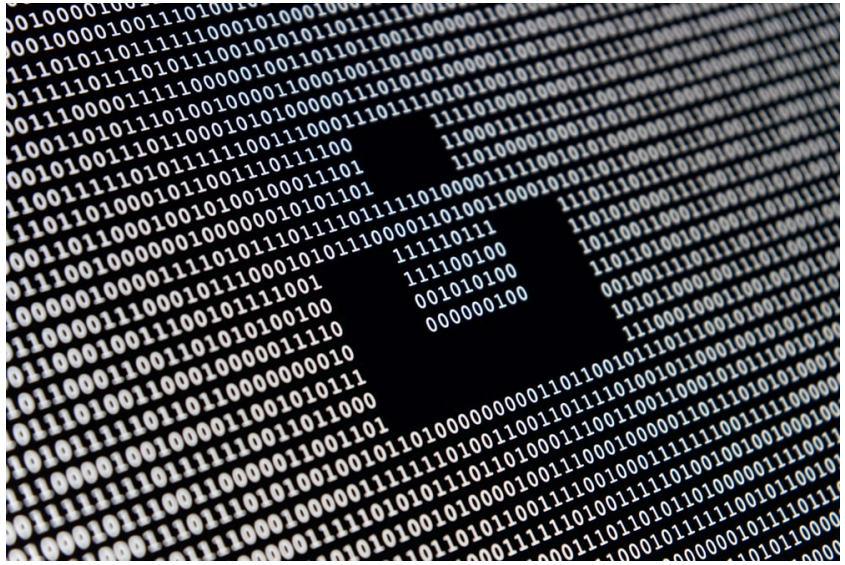
COS 217: Introduction to Programming Systems

Machine Language



PRINCETON UNIVERSITY

Instruction Set Architecture (ISA)

There are many kinds of computer chips out there:

ARM (AARCH64)

Intel x86 series

IBM PowerPC

RISC-V

MIPS

Each of these different "machine architectures" understands a different *machine language* – binary encoding of instructions

(and, in the old days, dozens more)

@swimstaralex (previous slide)

Machine Language

The first part of this lecture (today) covers

- A motivating example from Assignment 6: Buffer Overrun
- The AARCH64 machine language

The second part (our last lecture 😭) covers

- The assembly and linking processes

Flashback to last lecture …

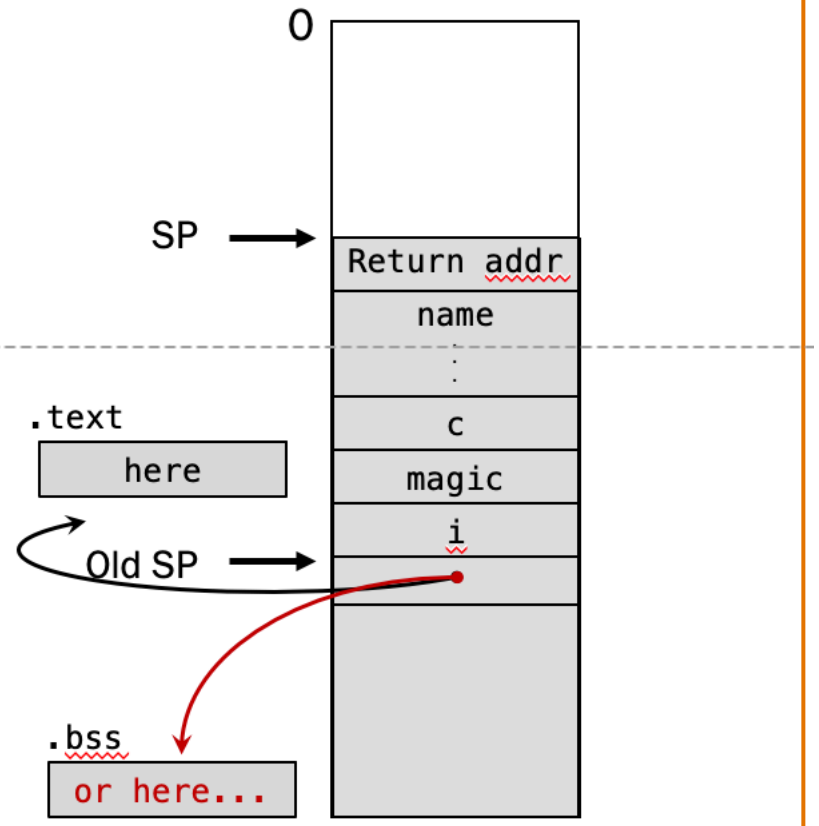
It Gets Much, Much Worse…

Buffer overrun can overwrite return address of a previous stack frame!

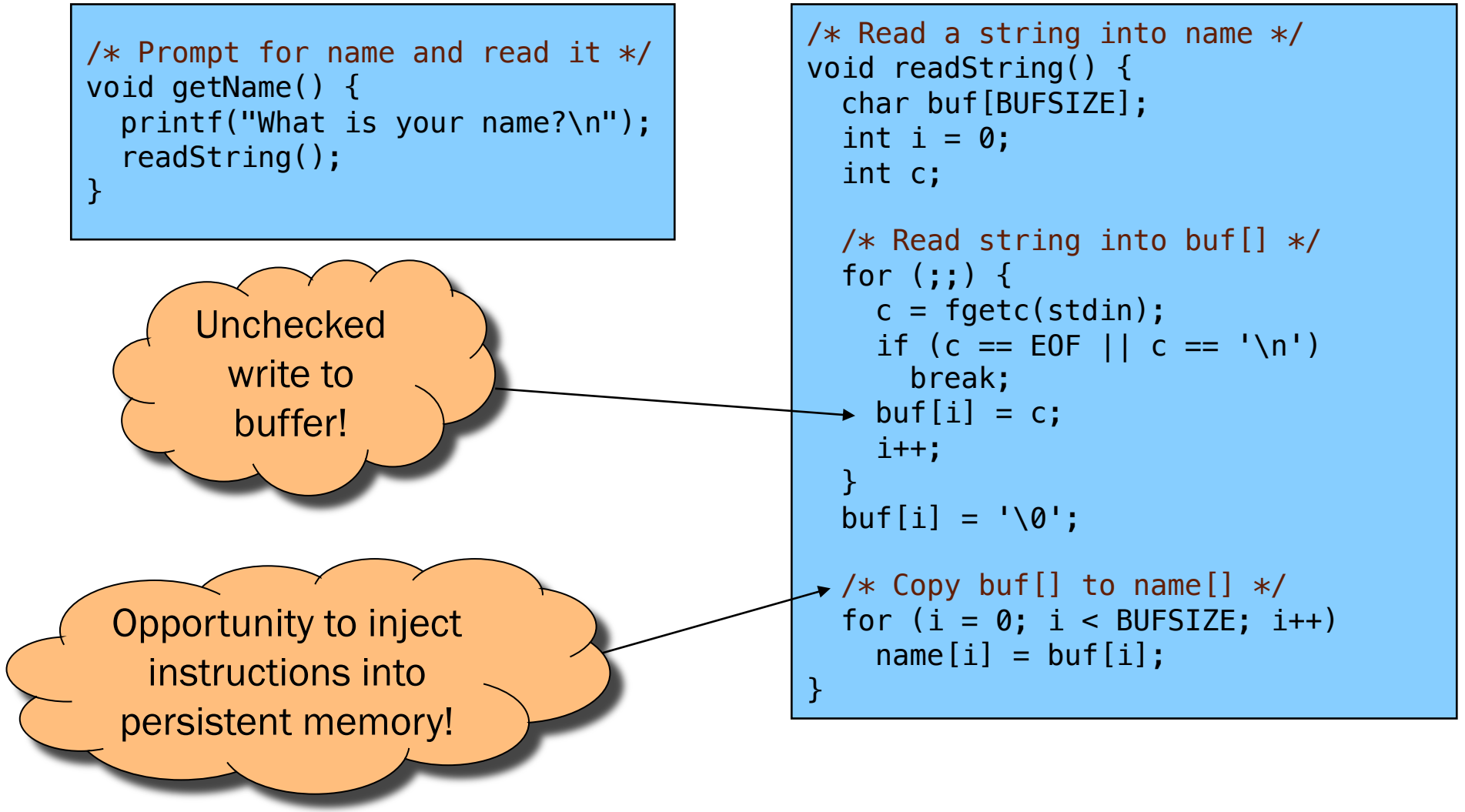
- Value can be an invalid address, leading to a segfault, or it can cleverly cause unintended control flow, or even cause arbitrary malicious code to execute!

```
#include <stdio.h>
int main(void)
{
   char name[12], c;
   int i = 0, magic = 42;
   printf("What is your name?\n");
   while ((c = getchar()) != '\n')
      name[i++] = c;
   name[i] = '\0';
   printf("Thank you, %s.\n", name);
   printf("The answer to life, the universe, "
          "and everything is %d\n", magic);
   return 0;
}
```

