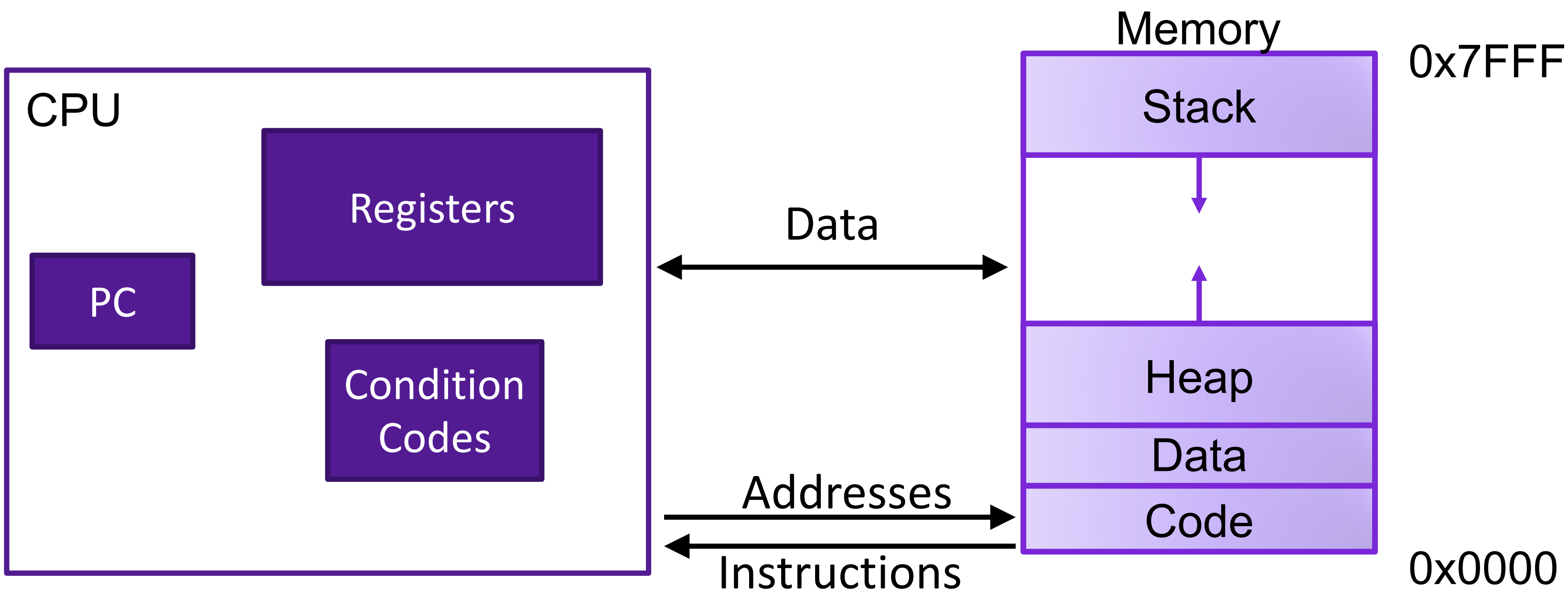
Lecture 8: Procedure Calls in Assembly

CS 105 Spring 2024

Review: Assembly/Machine Code View



Programmer-Visible State

- PC: Program counter
- 16 Registers
- Condition codes

Memory

- Byte addressable array
- Code and user data
- Stack to support procedures

Review: X86-64 Integer Registers

`%rax` (function result)	`%r8` (fifth argument)
`%rbx`	`%r9` (sixth argument)
`%rcx` (fourth argument)	`%r10`
`%rdx` (third argument)	`%r11`
`%rsi` (second argument)	`%r12`
`%rdi` (first argument)	`%r13`
`%rsp` (stack pointer)	`%r14`
`%rbp`	`%r15`

