

Lecture 9: Procedures

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601.229 Computer Systems Fundamentals



Control flow (part 2)

- ▶ Procedures
- ▶ Stacks:
 - ▶ Procedure calls and returns
 - ▶ Storage for local variables and temporary values
- ▶ Today's example programs are linked as `control2.zip` on the course website

Procedures

Procedures, call stack

- ▶ Procedures (a.k.a. functions, subroutines), the most important abstraction in programming
 - ▶ Can you imagine trying to write programs without them?
- ▶ *Call stack*: hardware-supported, runtime data structure
 - ▶ Stores *return addresses* so procedures know where to return to
 - ▶ Used to allocate *stack frames*: per-procedure-call storage area for local variables, temporary values, and (sometimes) argument values
 - ▶ As name suggests, is a stack, LIFO discipline (push and pop)

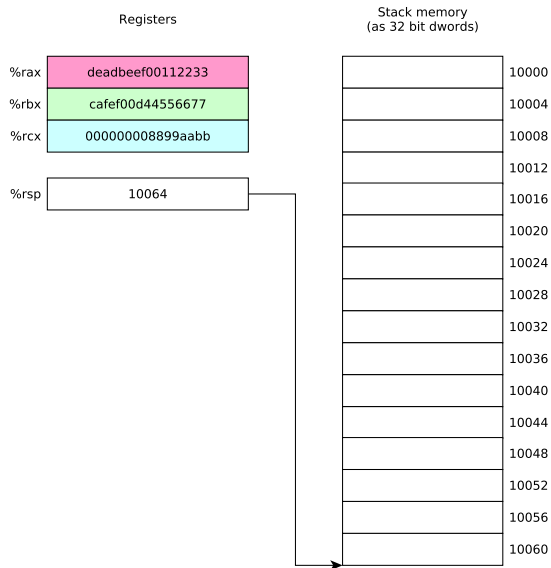
Stack pointer, instruction pointer

- ▶ *Stack pointer* register `%rsp`: contains address of current “top” of stack
 - ▶ Important: stack grows towards lower addresses, so top of stack is at lower address than bottom of stack
- ▶ *Instruction pointer* register `%rip`: contains code address of next instruction to be updated
 - ▶ Control flow changes the value of `%rip`
- ▶ Other architectures use the name “program counter” rather than “instruction pointer”, but they’re the same thing

push and pop

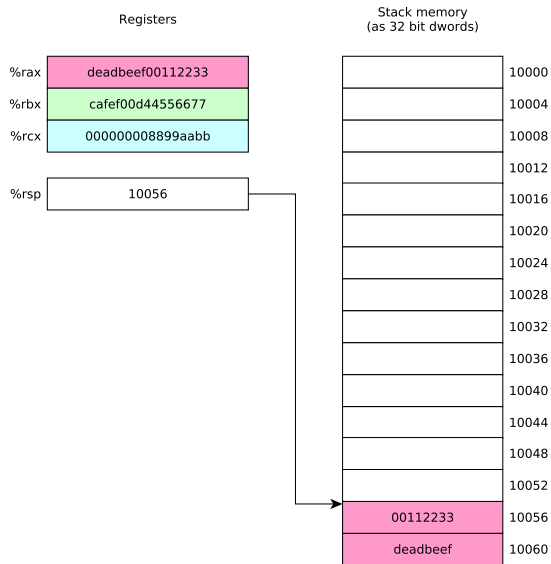
- ▶ `push`: push a data value onto the call stack
 - ▶ E.g., `pushq %rax`
 - ▶ Decrement `%rsp` by 8
 - ▶ Store value in `%rax` at memory location pointed-to by `%rsp`
- ▶ `pop`: pop a data value from the call stack
 - ▶ E.g., `popq %rax`
 - ▶ Load value at memory location pointed-to by `%rsp` into `%rax`
 - ▶ Increment `%rsp` by 8
- ▶ `push` and `pop` are amazingly useful for saving and restoring register values
- ▶ Various size operands (1, 2, 4, 8 bytes) can be pushed and popped; need to consider alignment

push and pop



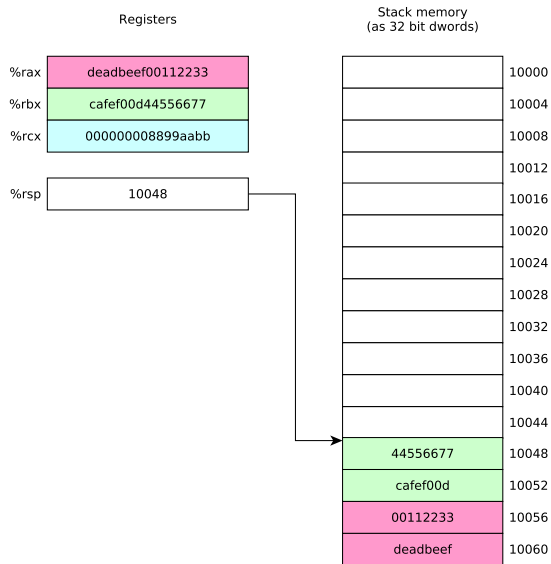
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pushq %rcx  
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push and pop