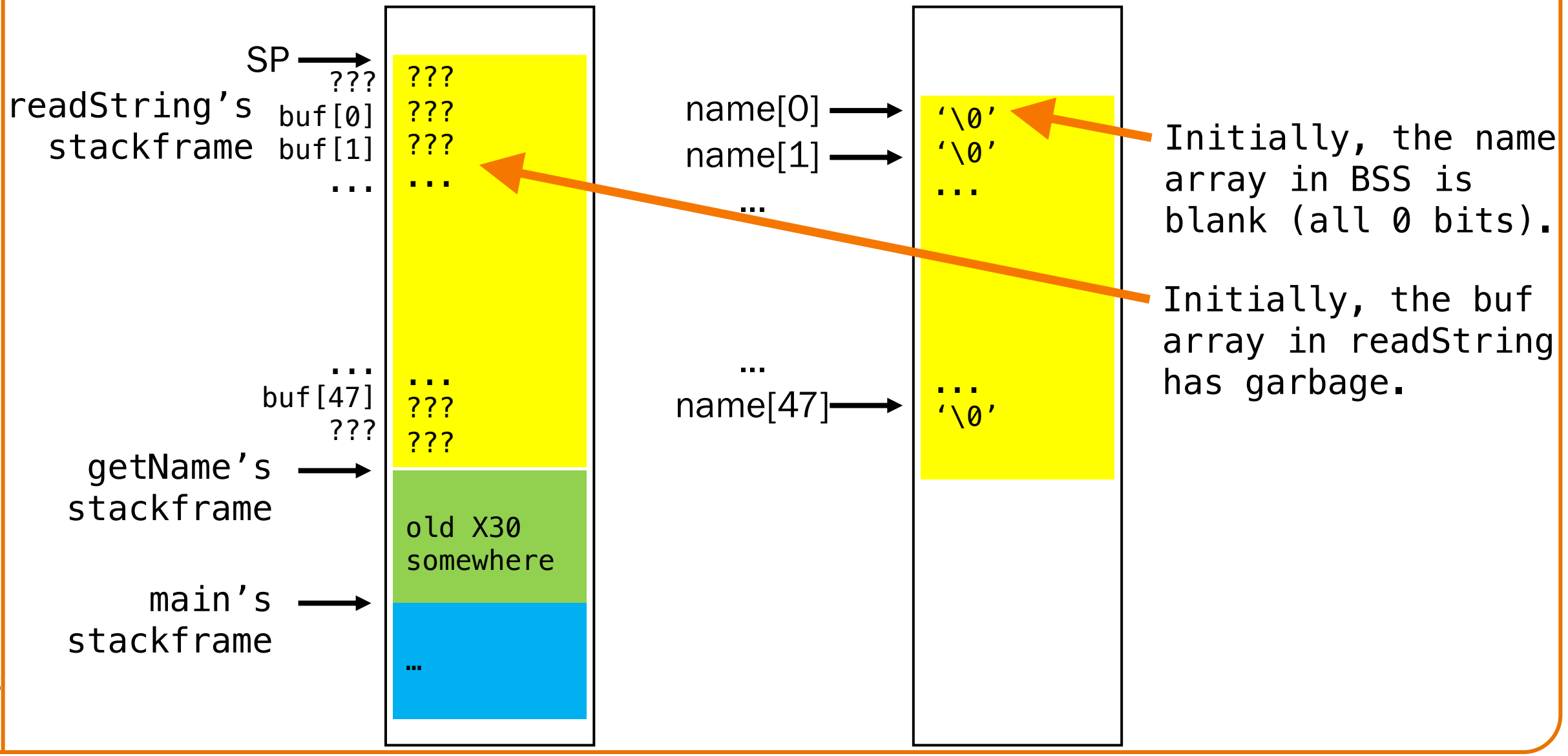
10



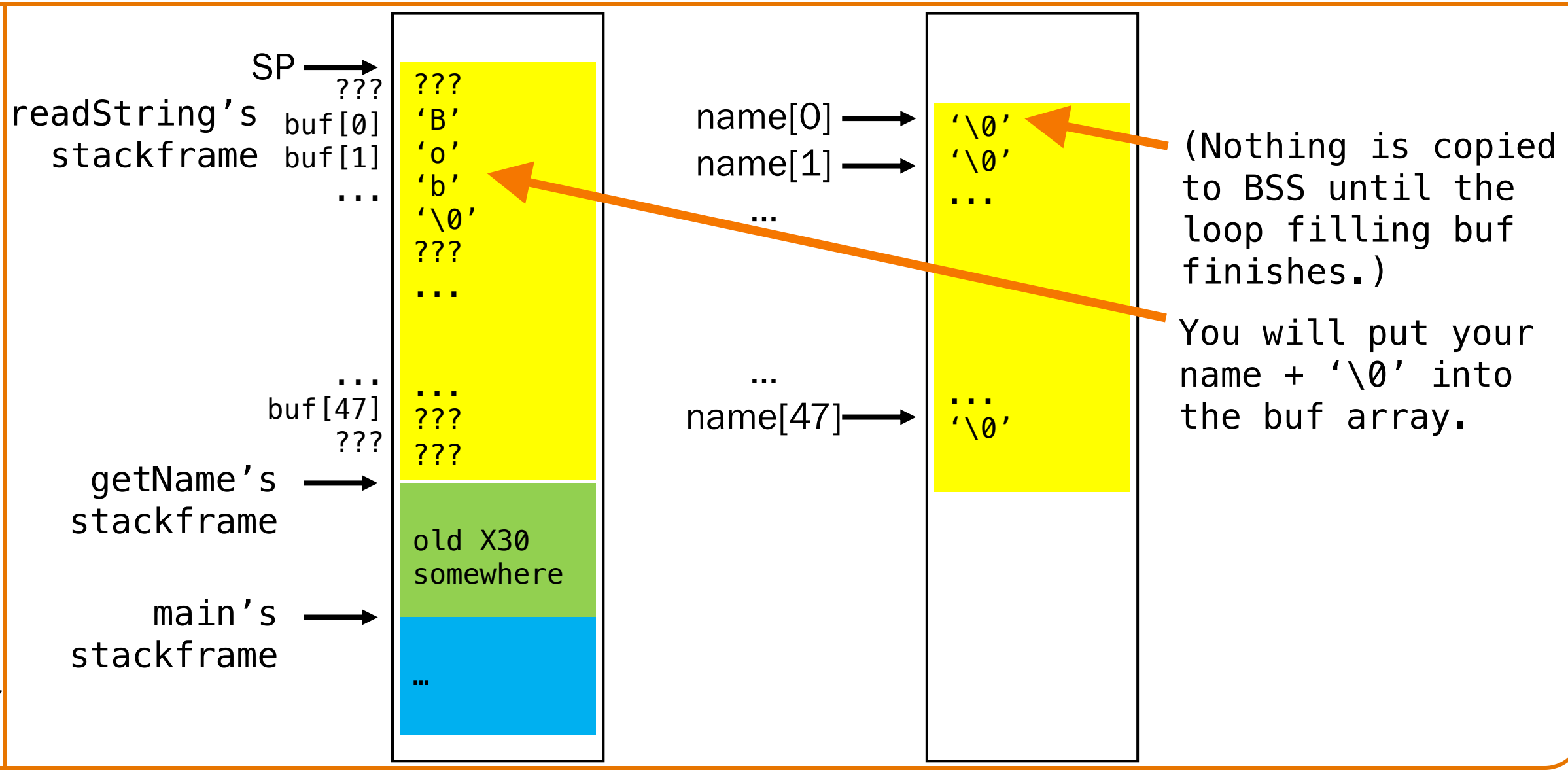
Assignment 6: Attack the “Grader” Program