Review: Assembly Operations

- Transfer data between memory and register
  - Load data from memory into register
  - Store register data into memory
- Perform arithmetic function on register or memory data
- Transfer control
  - Conditional branches
  - Jumps to/from procedures

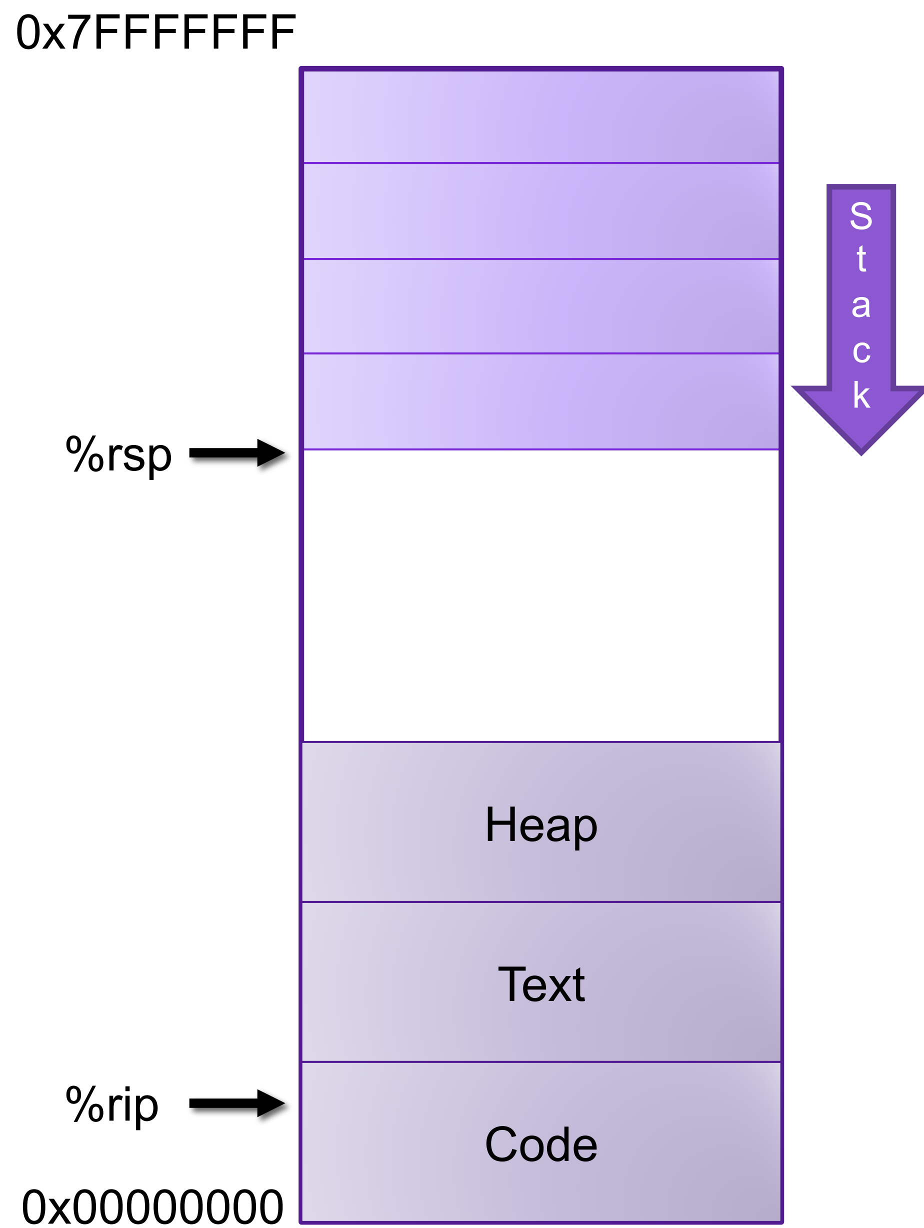
Procedures

- Procedures provide an abstraction that implements some functionality with designated arguments and (optional) return value
  - e.g., functions, methods, subroutines, handlers

