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)

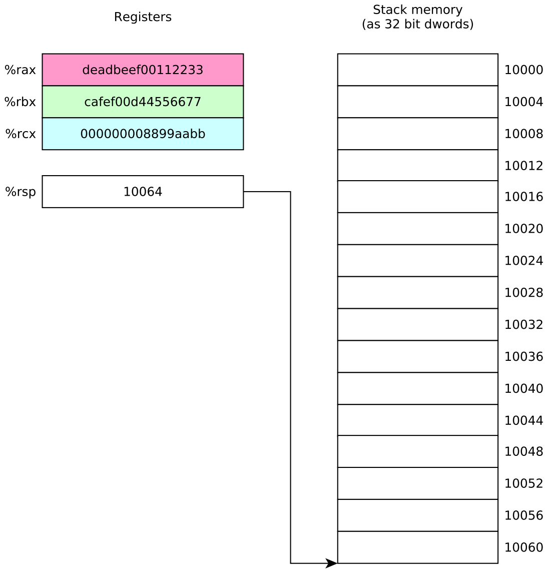
Stack pointer, instruction pointer

- *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


Registers
Stack memory
(as 32 bit dwords)
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%rbx
cafef00d44556677
%rcx
000000008899aabb
%rsp
10064
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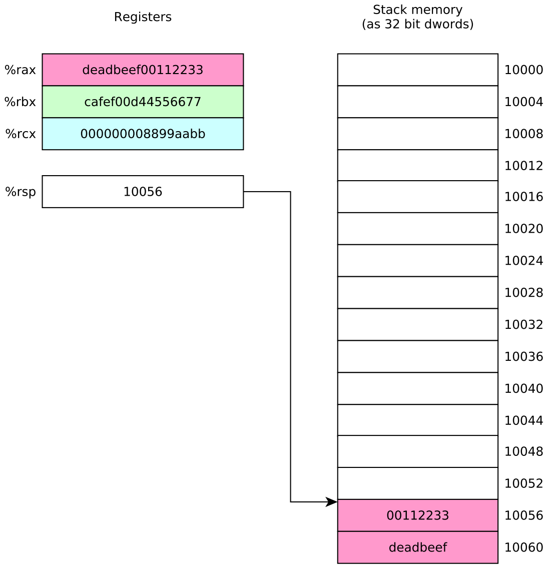
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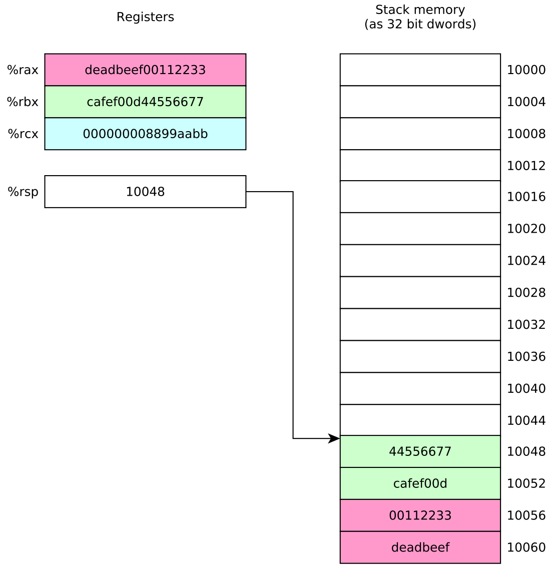
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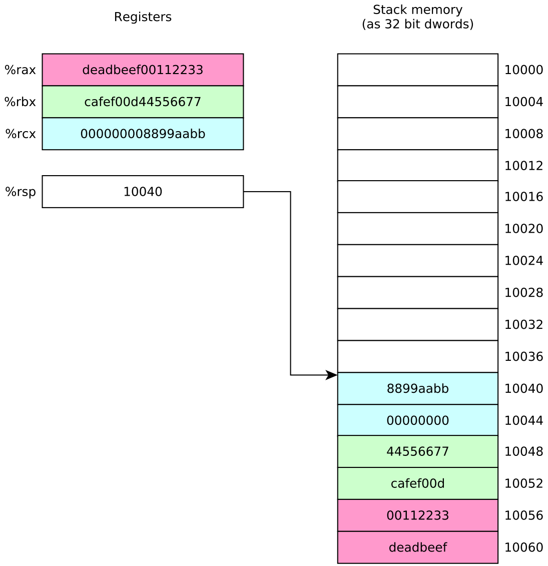
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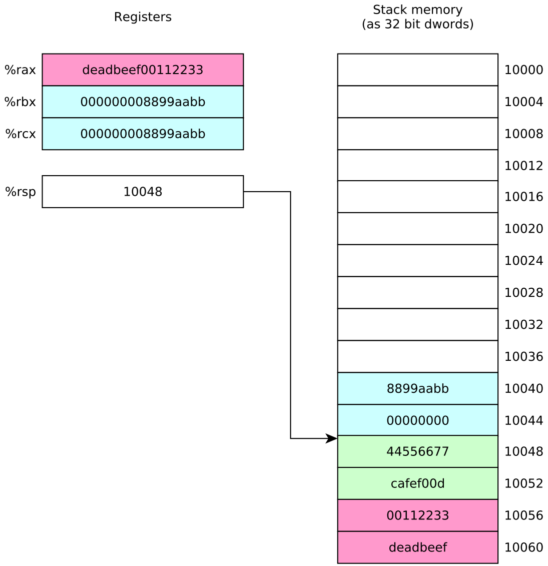
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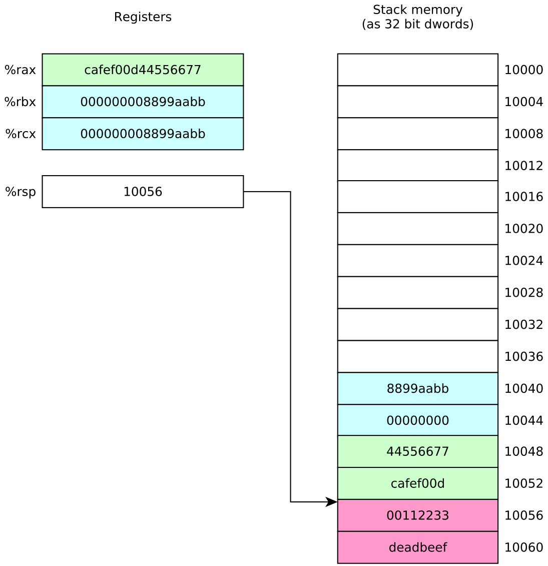
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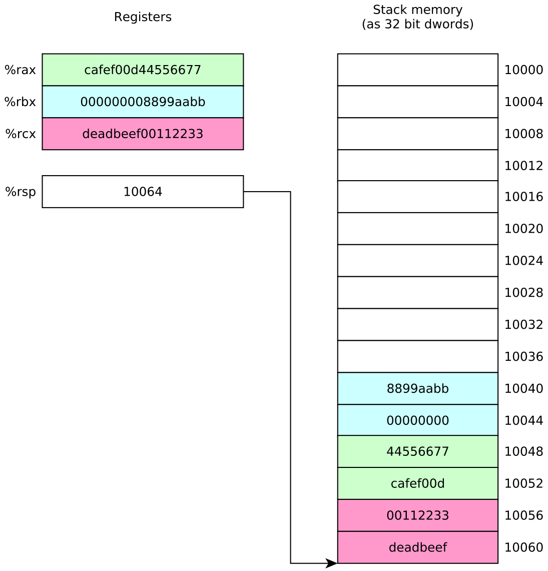
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call and ret