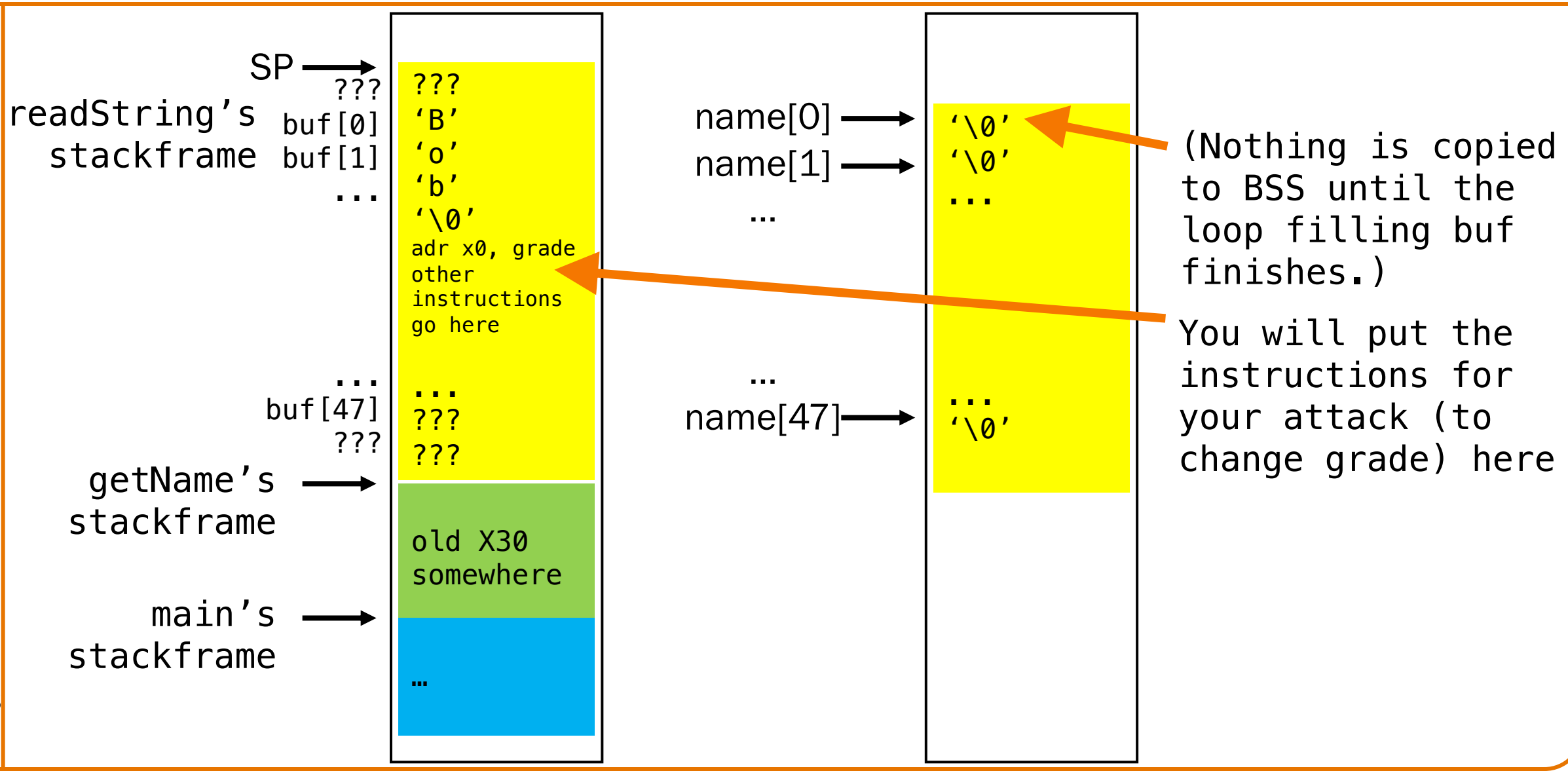
Memory Map of Stack and BSS Section



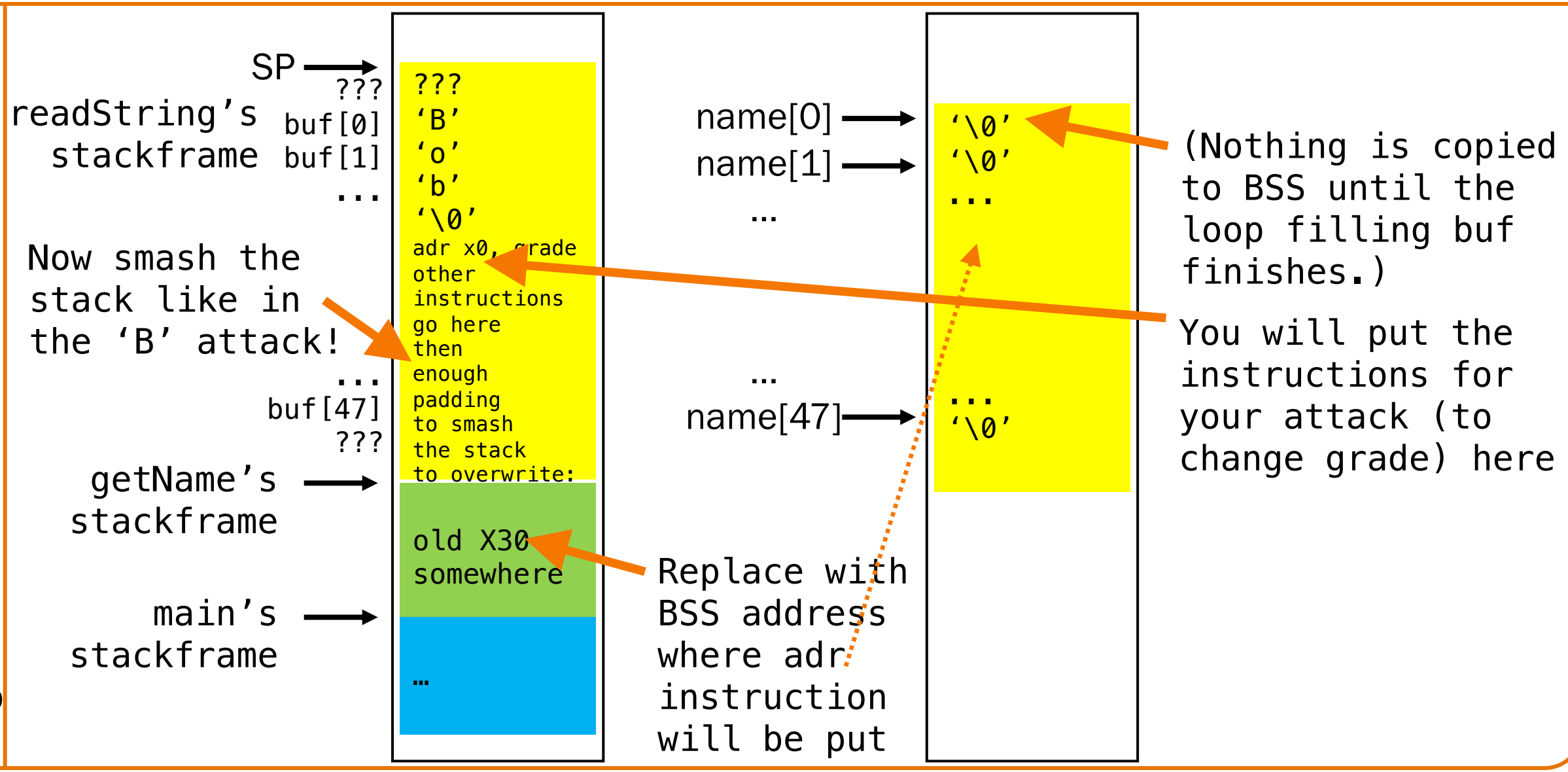
Memory Map of Stack and BSS Section



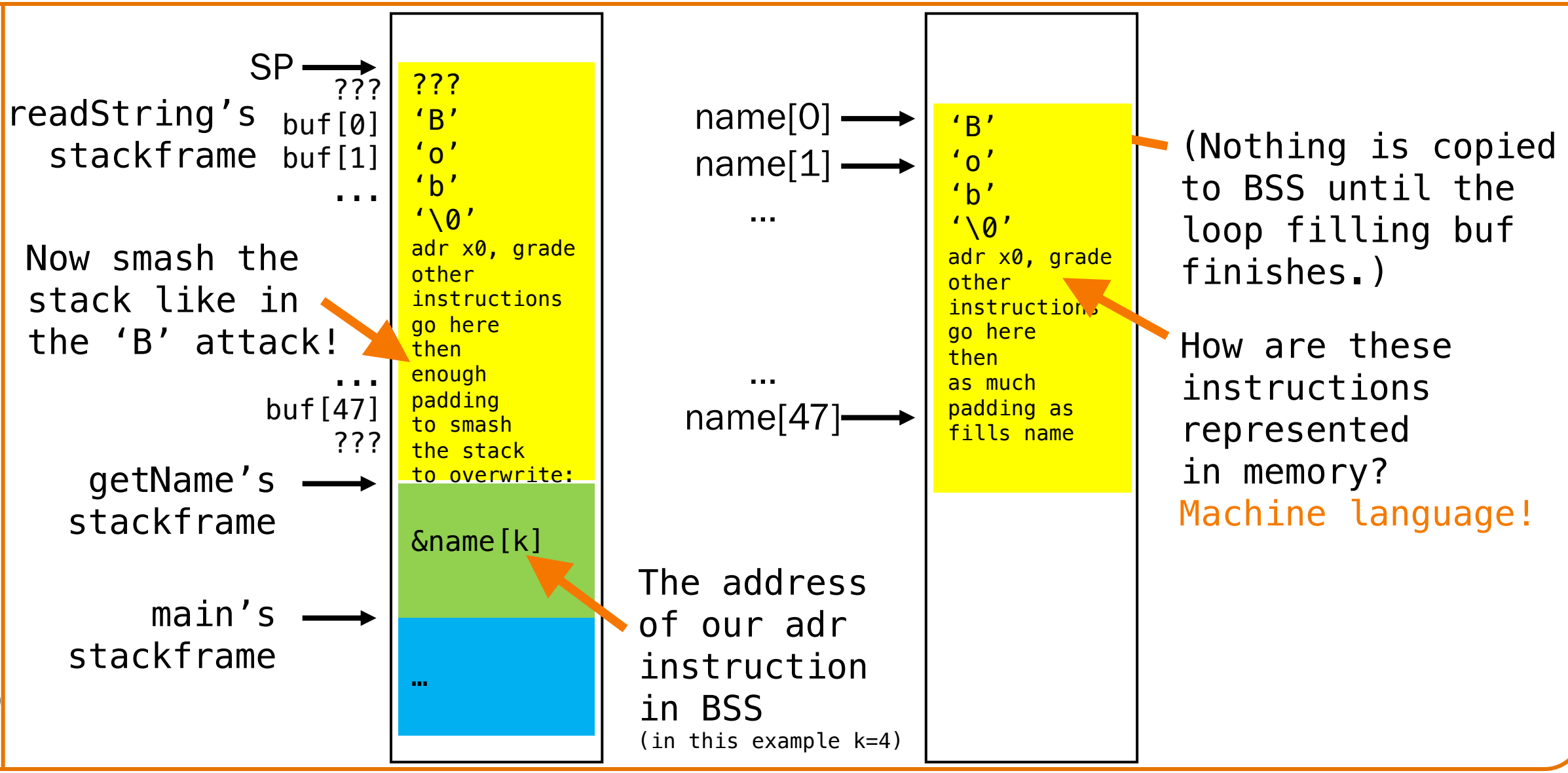
Memory Map of Stack and BSS Section



Memory Map of Stack and BSS Section



Memory Map of Stack and BSS Section



Agenda

A6 “A” Attack

AARCH64 Machine Language

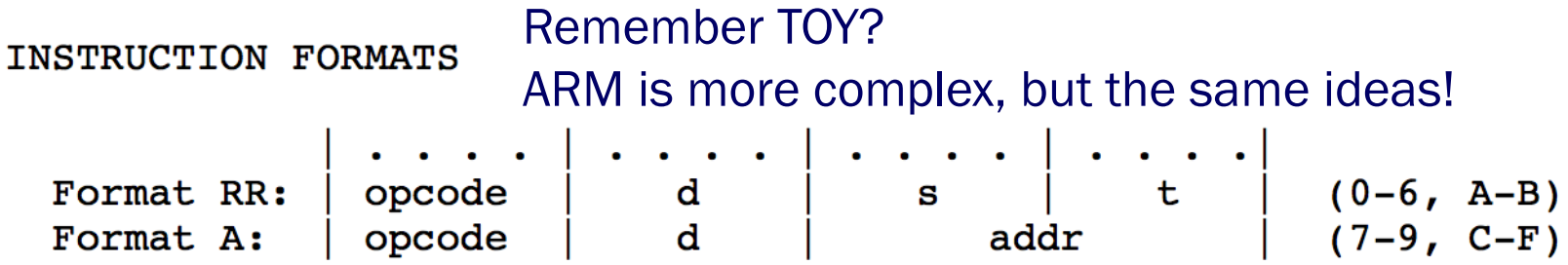
AARCH64 Machine Language after Assembly

AARCH64 Machine Language after Linking

Assembly Language: `add x1, x2, x3`

Machine Language: `1000 1011 0000 0011 0000 0000 0100 0001`

Machine Language: TOY → AARCH64



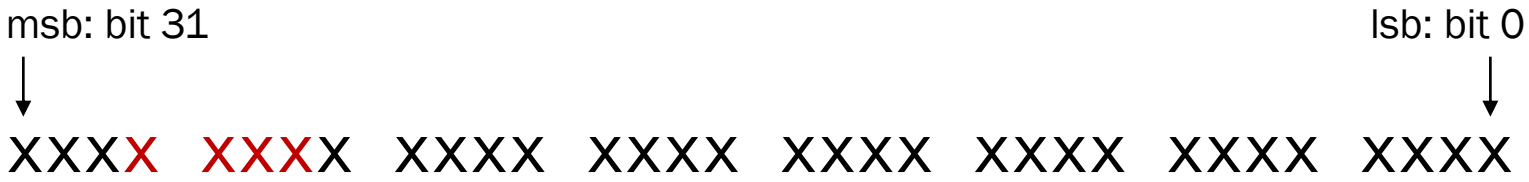
AARCH64 machine language

- All instructions are 32 bits long, 4-byte aligned
- Some bits allocated to *opcode*: what kind of instruction is this?
- Other bits specify register(s)
- Depending on instruction, other bits may be used for an immediate value, a memory offset, an offset to jump to, etc.

Instruction formats

- Variety of ways different instructions are encoded
- We'll go over quickly in class, to give you a flavor
- Refer to slides as reference for Assignment 6!
  (Every instruction format you'll need is in the following slides… we think…)

AARCH64 Instruction Format



Operation group

- Encoded in bits 25-28
- `x101`: Data processing – 3-register
- `100x`: Data processing – immediate + register(s)
- `101x`: Branch
- `x1x0`: Load/store

AARCH64 Instruction Format

Op. Group: Data processing – 3-register

- Instruction width in bit 31: 0 = 32-bit, 1 = 64-bit
- Whether to set condition flags (e.g. ADD vs ADDS) in bit 29
- Second source register in bits 16-20
- First source register in bits 5-9
- Destination register in bits 0-4
- Remaining bits encode additional information about instruction

AARCH64 Instruction Format

Example: `add x1, x2, x3`

- opcode = add
- Instruction width in bit 31: 1 = 64-bit
- Whether to set condition flags in bit 29: no
- Second source register in bits 16-20: 3
- First source register in bits 5-9: 2
- Destination register in bits 0-4: 1
- Additional information about instruction: none

AARCH64 Instruction Format

Op. Group: Data processing – immediate + register(s)

- Instruction width in bit 31: 0 = 32-bit, 1 = 64-bit
- Whether to set condition flags (e.g. ADD vs ADDS) in bit 29
- Immediate value in bits 10-21 for 2-register instructions, bits 5-20 for 1-register instructions
- Source register in bits 5-9
- Destination register in bits 0-4
- Remaining bits encode additional information about instruction

AARCH64 Instruction Format

Example: `subs w1, w2, 42`

- opcode: subtract immediate
- Instruction width in bit 31: 0 = 32-bit
- Whether to set condition flags in bit 29: yes
- Immediate value in bits 10-21: 101010_b = 42
- First source register in bits 5-9: 2
- Destination register in bits 0-4: 1
- Additional information about instruction: none

AARCH64 Instruction Format

Example: `mov x1, 42`

- opcode: move immediate
- Instruction width in bit 31: 1 = 64-bit
- Immediate value in bits 5-20: 101010_b = 42
- Destination register in bits 0-4: 1

AARCH64 Instruction Format

Op. Group: Branch

- *Relative* address of branch target in bits 0-25 for unconditional branch (`b`) and function call (`bl`)
- *Relative* address of branch target in bits 5-23 for conditional branch
- Because all instructions are 32 bits long and are 4-byte aligned, relative addresses end in 00. Because this is invariable, we can omit those two bits from our representation. Doing so provides more range with the same number of bits!
- Type of conditional branch encoded in bits 0-3

Displacement Discombobulation

msb: bit 31 ↓ lsb: bit 0 ↓

```
xxx1 01ii iiii iiii iiii iiii iiii iiii iiii
```

What is the range of the relative address?

A. 0 – 64MB

B. -32MB – +32MB

C. 0 – +256MB

D. -128MB – +128MB

D: 26 bits + 2 "chopped off" bits
= 28 bits: 256MB.

2's complement splits half
negative / half non-negative

AARCH64 Instruction Format

Example: `b someLabel`

- This depends on where `someLabel` is relative to this instruction!
  For this example, `someLabel` is 3 instructions (12 bytes) *earlier*
- opcode: unconditional branch
- *Relative* address in bits 0-25: two's complement of 11_b.
  Shift left by 2: $1100_b = 12$. So, offset is -12.

AARCH64 Instruction Format

Example: `bl someLabel`

- This depends on where `someLabel` is relative to this instruction!
  For this example, `someLabel` is 3 instructions (12 bytes) *earlier*
- opcode: branch and link (function call)
- *Relative* address in bits 0-25: two's complement of 11_b.
  Shift left by 2: $1100_b = 12$. So, offset is -12.

AARCH64 Instruction Format

Example: `ble someLabel`

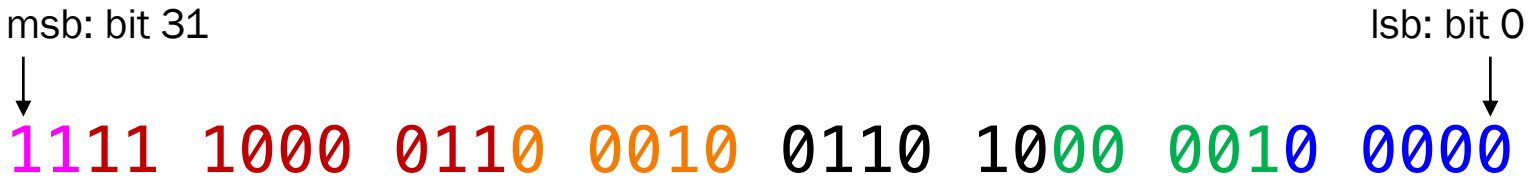
- This depends on where `someLabel` is relative to this instruction!
  For this example, `someLabel` is 3 instructions (12 bytes) *later*
- opcode: conditional branch
- *Relative* address in bits 5-23: 11_b. Shift left by 2: 1100_b = 12
- Conditional branch type in bits 0-3: LE

AARCH64 Instruction Format

Op. Group: Load / store

- Instruction width in bits 30-31: 00 = 8-bit, 01 = 16-bit, 10 = 32-bit, 11 = 64-bit
- For [Xn,Xm] addressing mode: second source register in bits 16-20
- For [Xn,offset] addressing mode: offset in bits 10-21,
  shifted left by 3 bits for 64-bit, 2 bits for 32-bit, 1 bit for 16-bit
- First source register in bits 5-9
- Destination register in bits 0-4
- Remaining bits encode additional information about instruction, e.g. scaled mode

AARCH64 Instruction Format



Example: `ldr x0, [x1, x2]`

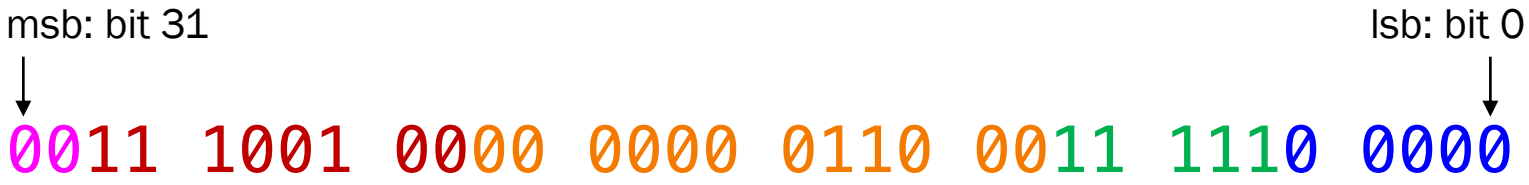
- opcode: load, register+register
- Instruction width in bits 30-31: 11 = 64-bit
- Second source register in bits 16-20: 2
- First source register in bits 5-9: 1
- Destination register in bits 0-4: 0
- Additional information about instruction: no LSL

AARCH64 Instruction Format

Example: `str x0, [sp,24]`

- opcode: store, register+offset
- Instruction width in bits 30-31: 11 = 64-bit
- Offset value in bits 12-20: 11_b, shifted left by 3 = 11000_b = 24
- "Source" (really destination!) register in bits 5-9: 31 = sp
- "Destination" (really source!) register in bits 0-4: 0
- Remember that store instructions use the opposite convention from others: "source" and "destination" are flipped!

AARCH64 Instruction Format



Example: `strb w0, [sp,24]`

- opcode: store, register+offset
- Instruction width in bits 30-31: 00 = 8-bit
- Offset value in bits 12-20: 11000_b (don't shift left!) = 24
- "Source" (really destination!) register in bits 5-9: 31 = sp
- "Destination" (really source!) register in bits 0-4: 0
- Remember that store instructions use the opposite convention from others: "source" and "destination" are flipped!

