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)

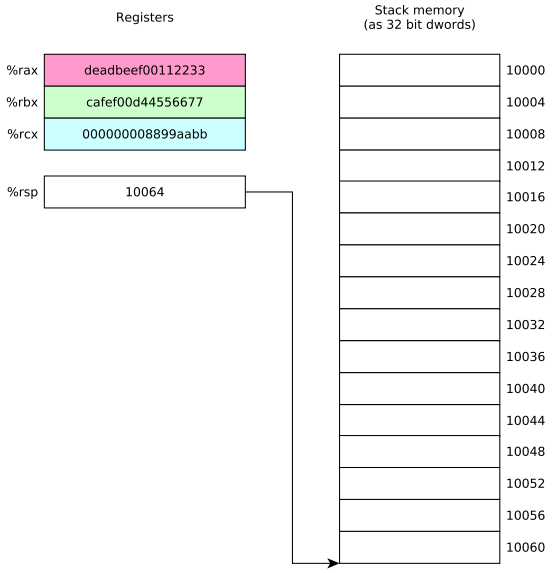
Stack pointer, instruction pointer

- *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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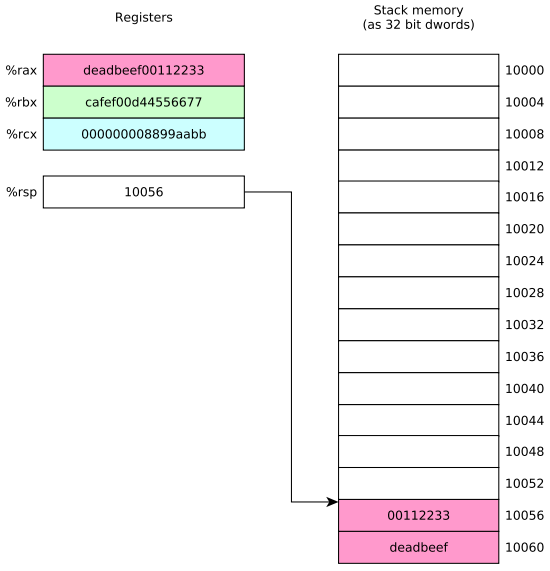


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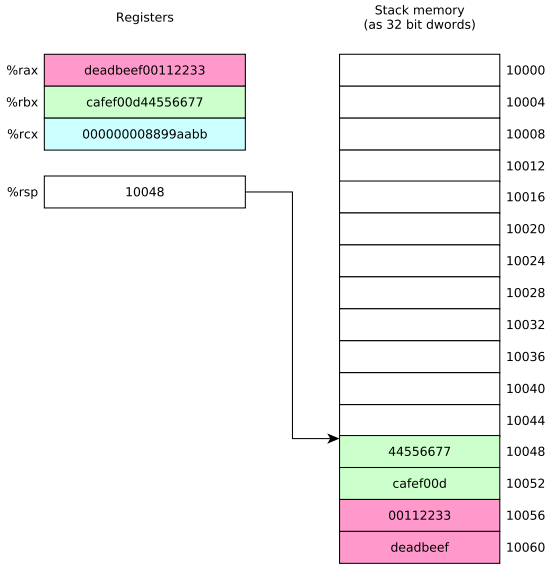


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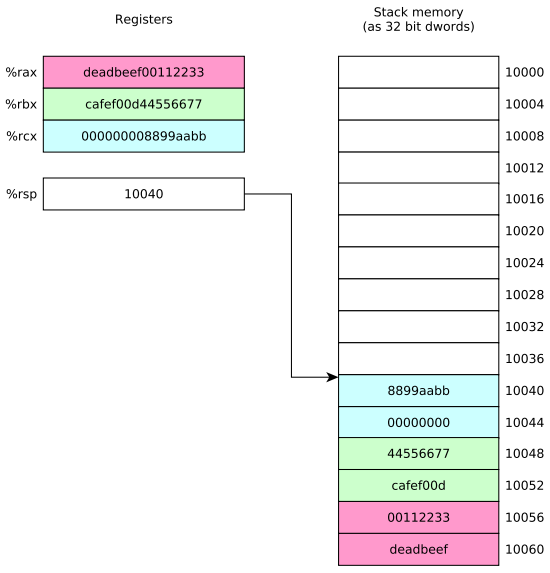