- `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` $\bmod 16 = 8$ 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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  - 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 *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

$$fib(0) = 0$$

$$fib(1) = 1$$

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

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

Before returning from procedure:

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

%rbp points to a memory location *just above* a block of N bytes allocated in the current stack frame. Note that

- N should be a multiple of 16 to ensure correct stack alignment
- The function will access memory locations in the allocated block using *negative* offsets from %rbp

Before allocating space in stack frame

```
--> pushq %rbp
    movq %rsp, %rbp
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```

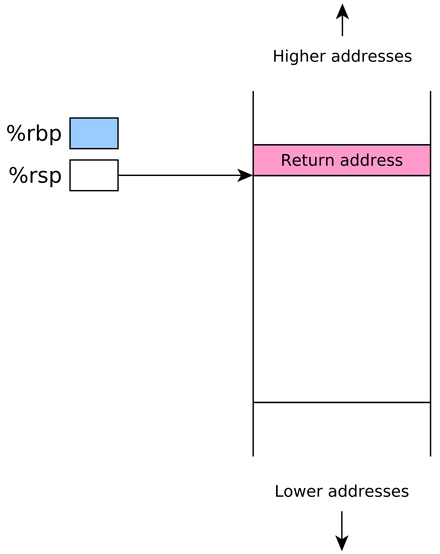

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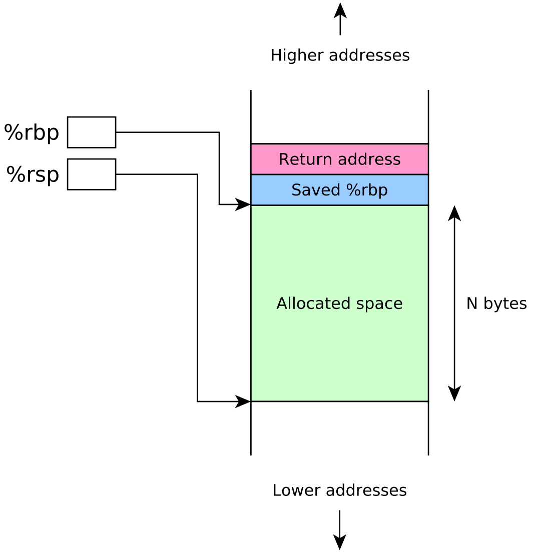

Putting it all together

- 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

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

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

        movl $0, %eax
        movq $sPromptMsg, %rdi
        call printf

        movl $0, %eax
        movq $sInputFmt, %rdi
        leaq -16(%rbp), %rsi
        leaq -8(%rbp), %rdx
        call scanf
```

```
        movq -16(%rbp), %rdi
        movq -8(%rbp), %rsi
        call addLongs

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

        addq $16, %rsp
        popq %rbp
        ret

        .align 16
addLongs:
        movq %rdi, %rax
        addq %rsi, %rax
        ret
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        pushq %rbp           <-- save orig value of %rbp
        movq %rsp, %rbp
        subq $16, %rsp

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        movq -16(%rbp), %rdi
        movq -8(%rbp), %rsi
        call addLongs

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

        addq $16, %rsp
        popq %rbp
        ret

        .align 16
addLongs:
        movq %rdi, %rax
        addq %rsi, %rax
        ret
```