- To support procedures at the machine level, we need mechanisms for:
  1) **Passing Control:** When procedure P calls procedure Q, program counter must be set to address of Q, when Q returns, program counter must be reset to instruction in P following procedure call
  2) **Passing Data:** Must handle parameters and return values
  3) **Allocating memory:** Q must be able to allocate (and deallocate) space for local variables

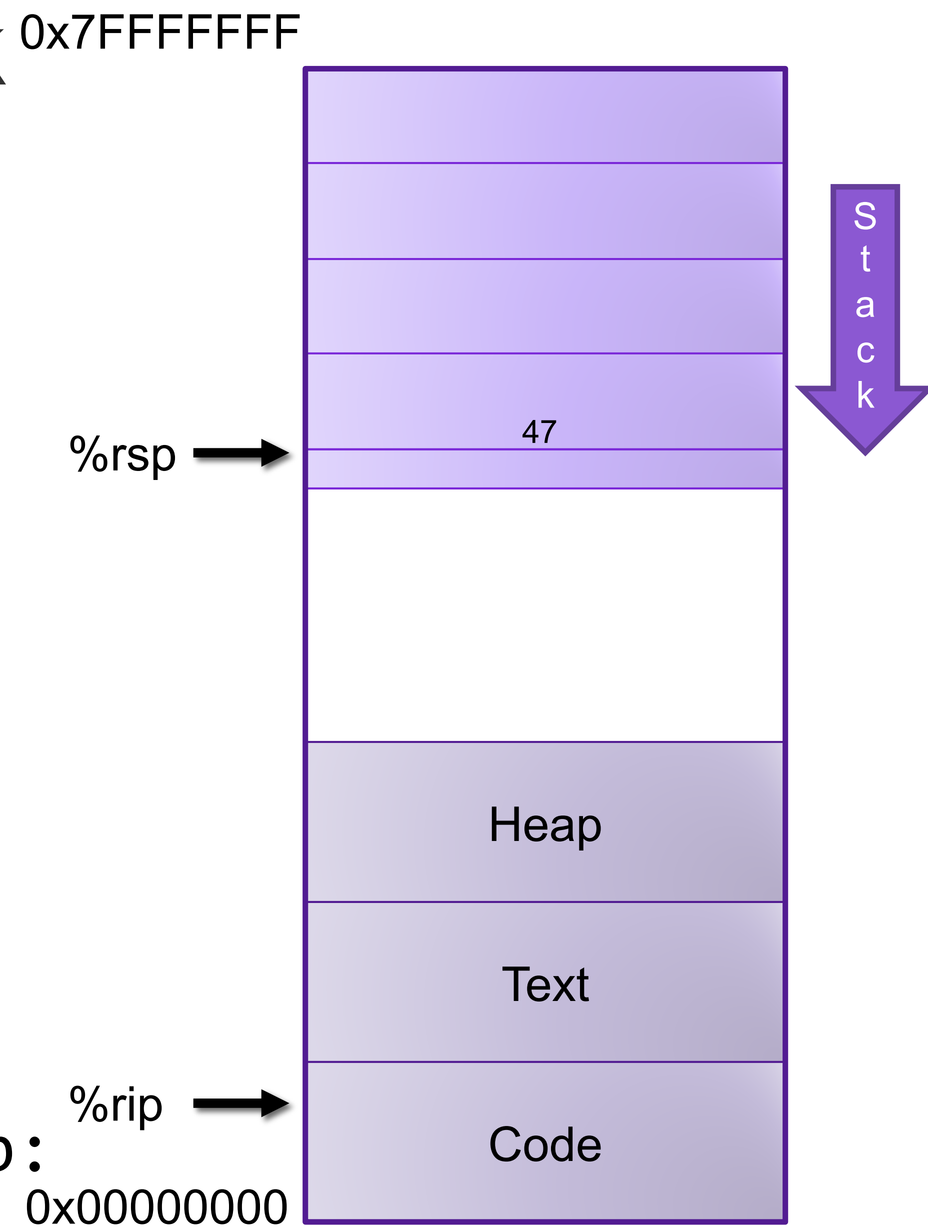
The Stack

- the stack is a region of memory (traditionally the "top" of memory)
- grows "down"
- provides storage for functions (i.e., space for allocating local variables)
- `%rsp` holds address of top element of stack