AARCH64 Instruction Format

ADR instruction

(Distinct from others w/ Op Group bits 100x)

- Specifies *relative* position of label (data location)
- 19 High-order bits of offset in bits 5-23
- 2 Low-order bits of offset in bits 29-30
- Destination register in bits 0-4

AARCH64 Instruction Format

Example: `adr x19, someLabel`

- This depends on where `someLabel` is relative to this instruction!
  For this example, `someLabel` is 50 bytes later
- opcode: generate address
- 19 High-order bits of offset in bits 5-23: 1100
- 2 Low-order bits of offset in bits 29-30: 10
- *Relative* data location is 110010_b = 50 bytes after this instruction
- Destination register in bits 0-4:19

Agenda

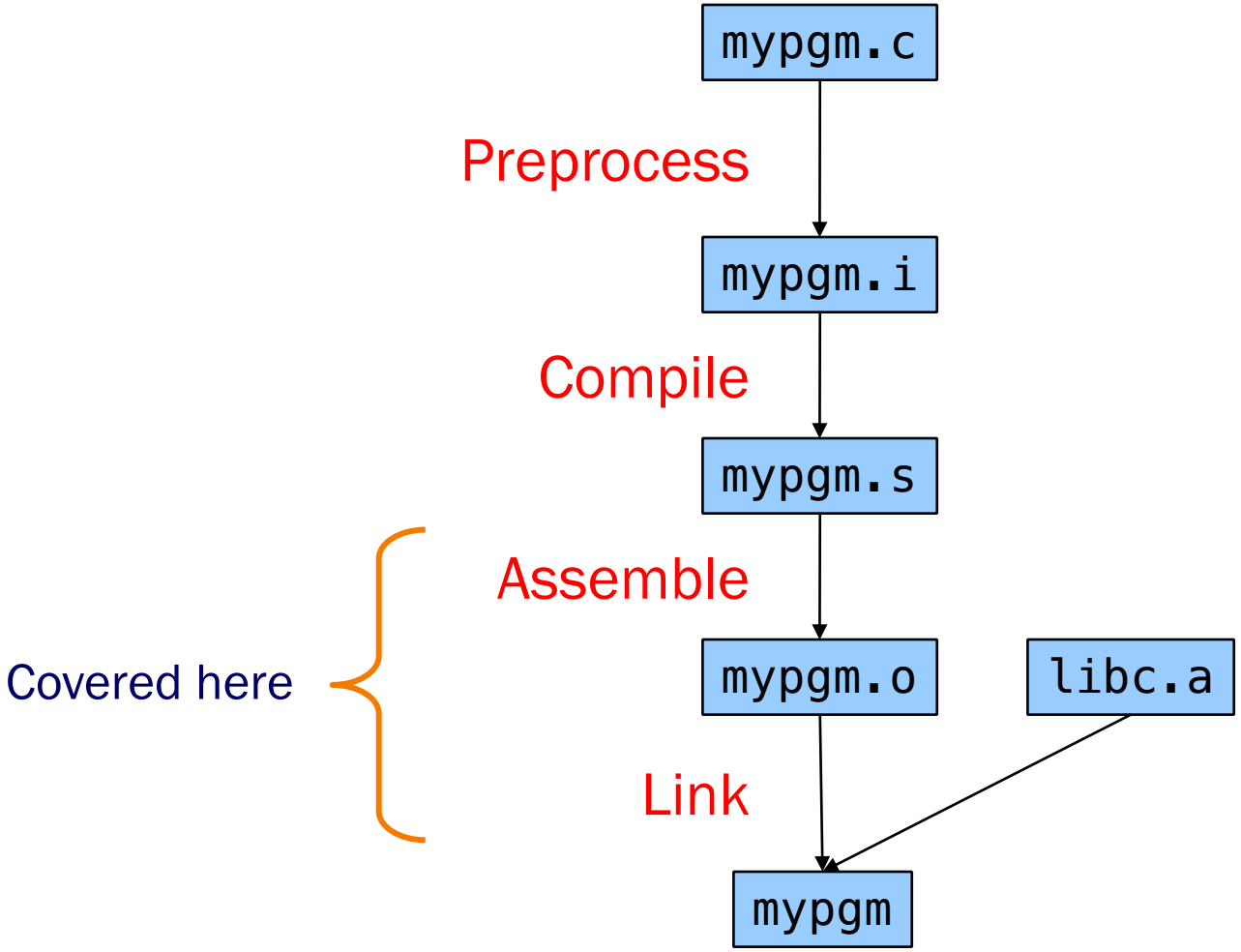
A6 “A” Attack

AARCH64 Machine Language

AARCH64 Machine Language after Assembly

AARCH64 Machine Language after Linking

The Build Process



An Example Program

A simple (nonsensical) program, in C and assembly:

```
#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
      .global  main
main:
      sub      sp, sp, 16
      str      x30, [sp]

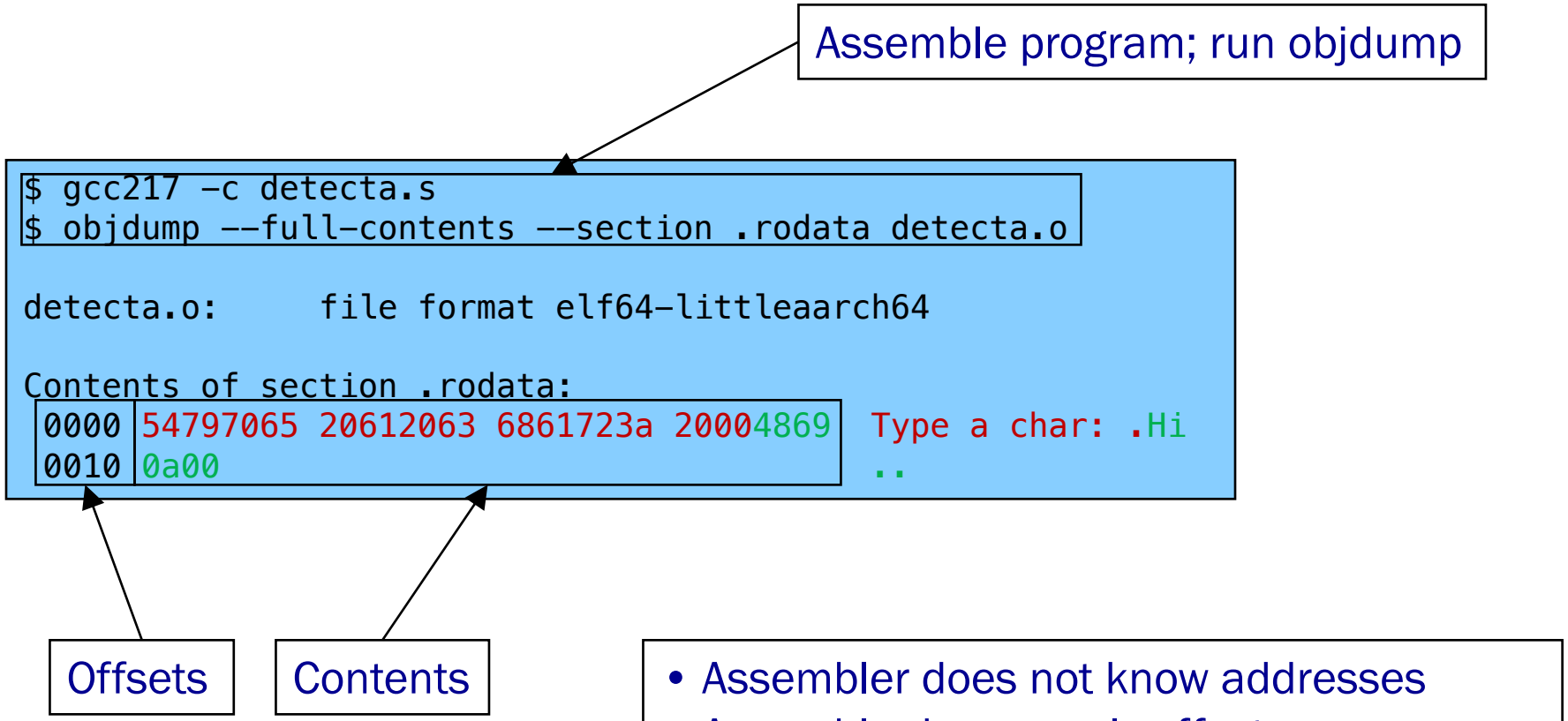
      adr      x0, msg1
      bl       printf

      bl       getchar
      cmp      w0, 'A'
      bne      skip

      adr      x0, msg2
      bl       printf
skip:
      mov      w0, 0
      ldr      x30, [sp]
      add      sp, sp, 16
      ret
```

Let's consider the machine language equivalent…

Examining Machine Lang: RODATA



- Assembler does not know addresses
- Assembler knows only offsets
- `"Type a char: "` starts at offset 0x0
- `"Hi\n"` starts at offset 0xe

Examining Machine Lang: TEXT

```
$ objdump --disassemble --reloc detecta.o

detecta.o:     file format elf64-littleaarch64

Disassembly of section .text:

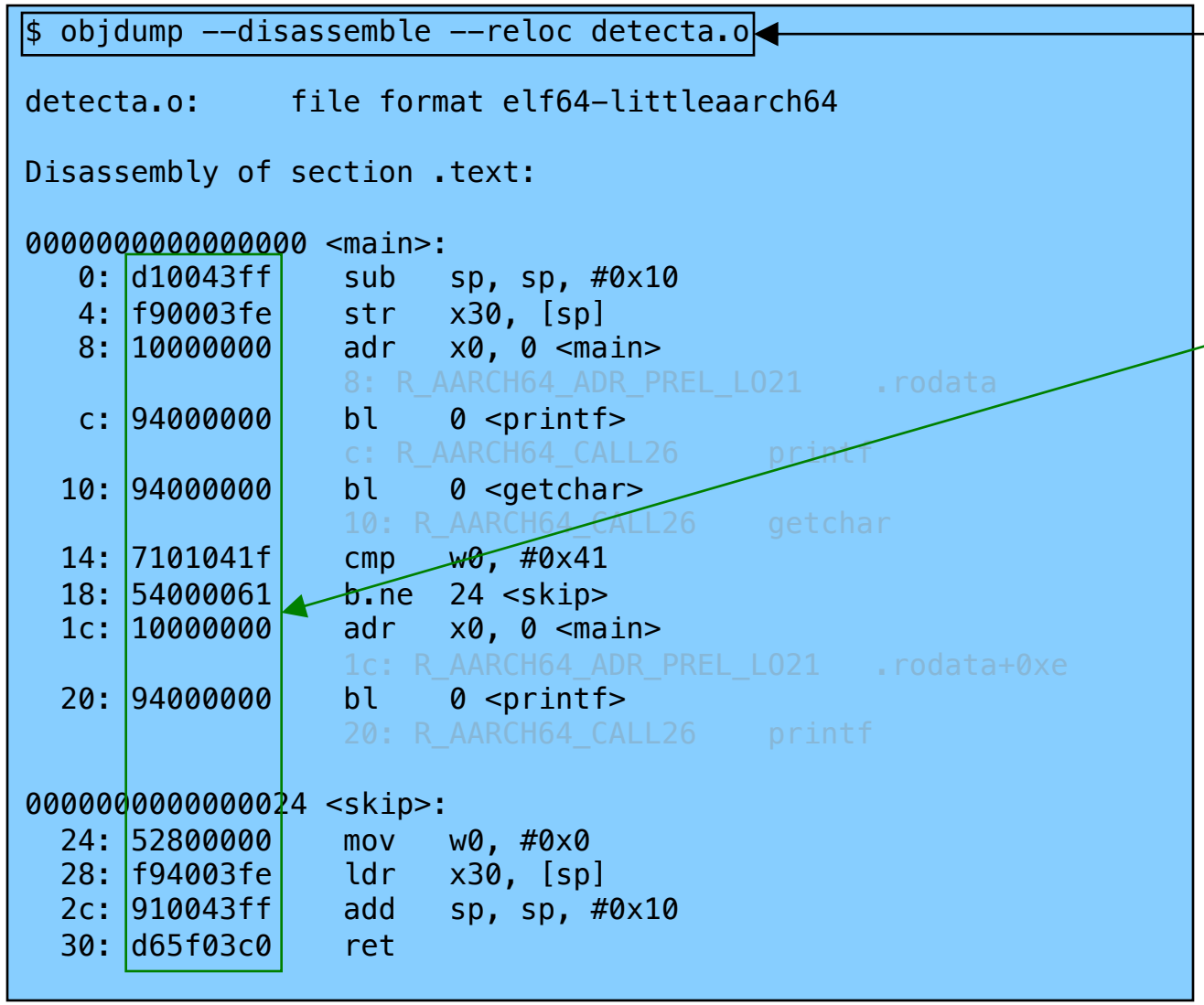
0000000000000000 <main>:
   0: d10043ff    sub   sp, sp, #0x10
   4: f90003fe    str   x30, [sp]
   8: 10000000    adr   x0, 0 <main>
                  8: R_AARCH64_ADR_PREL_LO21    .rodata
   c: 94000000    bl    0 <printf>
                  c: R_AARCH64_CALL26     printf
  10: 94000000    bl    0 <getchar>
                  10: R_AARCH64_CALL26    getchar
  14: 7101041f    cmp   w0, #0x41
  18: 54000061    b.ne  24 <skip>
  1c: 10000000    adr   x0, 0 <main>
                  1c: R_AARCH64_ADR_PREL_LO21   .rodata+0xe
  20: 94000000    bl    0 <printf>
                  20: R_AARCH64_CALL26    printf

0000000000000024 <skip>:
  24: 52800000    mov   w0, #0x0
  28: f94003fe    ldr   x30, [sp]
  2c: 910043ff    add   sp, sp, #0x10
  30: d65f03c0    ret
```