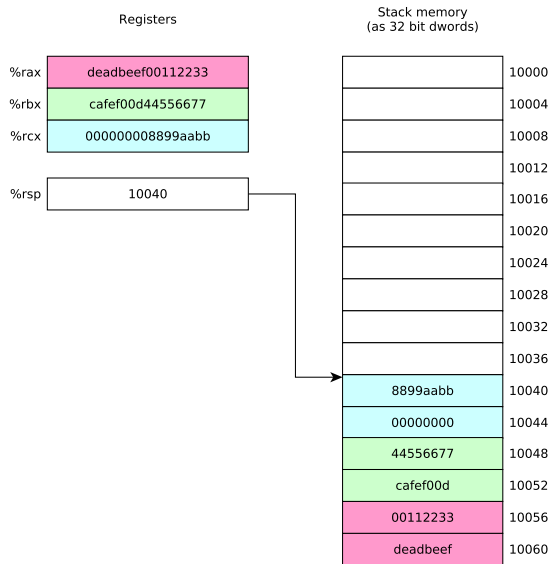
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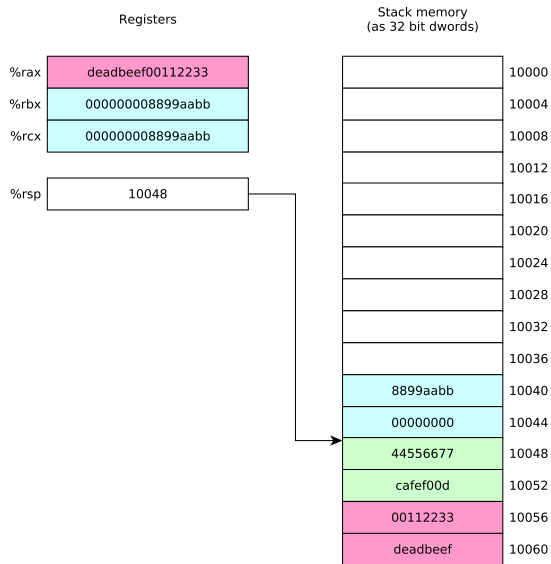
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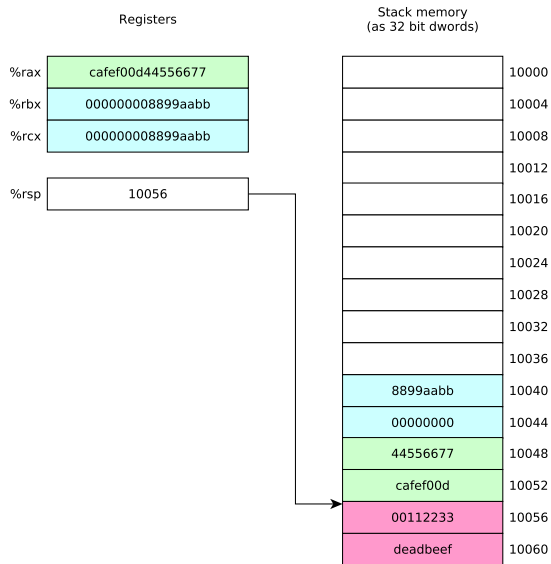
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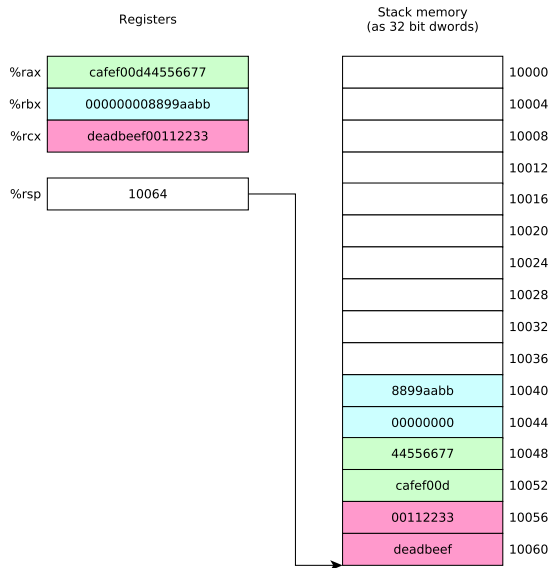
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call and ret

- ▶ `call` instruction: calls procedure
 - ▶ `%rip` contains address of instruction following `call` instruction
 - ▶ Push `%rip` onto stack (as though `pushq %rip` was executed): this is the *return address*
 - ▶ Change `%rip` to address of first instruction of called procedure
 - ▶ Called procedure starts executing
- ▶ `ret` instruction: return from procedure
 - ▶ Pop saved return address from stack into `%rip` (as though `popq %rip` was executed)
 - ▶ Execution continues at return address

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 - ▶ E.g., storage for an 8 byte value should be stored at an address which is a multiple of 8
- ▶ This is true of stack-allocated values!
- ▶ The Linux x86-64 calling conventions require `%rsp` to be a multiple of 16 at the point of a procedure call (to ensure that 16 byte values can be accessed on the stack if necessary)
- ▶ **Issue:** on entry to a procedure, $\text{\%rsp} \bmod 16 = 8$ because the `call` instruction (which called the procedure) pushed `%rip` (the program counter) onto the stack

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- ▶ The Linux `printf` function will segfault if the stack is misaligned

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 - ▶ They allow your code to interoperate with other code, including library routines and (OS) system calls
- ▶ **Always follow the appropriate register use conventions**

x86-64 Linux register use conventions

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- ▶ Callee-saved registers: `%rbx`, `%rbp`, `%r12`, `%r13`, `%r14`, `%r15`

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 - ▶ In general any procedure can freely modify them
 - ▶ A caller might need to save their contents to memory prior to calling a procedure and restore the value afterwards

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 - ▶ Use `pushq/popq` to save and restore their values on procedure entry and exit

Recursive Fibonacci computation

Compute n th Fibonacci number recursively (warning: exponential-time algorithm!)

The call stack inherently allows recursion: there is nothing special we need to do to make it work

Recall that

$$\text{fib}(0) = 0$$

$$\text{fib}(1) = 1$$

$$\text{For } n > 1, \text{fib}(n) = \text{fib}(n - 2) + \text{fib}(n - 1)$$

Recursive Fibonacci function (see fibRec.S for full program)

```
fib:
    cmpl $2, %edi          /* check base case */
    jae .LrecursiveCase   /* if n>=2, do recursive case */
    movl %edi, %eax        /* base case, just return n */
    ret

.LrecursiveCase:
    /* recursive case */
    pushq %r12             /* preserve value of %r12 */
    movl %edi, %r12d        /* save n in %r12 */
    subl $2, %edi           /* compute n-2 */
    call fib               /* compute fib(n-2) */
    movl %r12d, %edi        /* put saved n in %edi */
    subl $1, %edi           /* compute n-1 */
    movl %eax, %r12d        /* save fib(n-2) in %r12 */
    call fib               /* compute fib(n-1) */
    addl %r12d, %eax        /* return fib(n-2)+fib(n-1) */
    popq %r12              /* restore value of %r12 */
    ret                    /* done */
```

Running the program (with $N=9$)

```
$ gcc -c -g -no-pie -o fibRec.o fibRec.S
$ gcc -no-pie -o fibRec fibRec.o
$ ./fibRec
fib(9) = 34
```

Clicker quiz!