Modifying the Stack

- pushq S:
```
R[%rsp] ← R[%rsp] – 8
M[R[%rsp]] ← S
```
- popq D:
```
D ← M[R[%rsp]]
R[%rsp] ← R[%rsp] + 8
```
- explicitly modify %rsp:
```
subq $4, %rsp
addq $4, %rsp
```
- modify memory above %rsp:
```
movl $47, 4(%rsp)
```



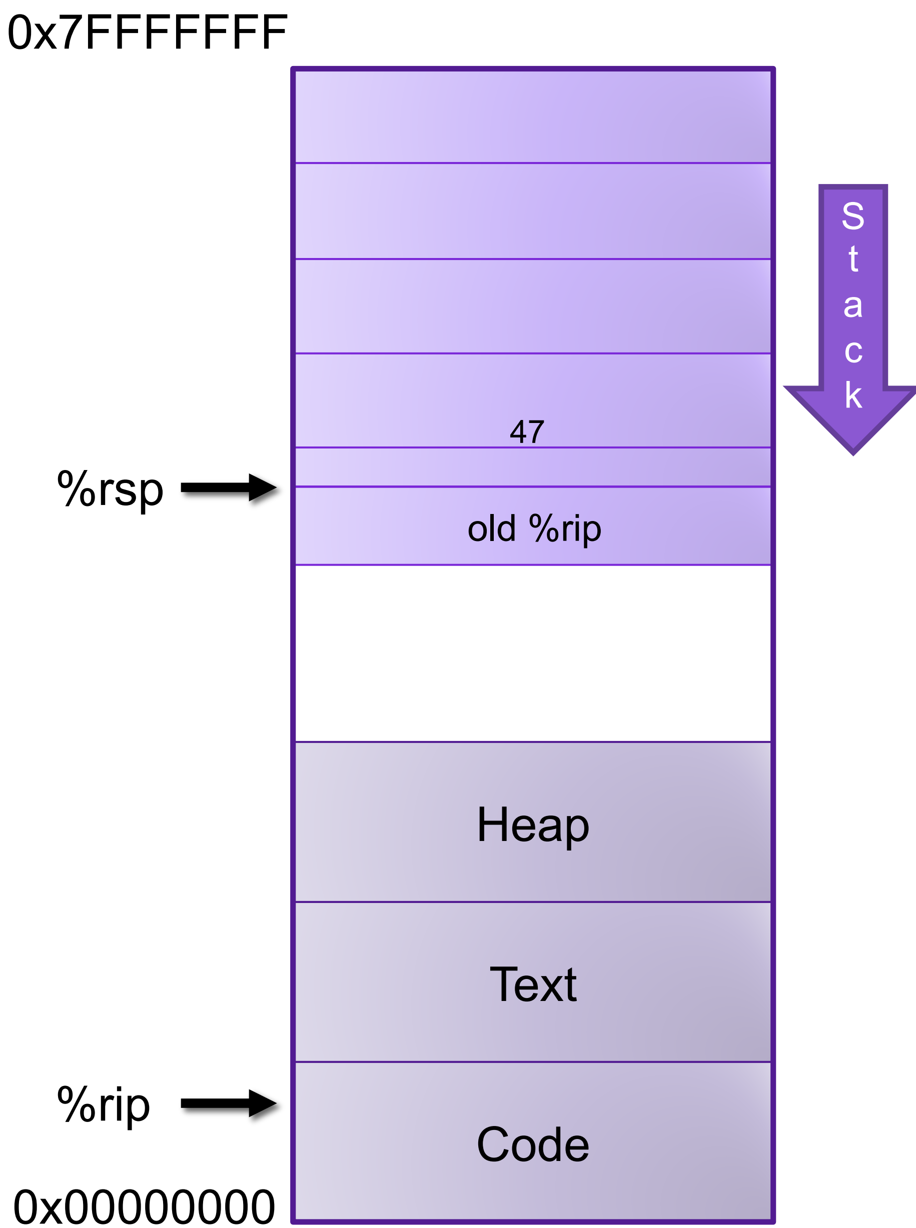
Modifying the Stack

- `call f:`

```
pushq %rip
movq &f, %rip
```

- `ret:`

```
popq %rip