Run objdump to see instructions

Assembly language

Examining Machine Lang: TEXT



Run objdump to see instructions

Machine language

Examining Machine Lang: TEXT

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  28: f94003fe    ldr   x30, [sp]
  2c: 910043ff    add   sp, sp, #0x10
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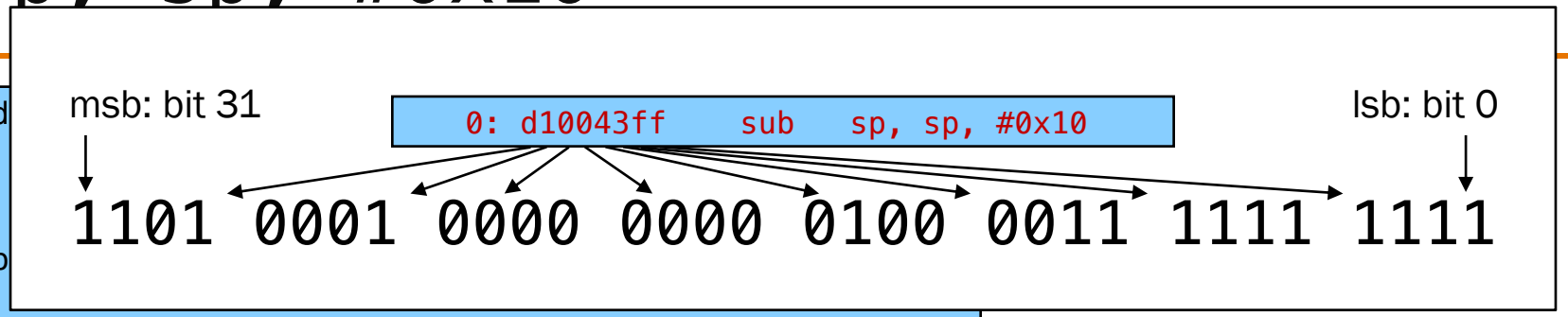
```

Run objdump to see instructions

Offsets

Let's examine one line at a time...

sub sp, sp, #0x10




```
$ objdump --d

detecta.o:

Disassembly o

0000000000000000 <main>:
   0: d10043ff    sub   sp, sp, #0x10
   4: f90003fe    str   x30, [sp]
   8: 10000000    adr   x0, 0 <main>
                  8: R_AARCH64_ADR_PREL_LO21    .rodata
   c: 94000000    bl    0 <printf>
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                  10: R_AARCH64_CALL26    getchar
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  18: 54000061    b.ne  24 <skip>
  1c: 10000000    adr   x0, 0 <main>
                  1c: R_AARCH64_ADR_PREL_LO21   .rodata+0xe
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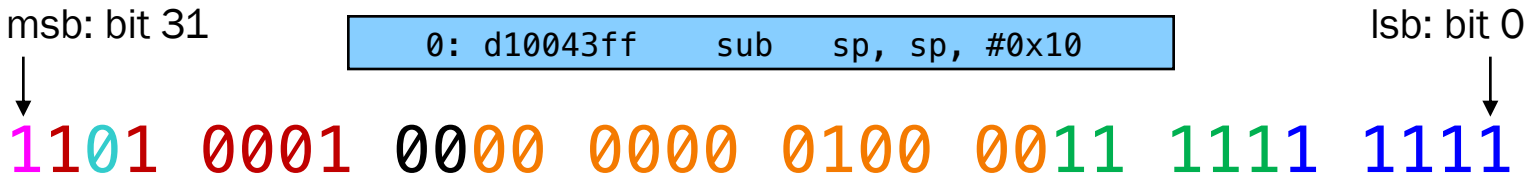
0000000000000024 <skip>:
  24: 52800000    mov   w0, #0x0
  28: f94003fe    ldr   x30, [sp]
  2c: 910043ff    add   sp, sp, #0x10
  30: d65f03c0    ret
```

sub sp, sp, #0x10



- opcode: subtract immediate
- Instruction width in bit 31: 1 = 64-bit
- Whether to set condition flags in bit 29: no
- Immediate value in bits 10-21: 10000_b = 0x10 = 16
- First source register in bits 5-9: 31 = sp
- Destination register in bits 0-4: 31 = sp
- Additional information about instruction: none

str x30, [sp]

```
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detecta.o:     file format elf64-littleaarch64

Disassembly of section .text:

0000000000000000 <main>:
   0: d10043ff    sub   sp, sp, #0x10
   4: f90003fe    str   x30, [sp]
   8: 10000000    adr   x0, 0 <main>
                  8: R_AARCH64_ADR_PREL_LO21    .rodata
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  1c: 10000000    adr   x0, 0 <main>
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  24: 52800000    mov   w0, #0x0
  28: f94003fe    ldr   x30, [sp]
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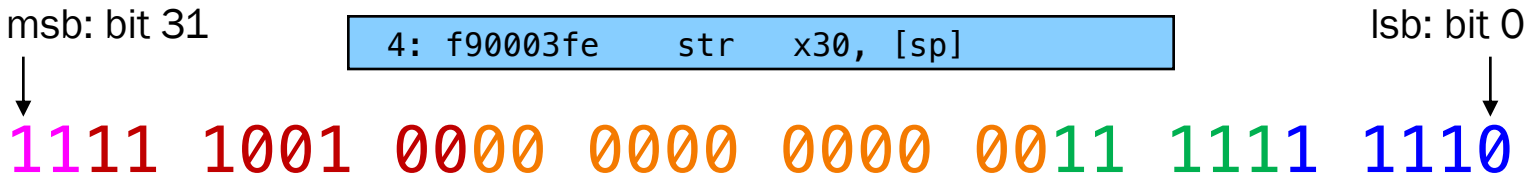
  30: d65f03c0    ret
```

str x30, [sp]



- opcode: store, register + offset
- Instruction width in bits 30-31: 11 = 64-bit
- Offset value in bits 12-20: 0
- “Source” (really destination) register in bits 5-9: 31 = sp
- “Destination” (really source) register in bits 0-4: 30
- Additional information about instruction: none

adr x0, 0 <main>

```
$ objdump --disassemble --reloc detecta.o

detecta.o:     file format elf64-littleaarch64

Disassembly of section .text:

0000000000000000 <main>:
   0: d10043ff    sub   sp, sp, #0x10
   4: f90003fe    str   x30, [sp]
   8: 10000000    adr   x0, 0 <main>
                  8: R_AARCH64_ADR_PREL_LO21    .rodata
   c: 94000000    bl    0 <printf>
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  14: 7101041f    cmp   w0, #0x41
  18: 54000061    b.ne  24 <skip>
  1c: 10000000    adr   x0, 0 <main>
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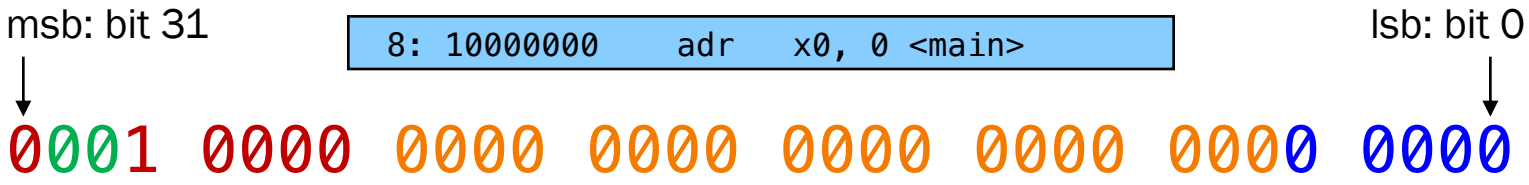
  24: 52800000    mov   w0, #0x0
  28: f94003fe    ldr   x30, [sp]
  2c: 910043ff    add   sp, sp, #0x10
  30: d65f03c0    ret
```

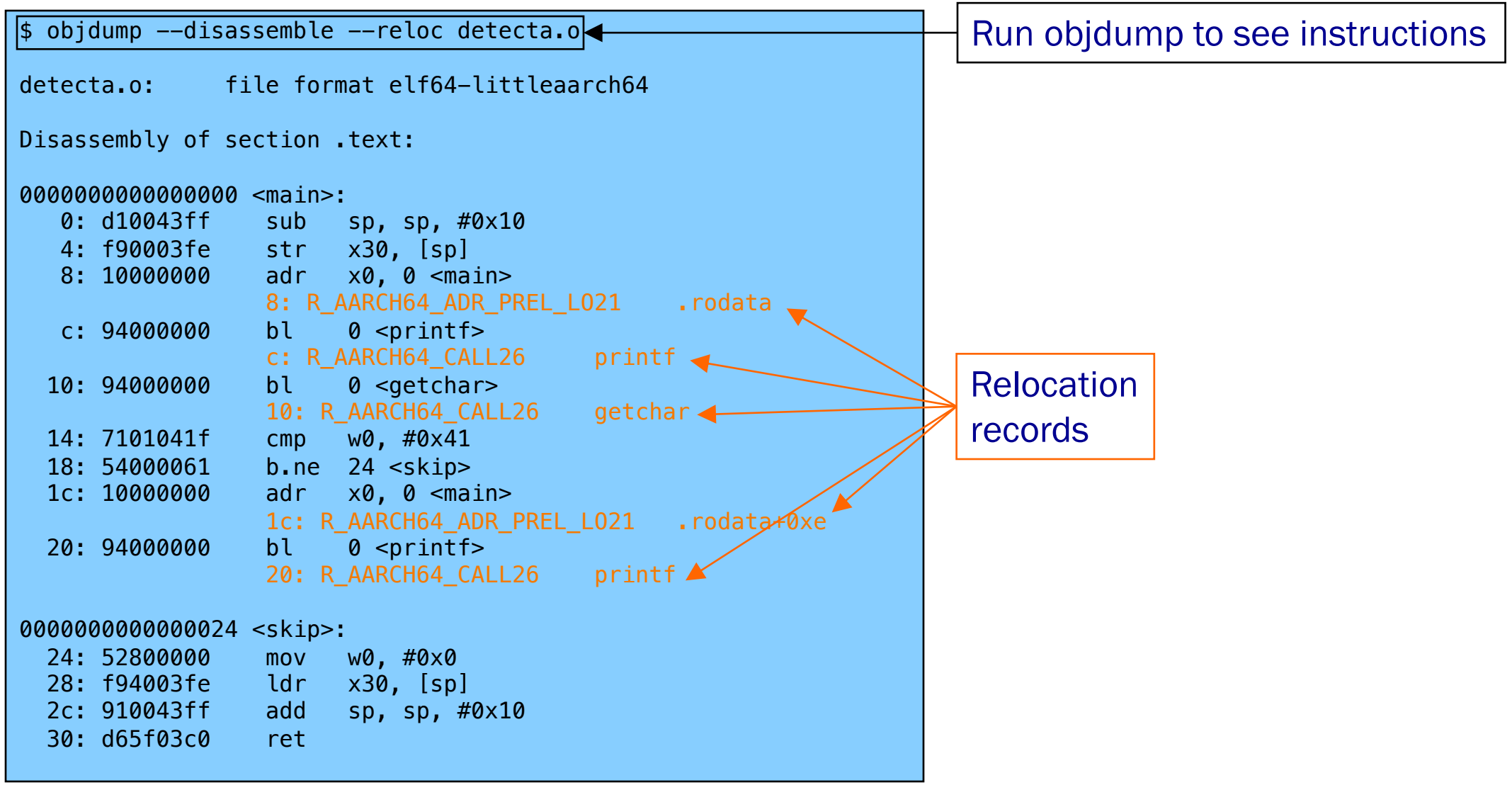
adr x0, 0 <main>



- opcode: generate address
- 19 High-order bits of relative address in bits 5-23: 0
- 2 Low-order bits of relative address in bits 29-30: 0
- *Relative* data location is 0 bytes after this instruction
- Destination register in bits 0-4:0

- Huh? That's not where `msg1` lives!
  - Assembler knew that `msg1` is a label within the RODATA section
  - But assembler didn't know address of RODATA section!
  - So, assembler couldn't generate this instruction completely, left a placeholder, and will request help from the linker

Examining Machine Lang: TEXT



R_AARCH64_ADR_PREL_LO21 .rodata