Clicker quiz omitted from public slides

Stack memory allocation

Allocating space for local variables

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- ▶ Could use heap allocation (i.e., `malloc`, `free`)
 - ▶ Has overhead due to bookkeeping, locking
- ▶ The call stack is an ideal place to allocate storage for local variables

Stack allocation

- ▶ Stack allocation of storage is simple:
 - ▶ To allocate n bytes, subtract n from `%rsp`
 - ▶ Updated `%rsp` is a pointer to the beginning of the allocated memory
 - ▶ To deallocate n bytes, add n to `%rsp`
- ▶ Complication: instructions such as `push` and `pop` change `%rsp`
- ▶ Solution: use the *frame pointer* register `%rbp` to keep track of allocated memory area

Using the frame pointer

On entry to procedure:

```
pushq %rbp
subq $N, %rsp
movq %rsp, %rbp
```

Before returning from procedure:

```
addq $N, %rsp
popq %rbp
```

`%rbp` points to a block of N bytes allocated in the current stack frame (make sure that $N \bmod 16 = 0$ to ensure correct stack alignment)

Putting it all together

- ▶ Let's examine a simple program which
 - ▶ Reads two 64 bit integer values from user
 - ▶ Computes their sum using a function
 - ▶ Prints out the sum
- ▶ Calling `scanf` to read input requires variables in which to store input values: we'll allocate them on the stack

addLongs, C version

```
#include <stdio.h>

long addLongs(long a, long b);

int main(void) {
    long x, y, sum;
    printf("Enter two integers: ");
    scanf("%ld %ld", &x, &y);
    sum = addLongs(x, y);
    printf("Sum is %ld\n", sum);
}

long addLongs(long a, long b) {
    return a + b;
}
```

Note: in the following code example, the value 0 should be stored in `%rax` prior to calls to `printf` and `scanf` to specify that there are no vector arguments

- ▶ Example code in `control2.zip` does do this

addLongs, assembly version

```
/* addLongs.S */

.section .rodata

sPromptMsg: .string "Enter two integers: "
sInputFmt:  .string "%ld %ld"
sResultMsg: .string "Sum is %ld\n"

.section .text

.globl main
main:
    pushq %rbp
    subq $16, %rsp
    movq %rsp, %rbp

    movq $sPromptMsg, %rdi
    call printf

    movq $sInputFmt, %rdi
    leaq 0(%rbp), %rsi
    leaq 8(%rbp), %rdx
    call scanf

    movq 0(%rbp), %rdi
    movq 8(%rbp), %rsi
    call addLongs

    addq $16, %rsp
    popq %rbp
    ret

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    call printf

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    leaq 0(%rbp), %rsi
    leaq 8(%rbp), %rdx
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    movq 0(%rbp), %rdi
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    subq $16, %rsp
    movq %rsp, %rbp  <-- point %rbp to alloc'ed buf

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    leaq 0(%rbp), %rsi  <-- pass address of 1st var
    leaq 8(%rbp), %rdx
    call scanf

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addLongs:
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addLongs, assembly version

```
/* addLongs.S */

.section .rodata

sPromptMsg: .string "Enter two integers: "
sInputFmt:  .string "%ld %ld"
sResultMsg: .string "Sum is %ld\n"

.section .text

.globl main
main:
    pushq %rbp
    subq $16, %rsp
    movq %rsp, %rbp

    movq $sPromptMsg, %rdi
    call printf

    movq $sInputFmt, %rdi
    leaq 0(%rbp), %rsi
    leaq 8(%rbp), %rdx  <-- pass address of 2nd var
    call scanf

    movq 0(%rbp), %rdi
    movq 8(%rbp), %rsi
    call addLongs

    addq $16, %rsp
    popq %rbp
    ret

addLongs:
    movq %rdi, %rax
    addq %rsi, %rax
    ret
```

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    call printf

    movq $sInputFmt, %rdi
    leaq 0(%rbp), %rsi
    leaq 8(%rbp), %rdx
    call scanf

    movq 0(%rbp), %rdi  <-- pass value of 1st var
    movq 8(%rbp), %rsi
    call addLongs

    addq $16, %rsp
    popq %rbp
    ret

addLongs:
    movq %rdi, %rax
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    movq $sInputFmt, %rdi
    leaq 0(%rbp), %rsi
    leaq 8(%rbp), %rdx
    call scanf

    movq 0(%rbp), %rdi
    movq 8(%rbp), %rsi <-- pass value of 2nd var
    call addLongs

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    popq %rbp
    ret

addLongs:
    movq %rdi, %rax
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```

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    movq $sInputFmt, %rdi
    leaq 0(%rbp), %rsi
    leaq 8(%rbp), %rdx
    call scanf

    movq 0(%rbp), %rdi
    movq 8(%rbp), %rsi
    call addLongs

    addq $16, %rsp <-- deallocate local vars
    popq %rbp
    ret

addLongs:
    movq %rdi, %rax
    addq %rsi, %rax
    ret
```

addLongs, assembly version

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    pushq %rbp
    subq $16, %rsp
    movq %rsp, %rbp

    movq $sPromptMsg, %rdi
    call printf

    movq $sInputFmt, %rdi
    leaq 0(%rbp), %rsi
    leaq 8(%rbp), %rdx
    call scanf

    movq 0(%rbp), %rdi
    movq 8(%rbp), %rsi
    call addLongs

    addq $16, %rsp
    popq %rbp      <-- restore frame pointer
    ret

addLongs:
    movq %rdi, %rax
    addq %rsi, %rax
    ret
```

addLongs, assembly version