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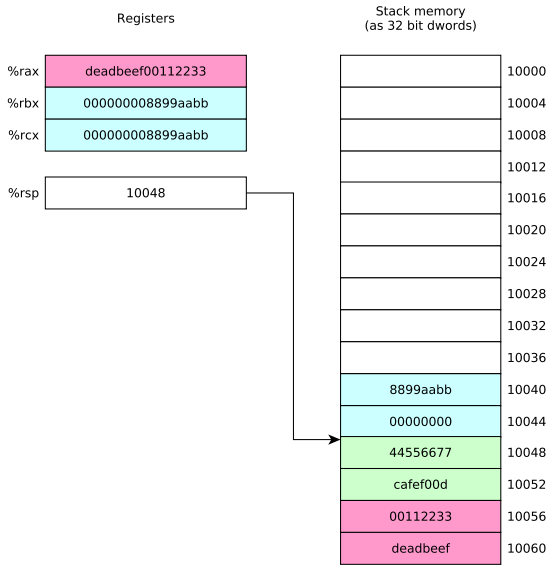


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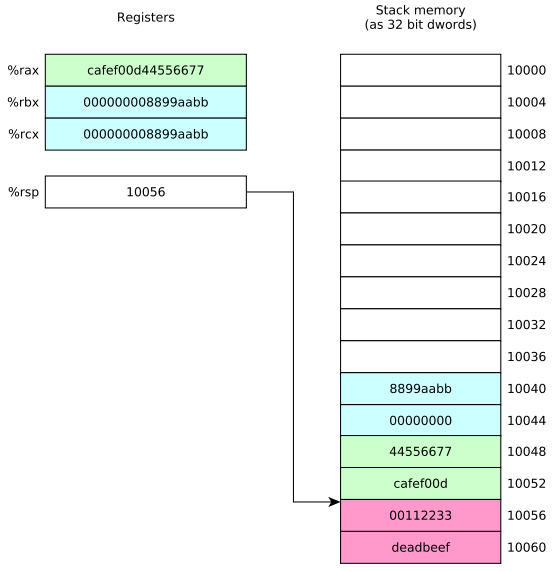


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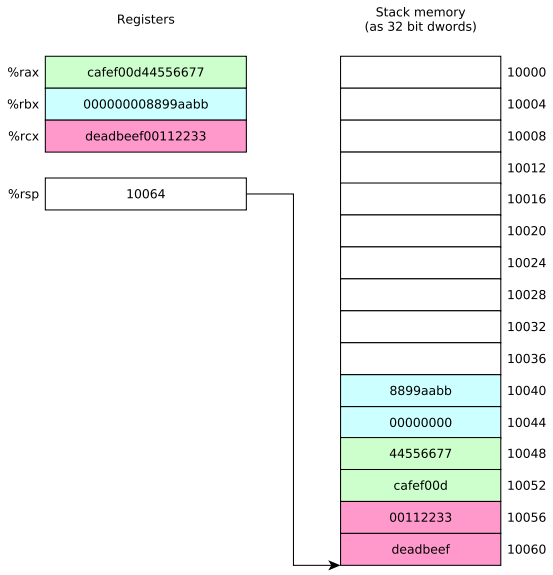


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call and ret

- `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 mulitple 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, `%rsp` $\mod 16 = 8$ 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`, `%14`, `%r15`

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  - 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 callee-saved registers for longer term values that need to persist across procedure calls
    - Use `pushq`/`popq` to save and restore their values on procedure entry and exit