```
$ objdump --disassemble --reloc detecta.o

detecta.o:     file format elf64-littleaarch64

Disassembly of section .text:

0000000000000000 <main>:
   0: d10043ff    sub   sp, sp, #0x10
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  18: 54000061    b.ne  24 <skip>
  1c: 10000000    adr   x0, 0 <main>
                  1c: R_AARCH64_ADR_PREL_LO21   .rodata+0xe
  20: 94000000    bl    0 <printf>
                  20: R_AARCH64_CALL26    printf

0000000000000024 <skip>:
  24: 52800000    mov   w0, #0x0
  28: f94003fe    ldr   x30, [sp]
  2c: 910043ff    add   sp, sp, #0x10
  30: d65f03c0    ret
```

Relocation Record 1

```
8: R_AARCH64_ADR_PREL_LO21    .rodata
```

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

Dear Linker,

Please patch the TEXT section at offset 0x8.
Patch in a 21-bit* signed offset of an address, relative to the PC, as appropriate for the adr instruction format.
When you determine the address of .rodata, use that to compute the offset you need to do the patch.

Sincerely,
Assembler

* 19 High-order bits of relative address in bits 5-23
2 Low-order bits of relative address in bits 29-30

bl 0 <printf>

```
$ objdump --disassemble --reloc detecta.o

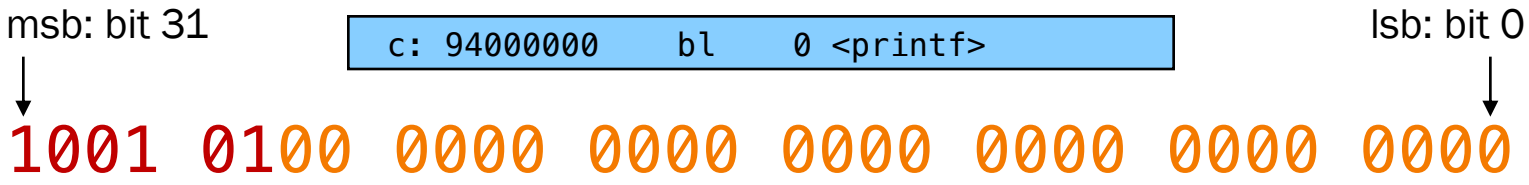
detecta.o:     file format elf64-littleaarch64

Disassembly of section .text:

0000000000000000 <main>:
   0: d10043ff    sub   sp, sp, #0x10
   4: f90003fe    str   x30, [sp]
   8: 10000000    adr   x0, 0 <main>
                  8: R_AARCH64_ADR_PREL_LO21    .rodata
   c: 94000000    bl    0 <printf>
                  c: R_AARCH64_CALL26     printf
  10: 94000000    bl    0 <getchar>
                  10: R_AARCH64_CALL26    getchar
  14: 7101041f    cmp   w0, #0x41
  18: 54000061    b.ne  24 <skip>
  1c: 10000000    adr   x0, 0 <main>
                  1c: R_AARCH64_ADR_PREL_LO21   .rodata+0xe
  20: 94000000    bl    0 <printf>
                  20: R_AARCH64_CALL26    printf

0000000000000024 <skip>:
  24: 52800000    mov   w0, #0x0
  28: f94003fe    ldr   x30, [sp]
  2c: 910043ff    add   sp, sp, #0x10
  30: d65f03c0    ret
```

`bl  0 <printf>`



- opcode: branch and link
- *Relative* address in bits 0-25: 0

- Huh? That's not where `printf` lives!
  - Assembler had to calculate [addr of `printf`] – [addr of this instr]
  - But assembler didn't know address of `printf` – it's off in some library (`libc`) and isn't present (yet)!
  - So, assembler couldn't generate this instruction completely, left a placeholder, and will request help from the linker

R_AARCH64_CALL26 printf

```
$ objdump --disassemble --reloc detecta.o

detecta.o:     file format elf64-littleaarch64

Disassembly of section .text:

0000000000000000 <main>:
   0: d10043ff    sub   sp, sp, #0x10
   4: f90003fe    str   x30, [sp]
   8: 10000000    adr   x0, 0 <main>
                  8: R_AARCH64_ADR_PREL_LO21    .rodata
   c: 94000000    bl    0 <printf>
                  c: R_AARCH64_CALL26     printf
  10: 94000000    bl    0 <getchar>
                  10: R_AARCH64_CALL26    getchar
  14: 7101041f    cmp   w0, #0x41
  18: 54000061    b.ne  24 <skip>
  1c: 10000000    adr   x0, 0 <main>
                  1c: R_AARCH64_ADR_PREL_LO21   .rodata+0xe
  20: 94000000    bl    0 <printf>
                  20: R_AARCH64_CALL26    printf

0000000000000024 <skip>:
  24: 52800000    mov   w0, #0x0
  28: f94003fe    ldr   x30, [sp]
  2c: 910043ff    add   sp, sp, #0x10
  30: d65f03c0    ret
```

Relocation Record 2

```
c: R_AARCH64_CALL26     printf
```

Dear Linker,

Please patch the TEXT section at offset 0xc. Patch in a 26-bit signed offset relative to the PC, appropriate for the function call (bl) instruction format. When you determine the address of printf, use that to compute the offset you need to do the patch.

Sincerely,
Assembler

bl 0 <getchar>

```
$ objdump --disassemble --reloc detecta.o

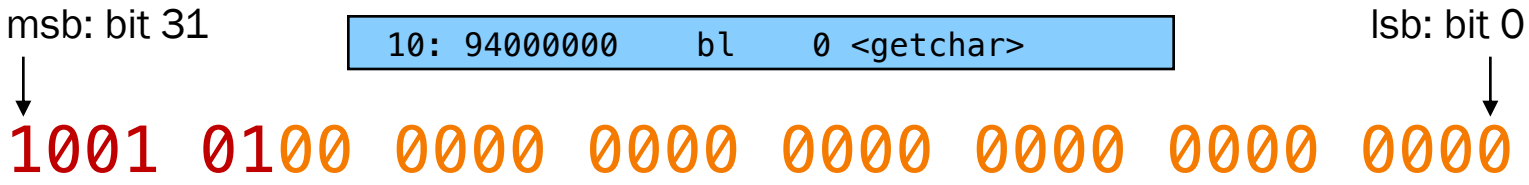
detecta.o:     file format elf64-littleaarch64

Disassembly of section .text:

0000000000000000 <main>:
   0: d10043ff    sub   sp, sp, #0x10
   4: f90003fe    str   x30, [sp]
   8: 10000000    adr   x0, 0 <main>
                  8: R_AARCH64_ADR_PREL_LO21    .rodata
   c: 94000000    bl    0 <printf>
                  c: R_AARCH64_CALL26     printf
  10: 94000000    bl    0 <getchar>
                  10: R_AARCH64_CALL26    getchar
  14: 7101041f    cmp   w0, #0x41
  18: 54000061    b.ne  24 <skip>
  1c: 10000000    adr   x0, 0 <main>
                  1c: R_AARCH64_ADR_PREL_LO21   .rodata+0xe
  20: 94000000    bl    0 <printf>
                  20: R_AARCH64_CALL26    printf

0000000000000024 <skip>:
  24: 52800000    mov   w0, #0x0
  28: f94003fe    ldr   x30, [sp]
  2c: 910043ff    add   sp, sp, #0x10
  30: d65f03c0    ret
```

bl 0 <getchar>



- opcode: branch and link
- *Relative* address in bits 0-25: 0

- Same situation as before – relocation record coming up!

Relocation Record 3

```
10: R_AARCH64_CALL26    getchar
```

Dear Linker,

Please patch the TEXT section at offset 0x10.
Patch in a 26-bit signed offset relative to the PC, appropriate for the function call (bl) instruction format.
When you determine the address of getchar, use that to compute the offset you need to do the patch.

Sincerely,
Assembler

cmp w0, #0x41

```
$ objdump --disassemble --reloc detecta.o

detecta.o:     file format elf64-littleaarch64

Disassembly of section .text:

0000000000000000 <main>:
   0: d10043ff    sub   sp, sp, #0x10
   4: f90003fe    str   x30, [sp]
   8: 10000000    adr   x0, 0 <main>
                  8: R_AARCH64_ADR_PREL_LO21    .rodata
   c: 94000000    bl    0 <printf>
                  c: R_AARCH64_CALL26     printf
  10: 94000000    bl    0 <getchar>
                  10: R_AARCH64_CALL26    getchar
  14: 7101041f    cmp   w0, #0x41
  18: 54000061    b.ne  24 <skip>
  1c: 10000000    adr   x0, 0 <main>
                  1c: R_AARCH64_ADR_PREL_LO21   .rodata+0xe
  20: 94000000    bl    0 <printf>
                  20: R_AARCH64_CALL26    printf

0000000000000024 <skip>:
  24: 52800000    mov   w0, #0x0
  28: f94003fe    ldr   x30, [sp]
  2c: 910043ff    add   sp, sp, #0x10
  30: d65f03c0    ret
```

`cmp w0, #0x41`

- Recall that `cmp` is really an assembler alias: this is the same instruction as `subs wzr, w0, 0x41`
- opcode: subtract immediate
- Instruction width in bit 31: 0 = 32-bit
- Whether to set condition flags in bit 29: yes
- Immediate value in bits 10-21: 1000001_b = 0x41 = 'A'
- First source register in bits 5-9: 0
- Destination register in bits 0-4: 31 = wzr
  - Note that register #31 (11111_b) is used to mean either sp or xzr/wzr, depending on the instruction

b.ne 24 <skip>

```
$ objdump --disassemble --reloc detecta.o

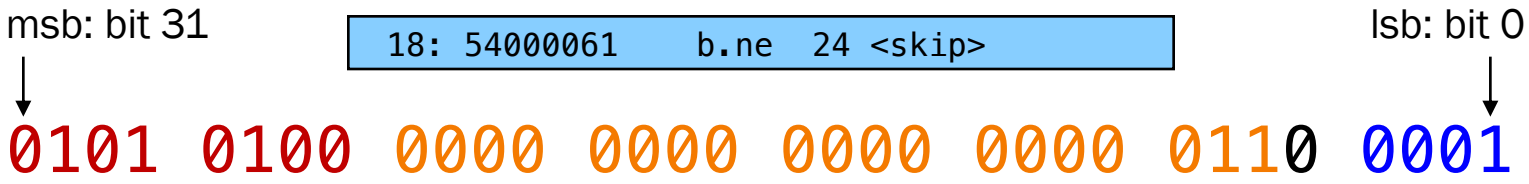
detecta.o:     file format elf64-littleaarch64

Disassembly of section .text:

0000000000000000 <main>:
   0: d10043ff    sub   sp, sp, #0x10
   4: f90003fe    str   x30, [sp]
   8: 10000000    adr   x0, 0 <main>
                  8: R_AARCH64_ADR_PREL_LO21    .rodata
   c: 94000000    bl    0 <printf>
                  c: R_AARCH64_CALL26     printf
  10: 94000000    bl    0 <getchar>
                  10: R_AARCH64_CALL26    getchar
  14: 7101041f    cmp   w0, #0x41
  18: 54000061    b.ne  24 <skip>
  1c: 10000000    adr   x0, 0 <main>
                  1c: R_AARCH64_ADR_PREL_LO21   .rodata+0xe
  20: 94000000    bl    0 <printf>
                  20: R_AARCH64_CALL26    printf

0000000000000024 <skip>:
  24: 52800000    mov   w0, #0x0
  28: f94003fe    ldr   x30, [sp]
  2c: 910043ff    add   sp, sp, #0x10
  30: d65f03c0    ret
```

b.ne 24 <skip>



- This instruction is at offset 0x18, and `skip` is at offset 0x24, which is 0x24 – 0x18 = 0xc = 12 bytes later
- opcode: conditional branch
- *Relative* address in bits 5-23: 11_b. Shift left by 2: 1100_b = 12
- Conditional branch type in bits 0-4: NE

- No need for relocation record!
  - Assembler had to calculate [addr of `skip`] – [addr of this instr]
  - Assembler *did* know offsets of `skip` and this instruction
  - So, assembler could generate this instruction completely, and does not need to request help from the linker

R_AARCH64_ADR_PREL_LO21 .rodata+0xe

```
$ objdump --disassemble --reloc detecta.o

detecta.o:     file format elf64-littleaarch64

Disassembly of section .text:

0000000000000000 <main>:
   0: d10043ff    sub   sp, sp, #0x10
   4: f90003fe    str   x30, [sp]
   8: 10000000    adr   x0, 0 <main>
                  8: R_AARCH64_ADR_PREL_LO21    .rodata
   c: 94000000    bl    0 <printf>
                  c: R_AARCH64_CALL26     printf
  10: 94000000    bl    0 <getchar>
                  10: R_AARCH64_CALL26    getchar
  14: 7101041f    cmp   w0, #0x41
  18: 54000061    b.ne  24 <skip>
  1c: 10000000    adr   x0, 0 <main>
                  1c: R_AARCH64_ADR_PREL_LO21   .rodata+0xe
  20: 94000000    bl    0 <printf>
                  20: R_AARCH64_CALL26    printf

0000000000000024 <skip>:
  24: 52800000    mov   w0, #0x0
  28: f94003fe    ldr   x30, [sp]
  2c: 910043ff    add   sp, sp, #0x10
  30: d65f03c0    ret
```

Relocation Record 4

```
1c: R_AARCH64_ADR_PREL_LO21    .rodata+0xe
```

Dear Linker,

Please patch the TEXT section at offset 0x1c.
Patch in a 21-bit signed offset of an address, relative to the PC, as appropriate for the adr instruction format.
When you determine the address of .rodata, add 0xe and use that to compute the offset you need to do the patch.

Sincerely,
Assembler

Another printf, with relocation record...