```
/* addLongs.S */
```

```
.section .rodata
```

```
sPromptMsg: .string "Enter two integers: "
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```
sInputFmt:  .string "%ld %ld"
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sResultMsg: .string "Sum is %ld\n"
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```
.section .text
```

```
.globl main
```

```
main:
```

```
    pushq %rbp
```

```
    subq $16, %rsp
```

```
    movq %rsp, %rbp
```

```
    movq $sPromptMsg, %rdi
```

```
    call printf
```

```
    movq $sInputFmt, %rdi
```

```
    leaq 0(%rbp), %rsi
```

```
    leaq 8(%rbp), %rdx
```

```
    call scanf
```

```
    movq 0(%rbp), %rdi
```

```
    movq 8(%rbp), %rsi
```

```
    call addLongs
```

```
    movq $sResultMsg, %rdi
```

```
    movq %rax, %rsi
```

```
    call printf
```

```
    addq $16, %rsp
```

```
    popq %rbp
```

```
    ret
```

```
addLongs:  <-- does not use stack, ignore alignment :-P
```

```
    movq %rdi, %rax
```

```
    addq %rsi, %rax
```

```
    ret
```

Running the program

```
$ gcc -c -no-pie -o addLongs.o addLongs.S
$ gcc -no-pie -o addLongs addLongs.o
$ ./addLongs
Enter two integers: 2 3
Sum is 5
```

Tracing the program

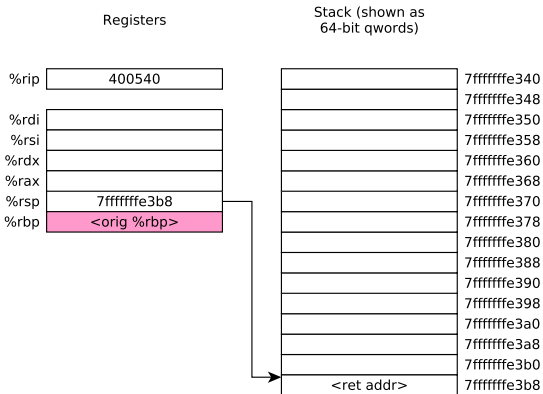
Using objdump to disassemble the executable (partial output):

```
$ objdump -d addLongs
addLongs:      file format elf64-x86-64
...
Disassembly of section .text:
...
0000000000400540 <main>:
  400540:      55                push    %rbp
  400541:      48 83 ec 10       sub     $0x10,%rsp
  400545:      48 89 e5          mov     %rsp,%rbp
  400548:      48 c7 c7 24 06 40 00 mov     $0x400624,%rdi
  40054f:      e8 dc fe ff ff   callq   400430 <printf@plt>
...
0000000000400590 <addLongs>:
  400590:      48 89 f8          mov     %rdi,%rax
  400593:      48 01 f0          add     %rsi,%rax
  400596:      c3              retq
```


Tracing the program

```
000000000400540 <main>:
  400540: push    %rbp
  400541: sub     $0x10,%rsp
  400545: mov     %rsp,%rbp
  400548: mov     $0x400624,%rdi
  40054f: callq   400430 <printf@plt>
  400554: mov     $0x400639,%rdi
  40055b: lea     0x0(%rbp),%rsi
  40055f: lea     0x8(%rbp),%rdx
  400563: callq   400440 <scanf@plt>
  400568: mov     0x0(%rbp),%rdi
  40056c: mov     0x8(%rbp),%rsi
  400570: callq   400590 <addLongs>
  400575: mov     $0x400641,%rdi
  40057c: mov     %rax,%rsi
  40057f: callq   400430 <printf@plt>
  400584: add     $0x10,%rsp
  400588: pop     %rbp
  400589: retq

000000000400590 <addLongs>:
  400590: mov     %rdi,%rax
  400593: add     %rsi,%rax
  400596: retq
```



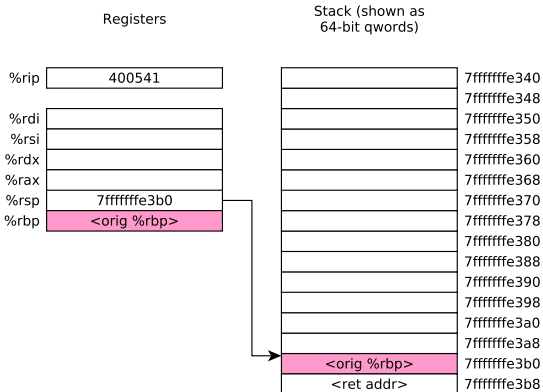
Tracing the program

000000000400540 <main>:

```
400540: push    %rbp
400541: sub     $0x10,%rsp
400545: mov     %rsp,%rbp
400548: mov     $0x400624,%rdi
40054f: callq   400430 <printf@plt>
400554: mov     $0x400639,%rdi
40055b: lea     0x0(%rbp),%rsi
40055f: lea     0x8(%rbp),%rdx
400563: callq   400440 <scanf@plt>
400568: mov     0x0(%rbp),%rdi
40056c: mov     0x8(%rbp),%rsi
400570: callq   400590 <addLongs>
400575: mov     $0x400641,%rdi
40057c: mov     %rax,%rsi
40057f: callq   400430 <printf@plt>
400584: add     $0x10,%rsp
400588: pop     %rbp
400589: retq
```

000000000400590 <addLongs>:

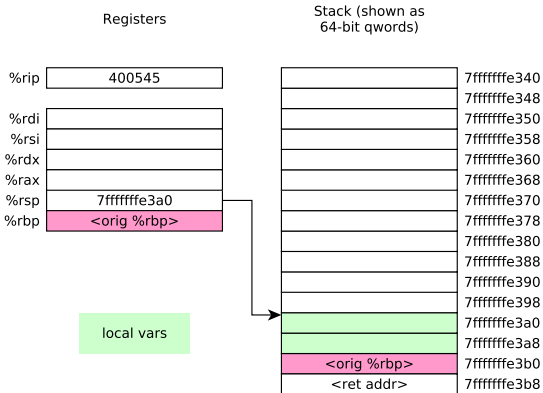
```
400590: mov     %rdi,%rax
400593: add     %rsi,%rax
400596: retq
```



Tracing the program