Recursive Fibonacci computation

Compute nth 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

$$fib(0) = 0$$

$$fib(1) = 1$$

For $n > 1$, $fib(n) = fib(n-2) + fib(n-1)$

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`)
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- 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 $N \mod 16 = 0$ 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;
}
```

addLongs, assembly version

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

    movq $sResultMsg, %rdi
    movq %rax, %rsi
    call printf

    addq $16, %rsp
    popq %rbp
    ret

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

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    call printf

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    leaq 8(%rbp), %rdx
    call scanf

    movq 0(%rbp), %rdi
    movq 8(%rbp), %rsi
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    movq $sResultMsg, %rdi
    movq %rax, %rsi
    call printf

    addq $16, %rsp
    popq %rbp
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main:
    pushq %rbp
    subq $16, %rsp
    movq %rsp, %rbp  <-- point %rbp to alloc'ed buf

    movq $sPromptMsg, %rdi
    call printf

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    movq $sPromptMsg, %rdi
    call printf

    movq $sInputFmt, %rdi
    leaq 0(%rbp), %rsi  <-- pass address of 1st var
    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:
    movq %rdi, %rax
    addq %rsi, %rax
    ret
```

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

    movq $sResultMsg, %rdi
    movq %rax, %rsi
    call printf

    addq $16, %rsp
    popq %rbp
    ret

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

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

    movq $sResultMsg, %rdi
    movq %rax, %rsi
    call printf

    addq $16, %rsp
    popq %rbp
    ret

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

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  <-- pass value of 2nd var
    call addLongs

    movq $sResultMsg, %rdi
    movq %rax, %rsi
    call printf

    addq $16, %rsp
    popq %rbp
    ret

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

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

    movq $sResultMsg, %rdi
    movq %rax, %rsi
    call printf

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

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

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

    movq $sResultMsg, %rdi
    movq %rax, %rsi
    call printf

    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: "
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

    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
```

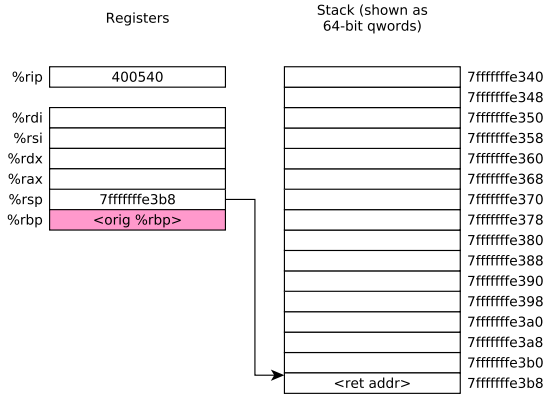
Tracing the program

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
```

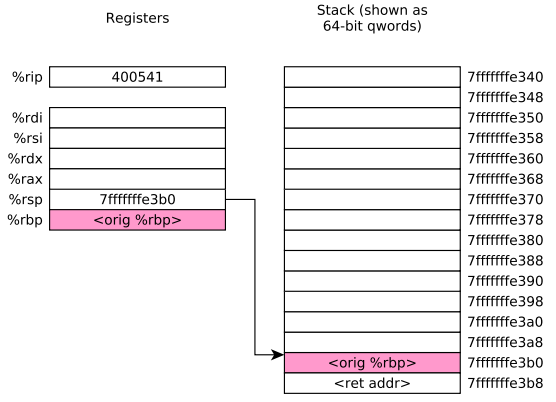
Tracing the program

```
0000000000400540 <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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```



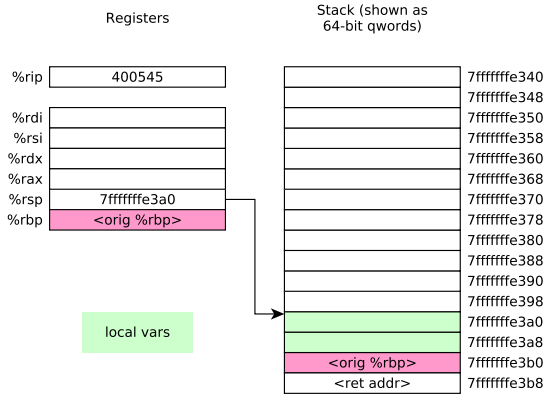
Tracing the program