addLongs, assembly version

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

        .section .text
        .globl main
        .align 16
main:
        pushq %rbp
        movq %rsp, %rbp  <-- %rbp points to top
        subq $16, %rsp       of alloc'ed area

        movl $0, %eax
        movq $sPromptMsg, %rdi
        call printf

        movl $0, %eax
        movq $sInputFmt, %rdi
        leaq -16(%rbp), %rsi
        leaq -8(%rbp), %rdx
        call scanf

        movq -16(%rbp), %rdi
        movq -8(%rbp), %rsi
        call addLongs

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

        addq $16, %rsp
        popq %rbp
        ret

        .align 16
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        movq %rdi, %rax
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addLongs, assembly version

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sInputFmt:  .string "%ld %ld"
sResultMsg: .string "Sum is %ld\n"

        .section .text
        .globl main
        .align 16
main:
        pushq %rbp
        movq %rsp, %rbp
        subq $16, %rsp    <-- allocate 16 byte area

        movl $0, %eax
        movq $sPromptMsg, %rdi
        call printf

        movl $0, %eax
        movq $sInputFmt, %rdi
        leaq -16(%rbp), %rsi
        leaq -8(%rbp), %rdx
        call scanf
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```
        movq -16(%rbp), %rdi
        movq -8(%rbp), %rsi
        call addLongs

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        movq %rax, %rsi
        call printf

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

        movl $0, %eax
        movq $sPromptMsg, %rdi
        call printf

        movl $0, %eax
        movq $sInputFmt, %rdi
        leaq -16(%rbp), %rsi  <-- pass address of 1st var
        leaq -8(%rbp), %rdx
        call scanf

        movq -16(%rbp), %rdi
        movq -8(%rbp), %rsi
        call addLongs

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

        addq $16, %rsp
        popq %rbp
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        .align 16
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        movq %rsp, %rbp
        subq $16, %rsp

        movl $0, %eax
        movq $sPromptMsg, %rdi
        call printf

        movl $0, %eax
        movq $sInputFmt, %rdi
        leaq -16(%rbp), %rsi
        leaq -8(%rbp), %rdx   <-- pass address of 2nd var
        call scanf
```

```
        movq -16(%rbp), %rdi
        movq -8(%rbp), %rsi
        call addLongs

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

        addq $16, %rsp
        popq %rbp
        ret

        .align 16
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        movq %rdi, %rax
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addLongs, assembly version

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        movl $0, %eax
        movq $sPromptMsg, %rdi
        call printf

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        movq $sInputFmt, %rdi
        leaq -16(%rbp), %rsi
        leaq -8(%rbp), %rdx
        call scanf
```

```
        movq -16(%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

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addLongs:
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addLongs, assembly version

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

        movl $0, %eax
        movq $sPromptMsg, %rdi
        call printf

        movl $0, %eax
        movq $sInputFmt, %rdi
        leaq -16(%rbp), %rsi
        leaq -8(%rbp), %rdx
        call scanf

        movq -16(%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

        .align 16
addLongs:
        movq %rdi, %rax
        addq %rsi, %rax
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addLongs, assembly version

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

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

        movl $0, %eax
        movq $sPromptMsg, %rdi
        call printf

        movl $0, %eax
        movq $sInputFmt, %rdi
        leaq -16(%rbp), %rsi
        leaq -8(%rbp), %rdx
        call scanf
```

```
        movq -16(%rbp), %rdi
        movq -8(%rbp), %rsi
        call addLongs