```
000000000400540 <main>:
  400540: push    %rbp
  400541: sub     $0x10,%rsp
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  400554: mov     $0x400639,%rdi
  40055b: lea     0x0(%rbp),%rsi
  40055f: lea     0x8(%rbp),%rdx
  400563: callq   400440 <scanf@plt>
  400568: mov     0x0(%rbp),%rdi
  40056c: mov     0x8(%rbp),%rsi
  400570: callq   400590 <addLongs>
  400575: mov     $0x400641,%rdi
  40057c: mov     %rax,%rsi
  40057f: callq   400430 <printf@plt>
  400584: add     $0x10,%rsp
  400588: pop     %rbp
  400589: retq

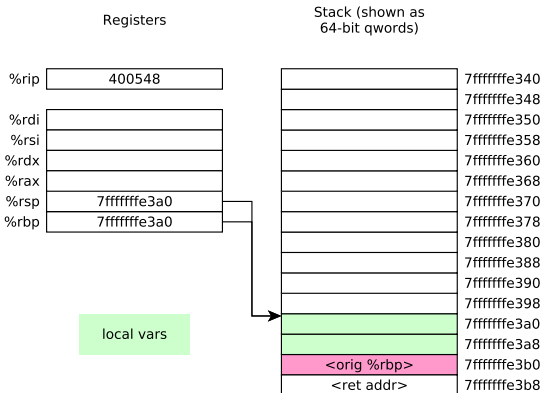
000000000400590 <addLongs>:
  400590: mov     %rdi,%rax
  400593: add     %rsi,%rax
  400596: retq
```



Tracing the program

```
000000000400540 <main>:
  400540: push    %rbp
  400541: sub     $0x10,%rsp
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  400570: callq   400590 <addLongs>
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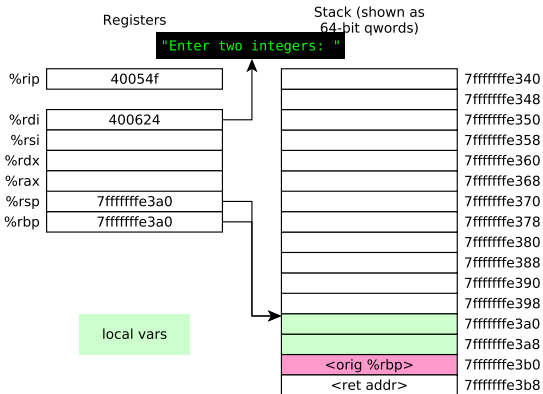
000000000400590 <addLongs>:
  400590: mov     %rdi,%rax
  400593: add     %rsi,%rax
  400596: retq
```



Tracing the program

```
000000000400540 <main>:
 400540: push    %rbp
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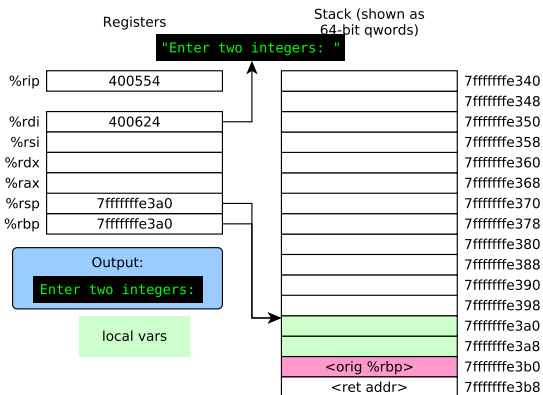
000000000400590 <addLongs>:
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```



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 40055b: lea     0x0(%rbp),%rsi
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 400589: retq