```
$ objdump --disassemble --reloc detecta.o

detecta.o:     file format elf64-littleaarch64

Disassembly of section .text:

0000000000000000 <main>:
   0: d10043ff    sub   sp, sp, #0x10
   4: f90003fe    str   x30, [sp]
   8: 10000000    adr   x0, 0 <main>
                  8: R_AARCH64_ADR_PREL_LO21    .rodata
   c: 94000000    bl    0 <printf>
                  c: R_AARCH64_CALL26     printf
  10: 94000000    bl    0 <getchar>
                  10: R_AARCH64_CALL26    getchar
  14: 7101041f    cmp   w0, #0x41
  18: 54000061    b.ne  24 <skip>
  1c: 10000000    adr   x0, 0 <main>
                  1c: R_AARCH64_ADR_PREL_LO21   .rodata+0xe
  20: 94000000    bl    0 <printf>
                  20: R_AARCH64_CALL26    printf

0000000000000024 <skip>:
  24: 52800000    mov   w0, #0x0
  28: f94003fe    ldr   x30, [sp]
  2c: 910043ff    add   sp, sp, #0x10
  30: d65f03c0    ret
```

Last Example: Your Turn!

What does this relocation record mean?

```
20: 94000000    bl    0 <printf>
                20: R_AARCH64_CALL26    printf
```

See context on previous slides with parallel records:
bl printf (#48)
bl getchar (#51)

Dear Linker,

Please patch the TEXT section at offset 0x20.
Patch in a 26-bit signed offset relative to the PC, appropriate for the function call (bl) instruction format.
When you determine the address of printf, use that to compute the offset you need to do the patch.

Sincerely,
Assembler

Everything Else is Similar…

```
$ objdump --disassemble --reloc detecta.o

detecta.o:     file format elf64-littleaarch64

Disassembly of section .text:

0000000000000000 <main>:
   0: d10043ff    sub   sp, sp, #0x10
   4: f90003fe    str   x30, [sp]
   8: 10000000    adr   x0, 0 <main>
                  8: R_AARCH64_ADR_PREL_LO21    .rodata
   c: 94000000    bl    0 <printf>
                  c: R_AARCH64_CALL26     printf
  10: 94000000    bl    0 <getchar>
                  10: R_AARCH64_CALL26    getchar
  14: 7101041f    cmp   w0, #0x41
  18: 54000061    b.ne  24 <skip>
  1c: 10000000    adr   x0, 0 <main>
                  1c: R_AARCH64_ADR_PREL_LO21   .rodata+0xe
  20: 94000000    bl    0 <printf>
                  20: R_AARCH64_CALL26    printf

0000000000000024 <skip>:
  24: 52800000    mov   w0, #0x0
  28: f94003fe    ldr   x30, [sp]
  2c: 910043ff    add   sp, sp, #0x10
  30: d65f03c0    ret
```

Exercise for you:
using information from these slides, create a bitwise breakdown of these instructions, and convince yourself that the hex values are correct!

Agenda

A6 “A” Attack

AARCH64 Machine Language

AARCH64 Machine Language after Assembly

AARCH64 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

```
$ gcc217 prontf.c
prontf.c: In function 'main':
prontf.c:6:1: warning: implicit declaration of function 'prontf' [-Wimplicit-function-declaration]
 {  prontf("hello, world\n");
 ^
/tmp/ccjA2CnG.o: In function `main':
prontf.c:(.text+0x10): undefined reference to `prontf'
collect2: error: ld returned 1 exit status
```

Resolution

- Linker resolves references

For our sample 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

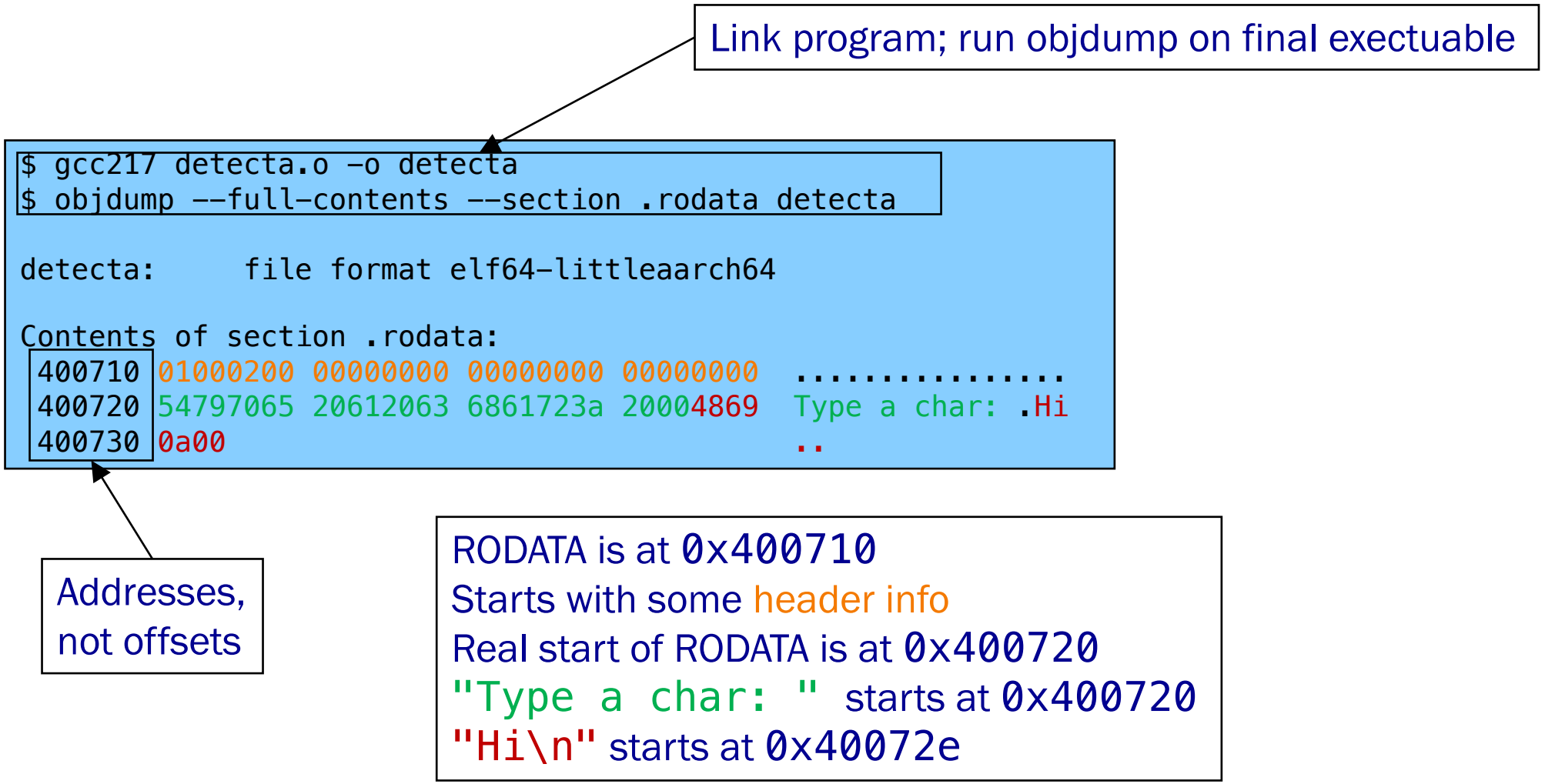
Linker Relocation

@impatrickt

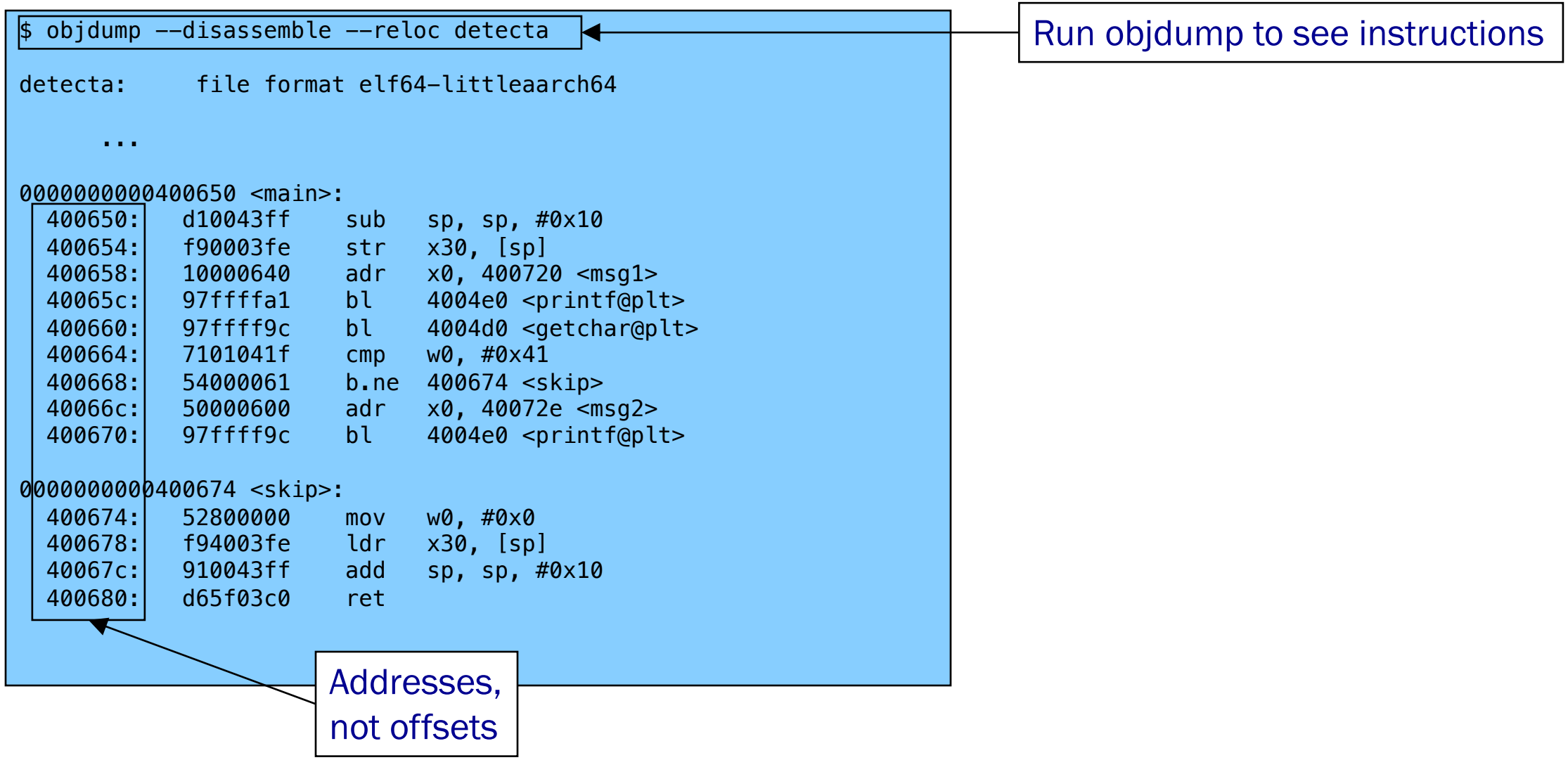
Relocation

- Linker relocates code into final combined sections with addresses
- Linker traverses relocation records, patching instructions as specified

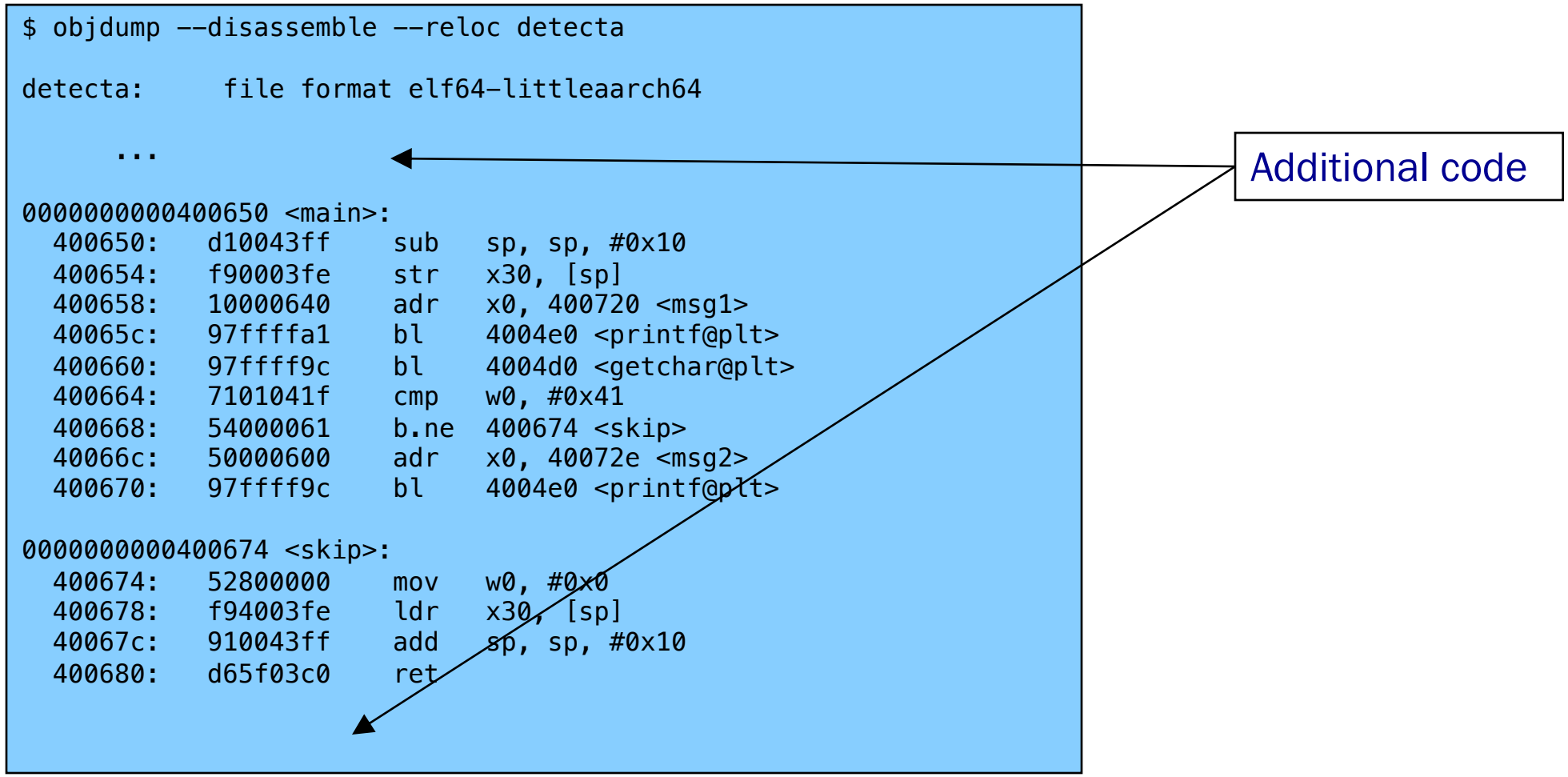
Examining Machine Language: RODATA



Examining Machine Language: TEXT



Examining Machine Language: TEXT



Examining Machine Language: TEXT

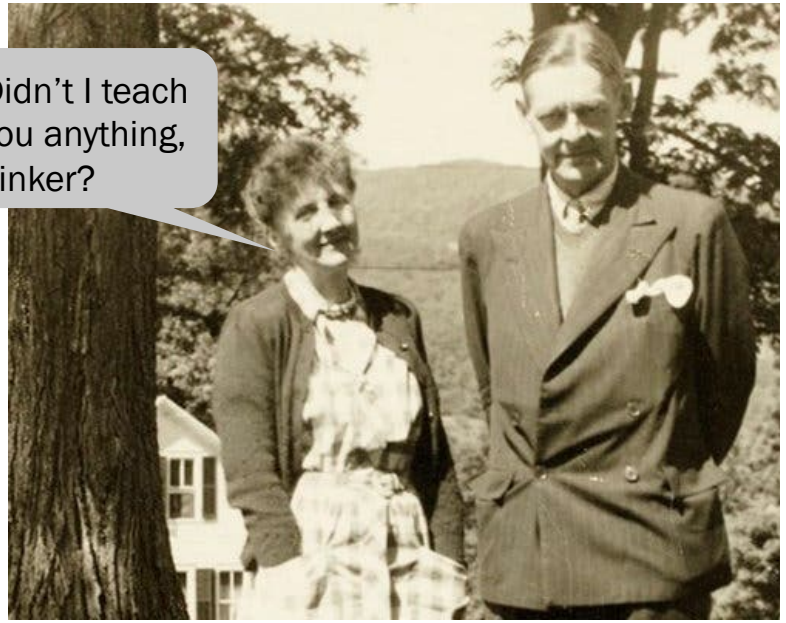
```
$ objdump --disassemble --reloc detecta