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

        addq $16, %rsp  <-- deallocate alloc'ed area
        popq %rbp
        ret

        .align 16
addLongs:
        movq %rdi, %rax
        addq %rsi, %rax
        ret
```

addLongs, assembly version

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

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

        movl $0, %eax
        movq $sPromptMsg, %rdi
        call printf

        movl $0, %eax
        movq $sInputFmt, %rdi
        leaq -16(%rbp), %rsi
        leaq -8(%rbp), %rdx
        call scanf
```

```
        movq -16(%rbp), %rdi
        movq -8(%rbp), %rsi
        call addLongs

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

        addq $16, %rsp
        popq %rbp        <-- restore orig value of %rbp
        ret

        .align 16
addLongs:
        movq %rdi, %rax
        addq %rsi, %rax
        ret
```

addLongs, assembly version

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

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

        movl $0, %eax
        movq $sPromptMsg, %rdi
        call printf

        movl $0, %eax
        movq $sInputFmt, %rdi
        leaq -16(%rbp), %rsi
        leaq -8(%rbp), %rdx
        call scanf

        movq -16(%rbp), %rdi
        movq -8(%rbp), %rsi
        call addLongs

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

        addq $16, %rsp
        popq %rbp
        ret

        .align 16
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
```

Running the program in gdb

```
$ gdb addLongs
...output omitted...
(gdb) break addLongs.S:28
Breakpoint 1 at 0x401172: file addLongs.S, line 28.
(gdb) run
Starting program: /home/daveho/.../src/control2/addLongs
Enter two integers: 3 4

Breakpoint 1, main () at addLongs.S:28
28                movq -16(%rbp), %rdi      /* pass first value */
(gdb) print *(long *)($rbp-16)
$1 = 3
(gdb) print *(long *)($rbp-8)
$2 = 4
```

Running the program in gdb

```
$ gdb addLongs
...output omitted...
(gdb) break addLongs.S:28  <-- set breakpoint just after scanf returns
Breakpoint 1 at 0x401172: file addLongs.S, line 28.
(gdb) run
Starting program: /home/daveho/.../src/control2/addLongs
Enter two integers: 3 4

Breakpoint 1, main () at addLongs.S:28
28                movq -16(%rbp), %rdi      /* pass first value */
(gdb) print *(long *)($rbp-16)
$1 = 3
(gdb) print *(long *)($rbp-8)
$2 = 4
```

Running the program in gdb

```
$ gdb addLongs
...output omitted...
(gdb) break addLongs.S:28
Breakpoint 1 at 0x401172: file addLongs.S, line 28.
(gdb) run                       <-- start the program
Starting program: /home/daveho/.../src/control2/addLongs
Enter two integers: 3 4

Breakpoint 1, main () at addLongs.S:28
28                movq -16(%rbp), %rdi      /* pass first value */
(gdb) print *(long *)($rbp-16)
$1 = 3
(gdb) print *(long *)($rbp-8)
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(gdb) break addLongs.S:28
Breakpoint 1 at 0x401172: file addLongs.S, line 28.
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Starting program: /home/daveho/.../src/control2/addLongs
Enter two integers: 3 4    <-- enter input values

Breakpoint 1, main () at addLongs.S:28
28                movq -16(%rbp), %rdi      /* pass first value */
(gdb) print *(long *)($rbp-16)
$1 = 3
(gdb) print *(long *)($rbp-8)
$2 = 4
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Breakpoint 1 at 0x401172: file addLongs.S, line 28.
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Starting program: /home/daveho/.../src/control2/addLongs
Enter two integers: 3 4

Breakpoint 1, main () at addLongs.S:28
28                movq -16(%rbp), %rdi      /* pass first value */
(gdb) print *(long *)($rbp-16)  <-- print first input value at -16(%rbp)
$1 = 3
(gdb) print *(long *)($rbp-8)
$2 = 4
```

Running the program in gdb

```
$ gdb addLongs
...output omitted...
(gdb) break addLongs.S:28
Breakpoint 1 at 0x401172: file addLongs.S, line 28.
(gdb) run
Starting program: /home/daveho/.../src/control2/addLongs
Enter two integers: 3 4

Breakpoint 1, main () at addLongs.S:28
28                movq -16(%rbp), %rdi      /* pass first value */
(gdb) print *(long *)($rbp-16)
$1 = 3
(gdb) print *(long *)($rbp-8)   <-- print second input value at -8(%rbp)
$2 = 4
```

Running the program in gdb

```
$ gdb addLongs
...output omitted...
(gdb) break addLongs.S:28
Breakpoint 1 at 0x401172: file addLongs.S, line 28.
(gdb) run
Starting program: /home/daveho/.../src/control2/addLongs
Enter two integers: 3 4

Breakpoint 1, main () at addLongs.S:28
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(gdb) print *(long *)($rbp-16)
$1 = 3
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