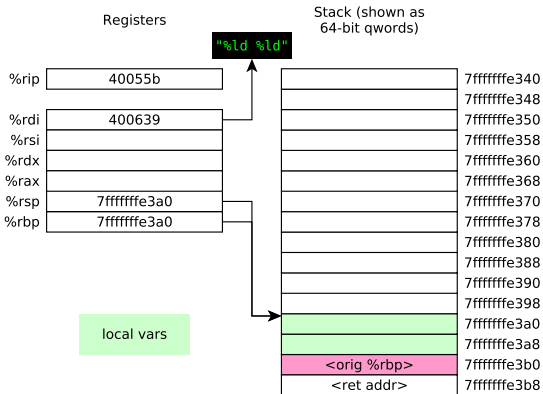
000000000400590 <addLongs>:
 400590: mov     %rdi,%rax
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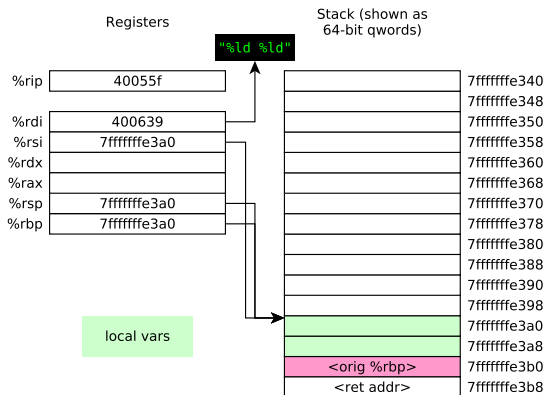
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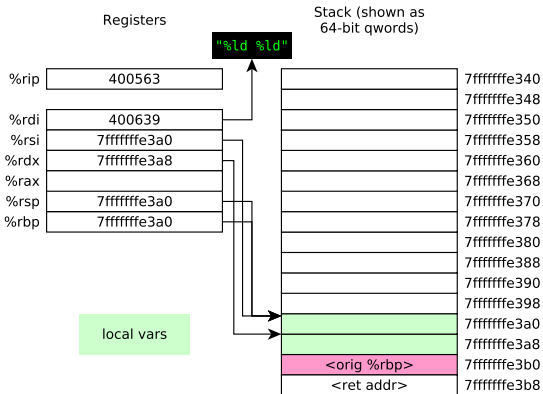
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 400590: mov     %rdi,%rax
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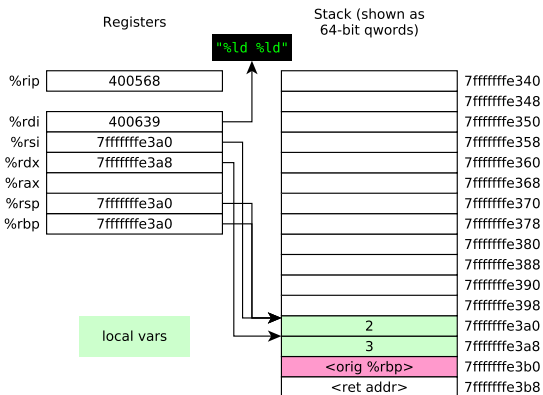
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 400570: callq   400590 <addLongs>
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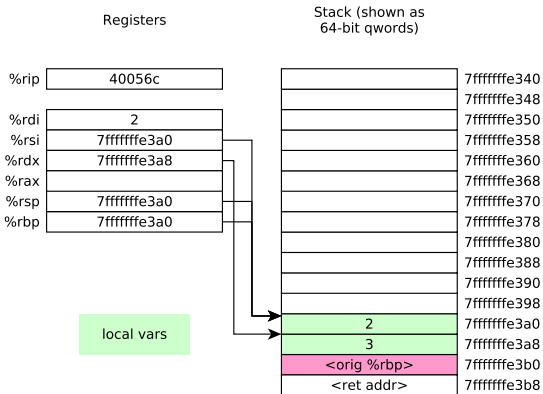
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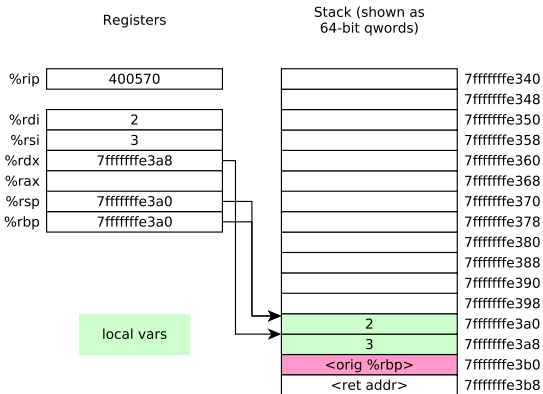
000000000400590 <addLongs>:
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 400570: callq   400590 <addLongs>
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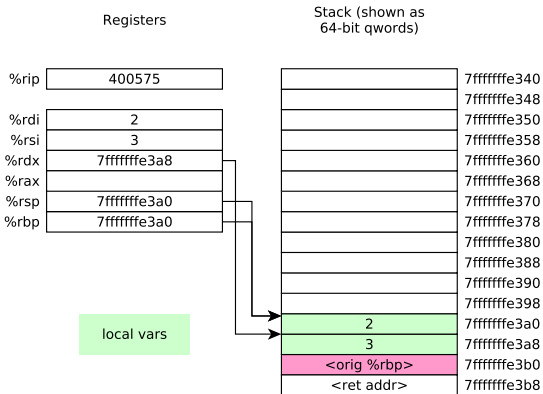
000000000400590 <addLongs>:
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Tracing the program

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000000000400540 <main>:
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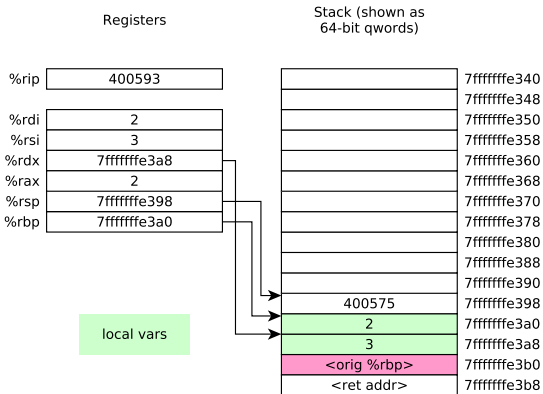
000000000400590 <addLongs>:
 400590: mov     %rdi,%rax
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```



Tracing the program

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000000000400540 <main>:
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 400570: callq   400590 <addLongs>
 400575: mov     $0x400641,%rdi
 40057c: mov     %rax,%rsi
 40057f: callq   400430 <printf@plt>
 400584: add     $0x10,%rsp
 400588: pop     %rbp
 400589: retq

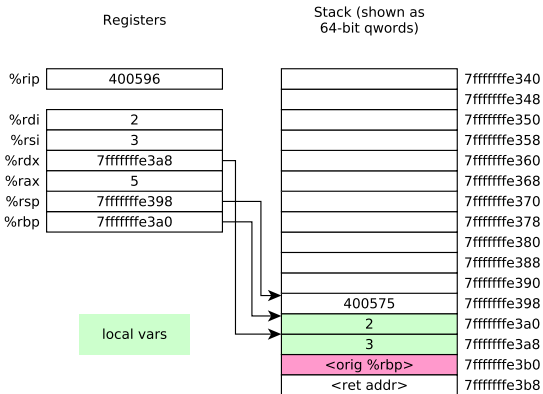
000000000400590 <addLongs>:
 400590: mov     %rdi,%rax
 400593: add     %rsi,%rax
 400596: retq
```



Tracing the program