```
0000000000400540 <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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```



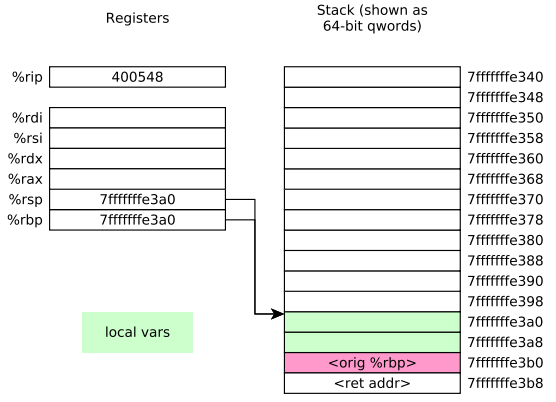
Tracing the program

```
0000000000400540 <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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```



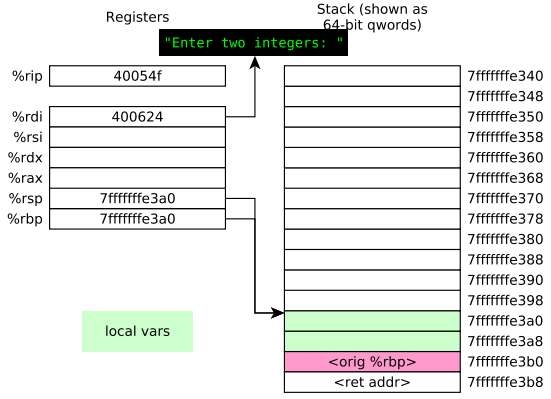
Tracing the program

```
0000000000400540 <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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```



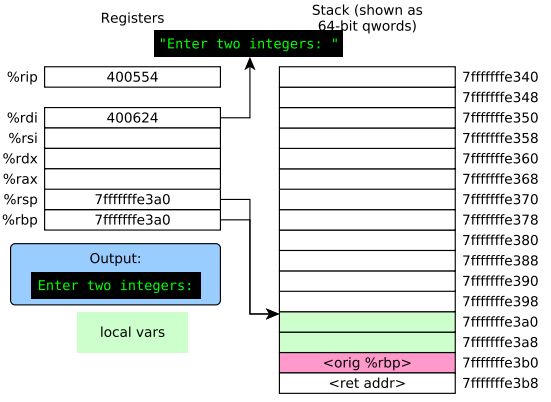
Tracing the program

```
0000000000400540 <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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```



Tracing the program

```
0000000000400540 <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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```



Tracing the program

```
0000000000400540 <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
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  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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```
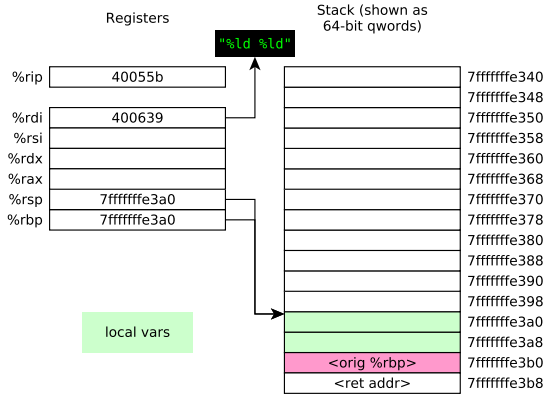
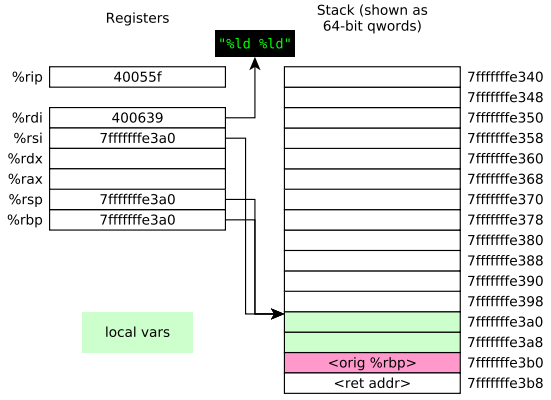



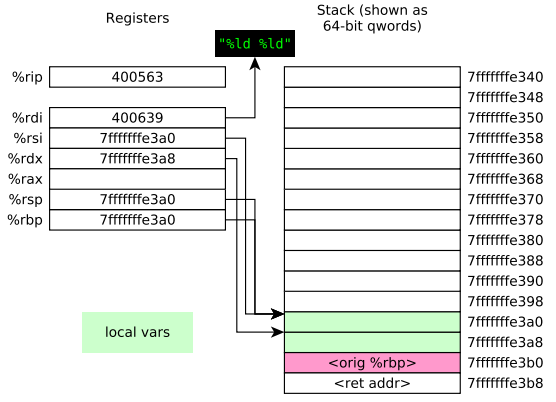
Tracing the program