detecta:     file format elf64-littleaarch64

      ...

0000000000400650 <main>:
  400650:   d10043ff    sub   sp, sp, #0x10
  400654:   f90003fe    str   x30, [sp]
  400658:   10000640    adr   x0, 400720 <msg1>
  40065c:   97ffffa1    bl    4004e0 <printf@plt>
  400660:   97ffff9c    bl    4004d0 <getchar@plt>
  400664:   7101041f    cmp   w0, #0x41
  400668:   54000061    b.ne  400674 <skip>
  40066c:   50000600    adr   x0, 40072e <msg2>
  400670:   97ffff9c    bl    4004e0 <printf@plt>

0000000000400674 <skip>:
  400674:   52800000    mov   w0, #0x0
  400678:   f94003fe    ldr   x30, [sp]
  40067c:   910043ff    add   sp, sp, #0x10
  400680:   d65f03c0    ret
```



No relocation records!

Let's see what the linker did with them…

https://library.princeton.edu/news/general/2020-12-13/insights-unsealed-ts-eliot-emily-hale-letters-one-year-later

adr x0, 400720 <msg1>

```
$ objdump --disassemble --reloc detecta

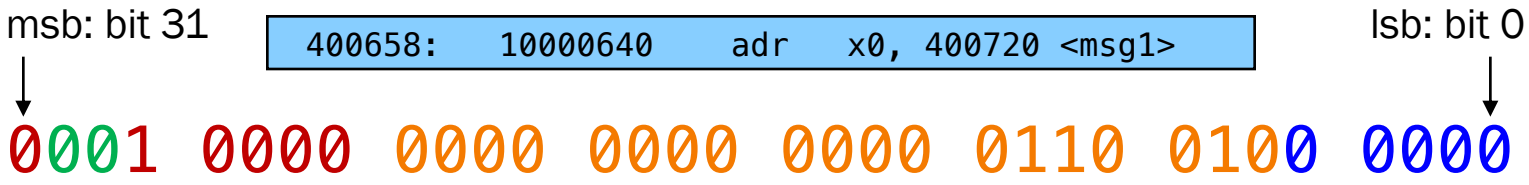
detecta:     file format elf64-littleaarch64

      ...

0000000000400650 <main>:
  400650:   d10043ff    sub   sp, sp, #0x10
  400654:   f90003fe    str   x30, [sp]
  400658:   10000640    adr   x0, 400720 <msg1>
  40065c:   97ffffa1    bl    4004e0 <printf@plt>
  400660:   97ffff9c    bl    4004d0 <getchar@plt>
  400664:   7101041f    cmp   w0, #0x41
  400668:   54000061    b.ne  400674 <skip>
  40066c:   50000600    adr   x0, 40072e <msg2>
  400670:   97ffff9c    bl    4004e0 <printf@plt>

0000000000400674 <skip>:
  400674:   52800000    mov   w0, #0x0
  400678:   f94003fe    ldr   x30, [sp]
  40067c:   910043ff    add   sp, sp, #0x10
  400680:   d65f03c0    ret
```

adr x0, 400720 <msg1>



- opcode: generate address
- 19 High-order bits of offset in bits 5-23: 110010
- 2 Low-order bits of offset in bits 29-30: 00
- *Relative* data location is 11001000b = 0xc8 bytes after this instruction
- Destination register in bits 0-4:0

- msg1 is at 0x400720
- this instruction is at 0x400658
- 0x400720 – 0x400658 = 0xc8 ✓

bl 4004e0 <printf@plt>

```
$ objdump --disassemble --reloc detecta

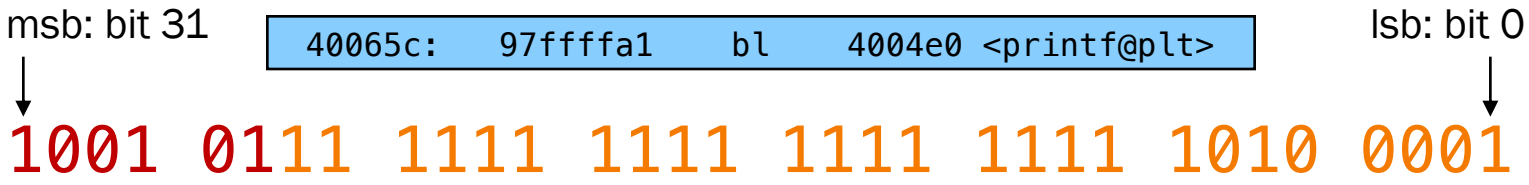
detecta:     file format elf64-littleaarch64

      ...

0000000000400650 <main>:
  400650:   d10043ff    sub   sp, sp, #0x10
  400654:   f90003fe    str   x30, [sp]
  400658:   10000640    adr   x0, 400720 <msg1>
  40065c:   97ffffa1    bl    4004e0 <printf@plt>
  400660:   97ffff9c    bl    4004d0 <getchar@plt>
  400664:   7101041f    cmp   w0, #0x41
  400668:   54000061    b.ne  400674 <skip>
  40066c:   50000600    adr   x0, 40072e <msg2>
  400670:   97ffff9c    bl    4004e0 <printf@plt>

0000000000400674 <skip>:
  400674:   52800000    mov   w0, #0x0
  400678:   f94003fe    ldr   x30, [sp]
  40067c:   910043ff    add   sp, sp, #0x10
  400680:   d65f03c0    ret
```

bl 4004e0 <printf@plt>



- opcode: branch and link
- *Relative* address in bits 0-25: 26-bit two's complement of 1011111_b .
  But remember to shift left by two bits (see earlier slides)!
  This gives $-1\,0111\,1100_b$ = –0x17c

- `printf` is at 0x4004e0
- this instruction is at 0x40065c
- 0x4004e0 – 0x40065c = –0x17c ✓

Everything Else is Similar…

```
$ objdump --disassemble --reloc detecta

detecta:     file format elf64-littleaarch64

      ...

0000000000400650 <main>:
  400650:   d10043ff    sub   sp, sp, #0x10
  400654:   f90003fe    str   x30, [sp]
  400658:   10000640    adr   x0, 400720 <msg1>
  40065c:   97ffffa1    bl    4004e0 <printf@plt>
  400660:   97ffff9c    bl    4004d0 <getchar@plt>
  400664:   7101041f    cmp   w0, #0x41
  400668:   54000061    b.ne  400674 <skip>
  40066c:   50000600    adr   x0, 40072e <msg2>
  400670:   97ffff9c    bl    4004e0 <printf@plt>

0000000000400674 <skip>:
  400674:   52800000    mov   w0, #0x0
  400678:   f94003fe    ldr   x30, [sp]
  40067c:   910043ff    add   sp, sp, #0x10
  400680:   d65f03c0    ret
```

Summary

AARCH64 Machine Language

- 32-bit instructions
- Formats have conventional locations for opcodes, registers, etc.

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

Wrapping Up the Course

Precepts end after the first precept this week: no precepts Wednesday/Thursday.

Assignment 5 due Thursday 4/27 at 9:00 PM.

Assignment 6 due on Dean's Date (Tuesday 5/9) at 5:00 PM.

- Extensions past 11:59 PM require permission of Dr. Moretti + your Dean

Final Exam: Wednesday 5/17 at 7:30 PM

- https://www.cs.princeton.edu/courses/archive/spr23/cos217/exam2.html

Review session on Monday 5/15 at 4:30 PM. Location TBA, likely CS 104.

Regular office hours continue through this week. Separate schedule for reading period.

- Exact schedule will be announced on Ed

We Have Covered:

Programming in the large

- Program design
- Programming style
- Building
- Testing
- Debugging
- Data structures
- Modularity
- Performance
- Version control

Programming at several levels

- The C programming language
- ARM Assembly Language
- ARM Machine Language
- (just a taste of) the bash shell

Core systems and organization ideas

- Storage hierarchy
- Compile, Assemble, Link
- (just a taste of) Processes and VM

The end.

```
return EXIT_SUCCESS;
```