```
000000000400540 <main>:
 400540: push    %rbp
 400541: sub     $0x10,%rsp
 400545: mov     %rsp,%rbp
 400548: mov     $0x400624,%rdi
 40054f: callq   400430 <printf@plt>
 400554: mov     $0x400639,%rdi
 40055b: lea     0x0(%rbp),%rsi
 40055f: lea     0x8(%rbp),%rdx
 400563: callq   400440 <scanf@plt>
 400568: mov     0x0(%rbp),%rdi
 40056c: mov     0x8(%rbp),%rsi
 400570: callq   400590 <addLongs>
 400575: mov     $0x400641,%rdi
 40057c: mov     %rax,%rsi
 40057f: callq   400430 <printf@plt>
 400584: add     $0x10,%rsp
 400588: pop     %rbp
 400589: retq

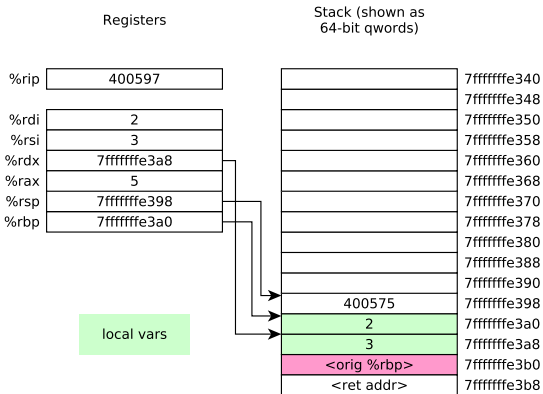
000000000400590 <addLongs>:
 400590: mov     %rdi,%rax
 400593: add     %rsi,%rax
 400596: retq
```



Tracing the program

```
000000000400540 <main>:
 400540: push    %rbp
 400541: sub     $0x10,%rsp
 400545: mov     %rsp,%rbp
 400548: mov     $0x400624,%rdi
 40054f: callq   400430 <printf@plt>
 400554: mov     $0x400639,%rdi
 40055b: lea     0x0(%rbp),%rsi
 40055f: lea     0x8(%rbp),%rdx
 400563: callq   400440 <scanf@plt>
 400568: mov     0x0(%rbp),%rdi
 40056c: mov     0x8(%rbp),%rsi
 400570: callq   400590 <addLongs>
 400575: mov     $0x400641,%rdi
 40057c: mov     %rax,%rsi
 40057f: callq   400430 <printf@plt>
 400584: add     $0x10,%rsp
 400588: pop     %rbp
 400589: retq

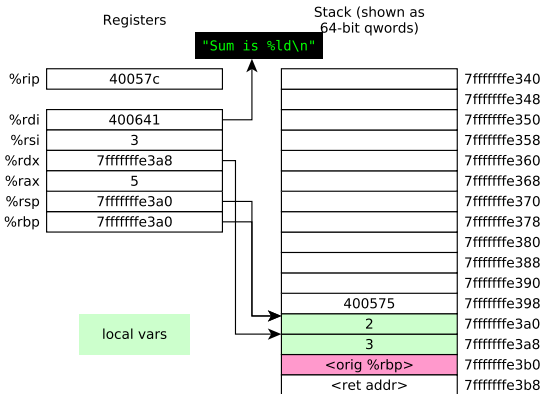
000000000400590 <addLongs>:
 400590: mov     %rdi,%rax
 400593: add     %rsi,%rax
 400596: retq
```



Tracing the program

```
000000000400540 <main>:
 400540: push    %rbp
 400541: sub     $0x10,%rsp
 400545: mov     %rsp,%rbp
 400548: mov     $0x400624,%rdi
 40054f: callq   400430 <printf@plt>
 400554: mov     $0x400639,%rdi
 40055b: lea     0x0(%rbp),%rsi
 40055f: lea     0x8(%rbp),%rdx
 400563: callq   400440 <scanf@plt>
 400568: mov     0x0(%rbp),%rdi
 40056c: mov     0x8(%rbp),%rsi
 400570: callq   400590 <addLongs>
400575: mov     $0x400641,%rdi
 40057c: mov     %rax,%rsi
 40057f: callq   400430 <printf@plt>
 400584: add     $0x10,%rsp
 400588: pop     %rbp
 400589: retq

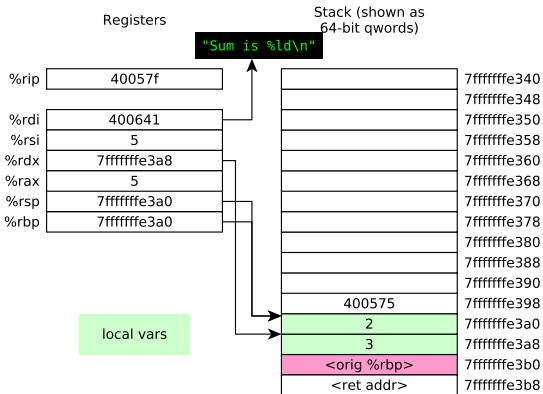
000000000400590 <addLongs>:
 400590: mov     %rdi,%rax
 400593: add     %rsi,%rax
 400596: retq
```



Tracing the program

```
000000000400540 <main>:
 400540: push    %rbp
 400541: sub     $0x10,%rsp
 400545: mov     %rsp,%rbp
 400548: mov     $0x400624,%rdi
 40054f: callq   400430 <printf@plt>
 400554: mov     $0x400639,%rdi
 40055b: lea     0x0(%rbp),%rsi
 40055f: lea     0x8(%rbp),%rdx
 400563: callq   400440 <scanf@plt>
 400568: mov     0x0(%rbp),%rdi
 40056c: mov     0x8(%rbp),%rsi
 400570: callq   400590 <addLongs>
 400575: mov     $0x400641,%rdi
40057c: mov     %rax,%rsi
 40057f: callq   400430 <printf@plt>
 400584: add     $0x10,%rsp
 400588: pop     %rbp
 400589: retq