```
0000000000400540 <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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```



Tracing the program

```
0000000000400540 <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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```



Tracing the program

```
0000000000400540 <main>:
  400540: push   %rbp
  400541: sub    $0x10,%rsp
  400545: mov    %rsp,%rbp
  400548: mov    $0x400624,%rdi
  40054f: callq  400430 <printf@plt>
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  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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```
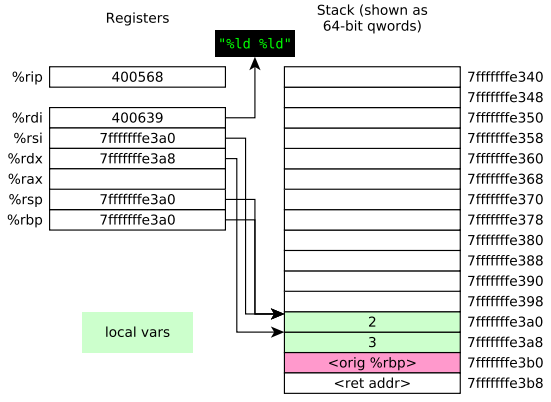
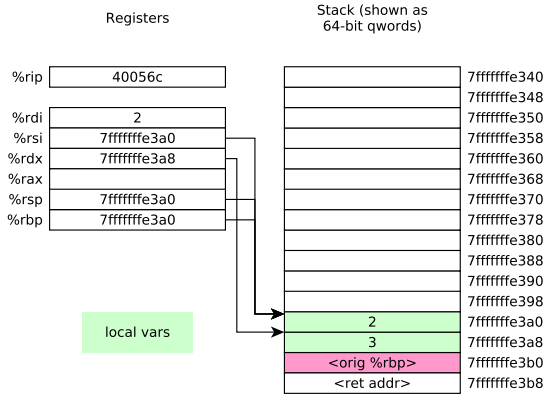



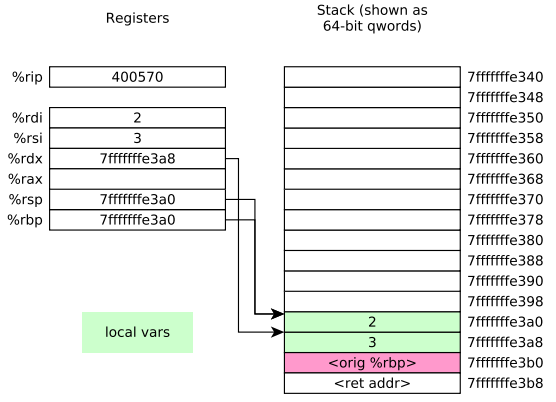
Tracing the program

```
0000000000400540 <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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```



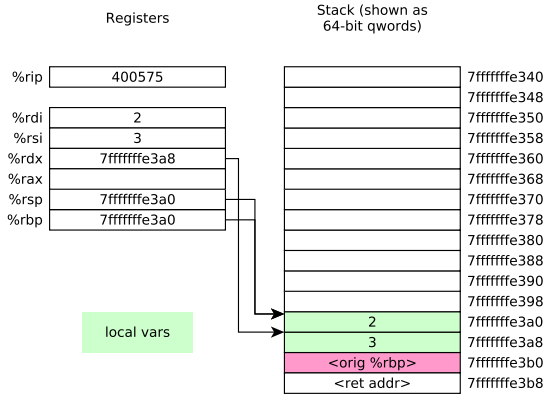
Tracing the program

