Princeton University

Computer Science 217: Introduction to Programming Systems

Machine Language

1

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

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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)

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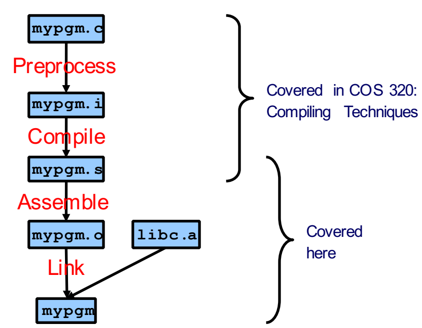
The Build Process



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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*

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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!

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Agenda

x86-64 Machine Language

Buffer overrun vulnerabilities

x86-64 Machine Language after Assembly

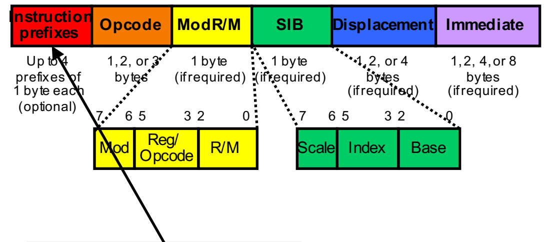
x86-64 Machine Language after Linking

Assembly Language: `addq %rax, %rbx`

Machine Language: `01001000 00000001 11000011`

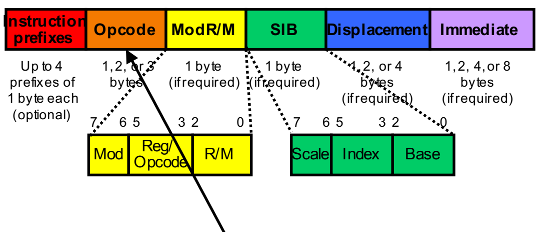
x86-64 Instruction Format

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



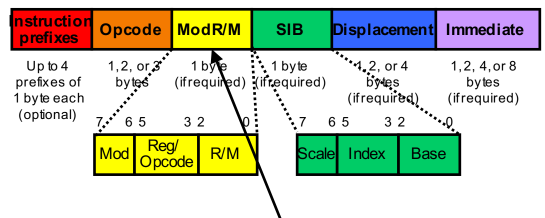
Instruction prefix
- Sometimes a repeat count
- Rarely used; don't be concerned

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

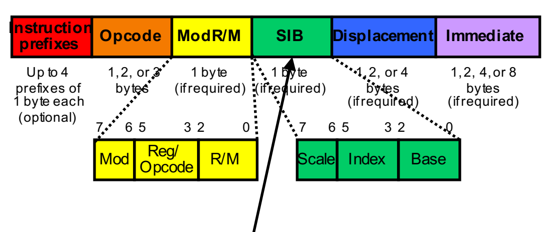
x86-64 Instruction Format (cont.)

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

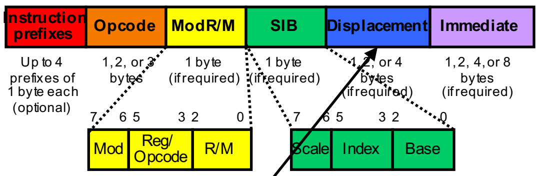
Similar mappings exist for 4-byte, 2-byte and 1-byte registers

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

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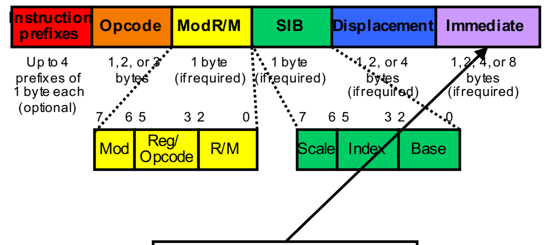
x86-64 Instruction Format (cont.)



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

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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)

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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

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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

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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!!!

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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?

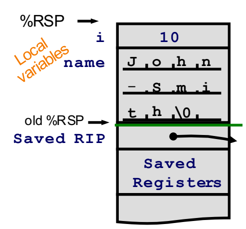
```
% a.out
What is your name?
adsli57asdkhj5jklds;ahj5;klsaduj5klysdukl5aujksd5ukals;5uj;akukla
Segmentation fault
%
```

```
#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.
%
```

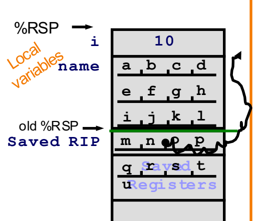
```
#include <stdio.h>
int main(int argc, char **argv) {
  char name[12];  int i;
  printf("What is your name?\n");
  for (i=0; ; i++) {
    int c = getchar();
    if (c=='\n' || c ==EOF) break;
    name[i] = c;
  }
  name[i]='\0';
  printf("Thank you, %s.\n", name);
  return 0;
}
```



