf`
= …004003f8$_H$

Linker replaced 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