```
0000000000400540 <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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```



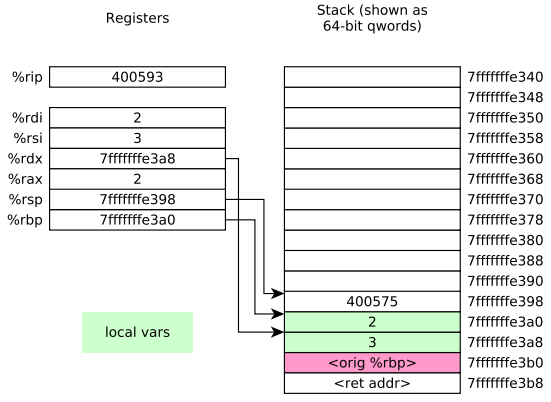
Tracing the program

```
0000000000400540 <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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```



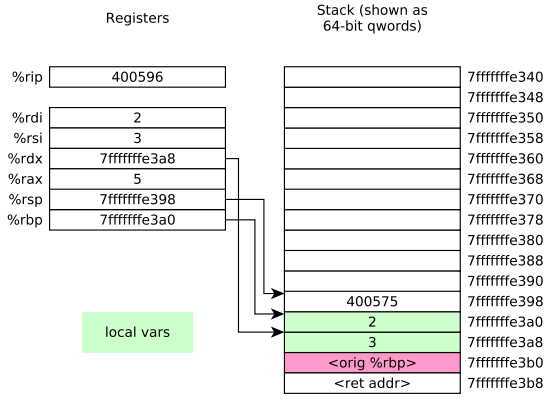
Tracing the program

```
0000000000400540 <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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```



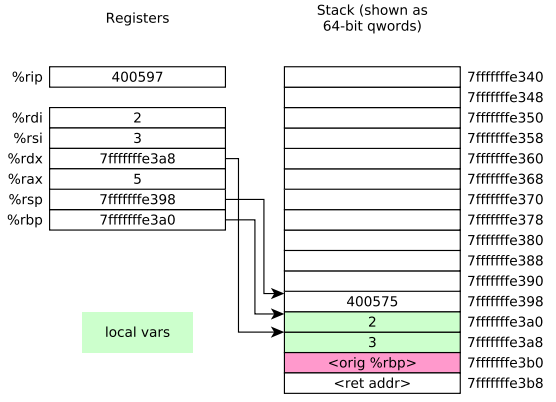
Tracing the program

```
0000000000400540 <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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```



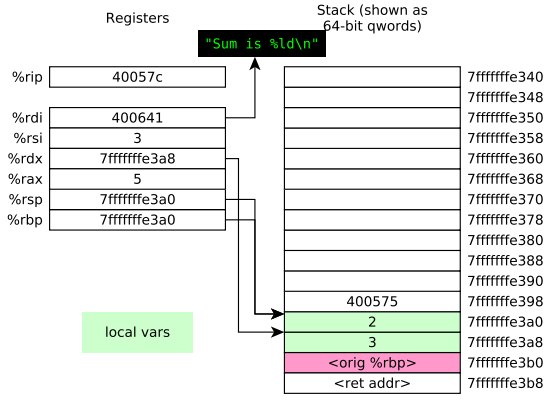
Tracing the program

```
0000000000400540 <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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```