Buffer overrun

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

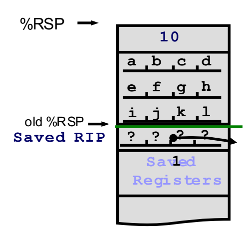
```
#include <stdio.h>
int main(int argc, char **argv) {
  char name[12];  int i;
  printf("What is your name?\n");
  for (i=0; ; i++) {
    int c = getchar();
    if (c=='\n' || c ==EOF) break;
    name[i] = c;
  }
  name[i]='\0';
  printf("Thank you, %s.\n", name);
  return 0;
}
```



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**

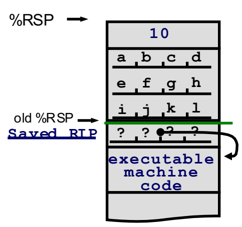
What is your name?

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;
}
```



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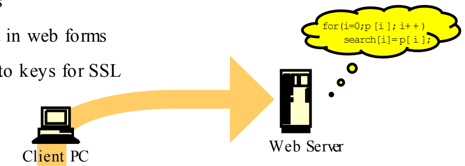
Attacking a web server

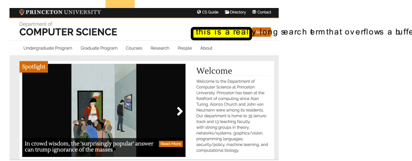
URLs

Input in web forms

Crypto keys for SSL

etc.





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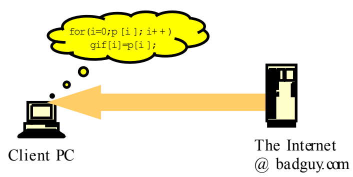
Attacking everything in sight



E-mail client

PDF viewer

Operating-system kernel

TCP/IP stack

Any application that ever sees input directly from the outside

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Defenses against this attack

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

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

Not a single one of these would have prevented the "Heartbleed" attack

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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.

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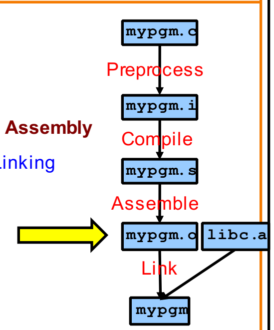
Agenda

x86-64 Machine Language

Buffer overrun vulnerabilities

x86-64 Machine Language after Assembly

x86-64 Machine Language after Linking



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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;
}
```

Let's consider the machine lang equivalent after assembly…

```
          .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
```

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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                                     ..
```

Offsets

Contents

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

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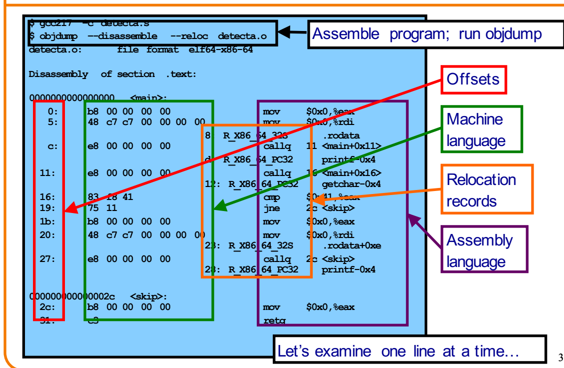
Examining Machine Lang: TEXT



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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
```

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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
```

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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
```

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movq $msg1, %rdi

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

```
01001000   11000111   11001011 1   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

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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
```

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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

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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
```

40

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

41

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
```

42

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

43

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
```

44

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

45

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
```

46

Relocation Record 3

`12: R_X86_64_PC32getchar-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

47

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
```

48

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')
```

49

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
```

50

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
  $2c_H - 1b_H = 11_H = 17_D$

51

jne skip

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

52

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
```

53

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
```

54

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
```

55

movq $msg2, %rdi

Assembly lang: `movq $msg2, %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 `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

56

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
```

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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

58

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
```

59

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 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

60

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
```

61

Relocation Record 5

`28: R_X86_64_PC32printf-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

62

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
```

63

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
```

64

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
```

65

ret

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

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

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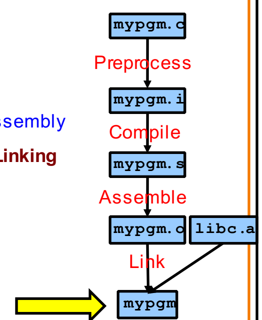
Agenda

x86-64 Machine Language

Buffer overrun vulnerabilities

x86-64 Machine Language after Assembly

x86-64 Machine Language after Linking



67

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**

68

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

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Linker Relocation

Relocation

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

70

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

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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…

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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

73

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    $0x41,%eax
  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            callq

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**

74

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
  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$_D$

75

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
  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$_D$

76

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**

77

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$_D$

78

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

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