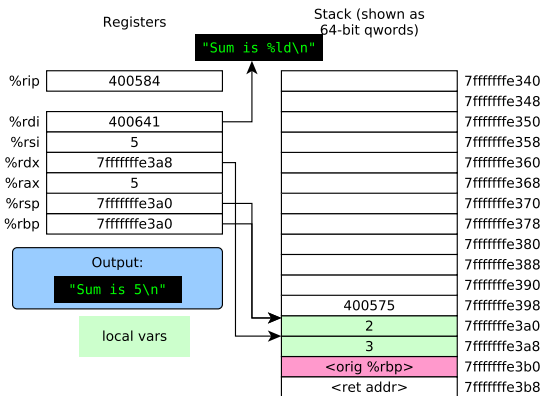
000000000400590 <addLongs>:
 400590: mov     %rdi,%rax
 400593: add     %rsi,%rax
 400596: retq
```



Tracing the program

```
000000000400540 <main>:
 400540: push    %rbp
 400541: sub     $0x10,%rsp
 400545: mov     %rsp,%rbp
 400548: mov     $0x400624,%rdi
 40054f: callq   400430 <printf@plt>
 400554: mov     $0x400639,%rdi
 40055b: lea     0x0(%rbp),%rsi
 40055f: lea     0x8(%rbp),%rdx
 400563: callq   400440 <scanf@plt>
 400568: mov     0x0(%rbp),%rdi
 40056c: mov     0x8(%rbp),%rsi
 400570: callq   400590 <addLongs>
 400575: mov     $0x400641,%rdi
 40057c: mov     %rax,%rsi
 40057f: callq   400430 <printf@plt>
 400584: add     $0x10,%rsp
 400588: pop     %rbp
 400589: retq

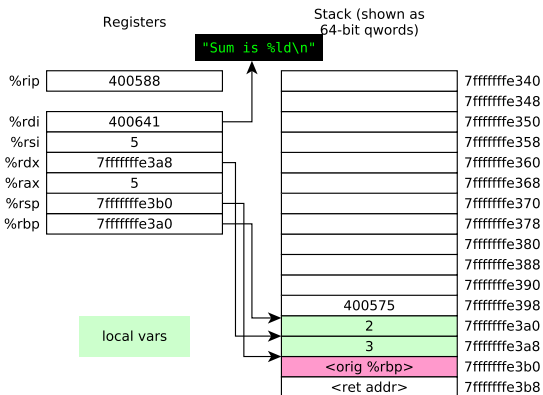
000000000400590 <addLongs>:
 400590: mov     %rdi,%rax
 400593: add     %rsi,%rax
 400596: retq
```



Tracing the program

```
000000000400540 <main>:
 400540: push    %rbp
 400541: sub     $0x10,%rsp
 400545: mov     %rsp,%rbp
 400548: mov     $0x400624,%rdi
 40054f: callq   400430 <printf@plt>
 400554: mov     $0x400639,%rdi
 40055b: lea     0x0(%rbp),%rsi
 40055f: lea     0x8(%rbp),%rdx
 400563: callq   400440 <scanf@plt>
 400568: mov     0x0(%rbp),%rdi
 40056c: mov     0x8(%rbp),%rsi
 400570: callq   400590 <addLongs>
 400575: mov     $0x400641,%rdi
 40057c: mov     %rax,%rsi
 40057f: callq   400430 <printf@plt>
400584: add     $0x10,%rsp
 400588: pop     %rbp
 400589: retq

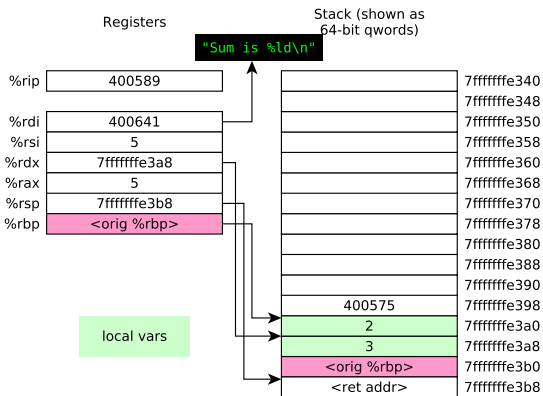
000000000400590 <addLongs>:
 400590: mov     %rdi,%rax
 400593: add     %rsi,%rax
 400596: retq
```



Tracing the program

```
000000000400540 <main>:
 400540: push    %rbp
 400541: sub     $0x10,%rsp
 400545: mov     %rsp,%rbp
 400548: mov     $0x400624,%rdi
 40054f: callq   400430 <printf@plt>
 400554: mov     $0x400639,%rdi
 40055b: lea     0x0(%rbp),%rsi
 40055f: lea     0x8(%rbp),%rdx
 400563: callq   400440 <scanf@plt>
 400568: mov     0x0(%rbp),%rdi
 40056c: mov     0x8(%rbp),%rsi
 400570: callq   400590 <addLongs>
 400575: mov     $0x400641,%rdi
 40057c: mov     %rax,%rsi
 40057f: callq   400430 <printf@plt>
 400584: add     $0x10,%rsp
 400588: pop     %rbp
 400589: retq

000000000400590 <addLongs>:
 400590: mov     %rdi,%rax
 400593: add     %rsi,%rax
 400596: retq
```



Tracing the program

```
000000000400540 <main>:
 400540: push    %rbp
 400541: sub     $0x10,%rsp
 400545: mov     %rsp,%rbp
 400548: mov     $0x400624,%rdi
 40054f: callq   400430 <printf@plt>
 400554: mov     $0x400639,%rdi
 40055b: lea     0x0(%rbp),%rsi
 40055f: lea     0x8(%rbp),%rdx
 400563: callq   400440 <scanf@plt>
 400568: mov     0x0(%rbp),%rdi
 40056c: mov     0x8(%rbp),%rsi
 400570: callq   400590 <addLongs>
 400575: mov     $0x400641,%rdi
 40057c: mov     %rax,%rsi
 40057f: callq   400430 <printf@plt>
 400584: add     $0x10,%rsp
 400588: pop     %rbp
 400589: retq

000000000400590 <addLongs>:
 400590: mov     %rdi,%rax
 400593: add     %rsi,%rax
 400596: retq
```