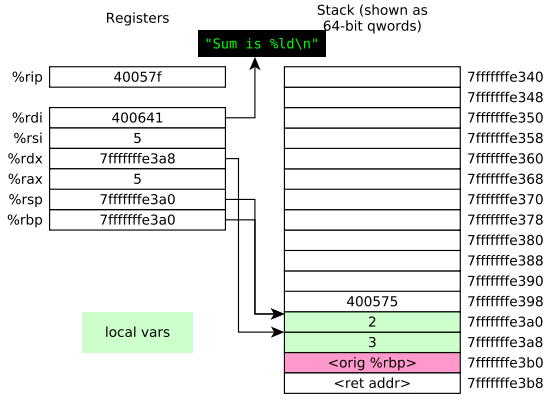
Tracing the program

```
0000000000400540 <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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```



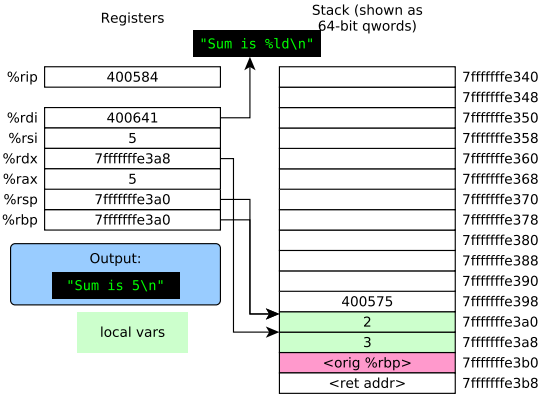
Tracing the program

```
0000000000400540 <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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```



Tracing the program

```
0000000000400540 <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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```



Tracing the program

```
0000000000400540 <main>:
  400540: push   %rbp
  400541: sub    $0x10,%rsp
  400545: mov    %rsp,%rbp
  400548: mov    $0x400624,%rdi
  40054f: callq  400430 <printf@plt>
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  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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```
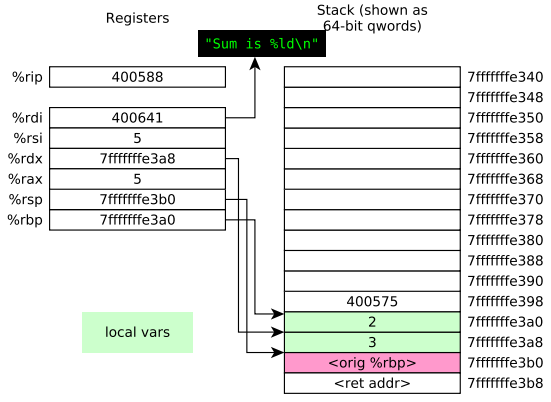
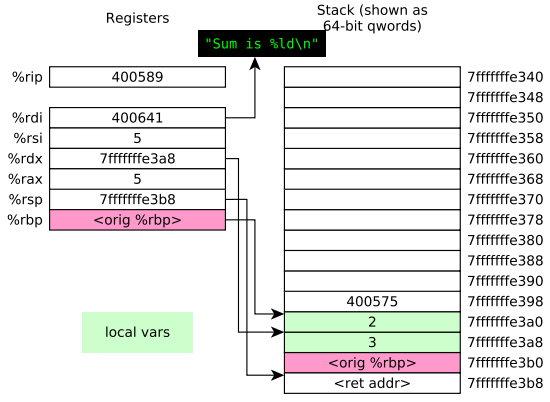
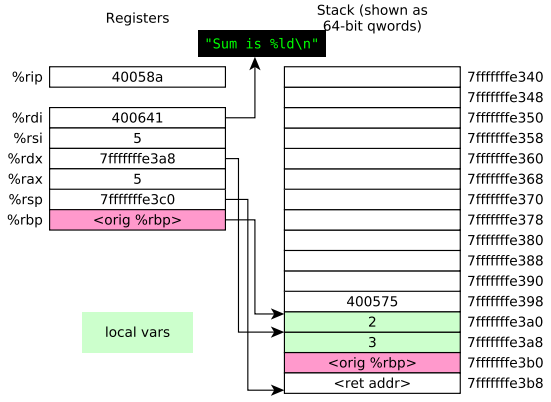



Tracing the program

```
0000000000400540 <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
0000000000400590 <addLongs>:
  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
  400596: retq
```



Tracing the program

```
0000000000400540 <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
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  400590: mov    %rdi,%rax
  400593: add    %rsi,%rax
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```