```



Example: Modifying the Stack

```
int proc(int* p){
  return p[3];
}

int example1(int x) {
  int a[4];
  a[3] = 10;
  return proc(a) + 1;
}
```

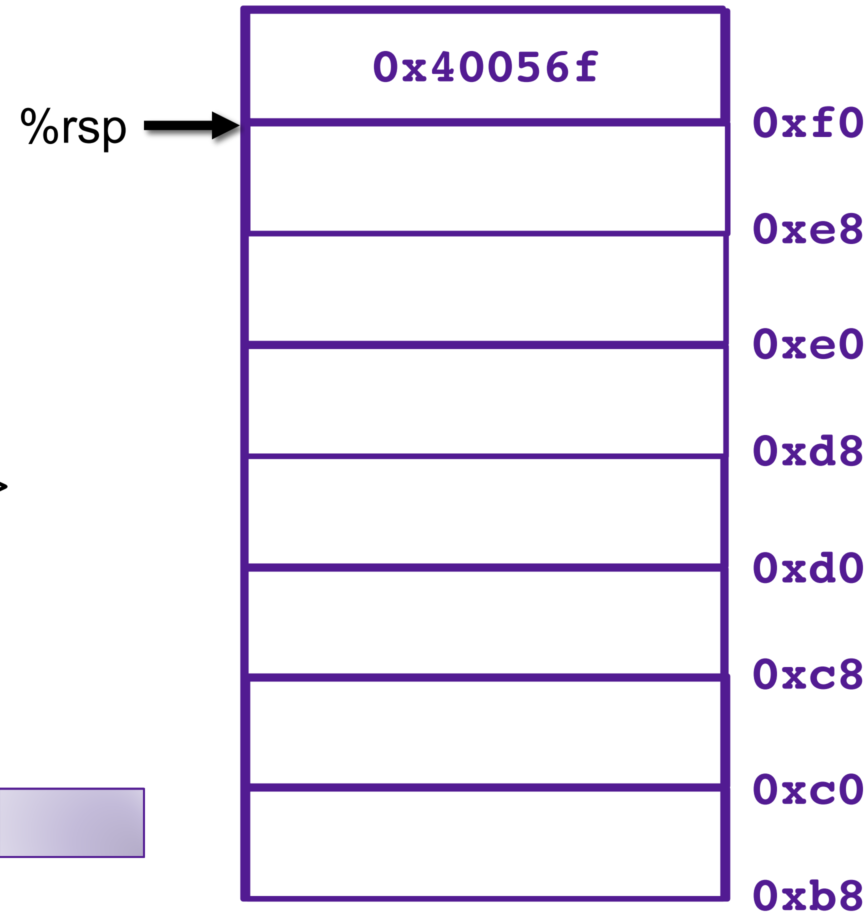
```
proc:
  movl   12(%rdi), %eax
  ret
```

```
example1:
  subq   $16, %rsp
  movl   $10, 12(%rsp)
  movq   %rsp, %rdi
  call   0x400596 <proc>
  addl   $1, %rax
  addq   $16, %rsp
  ret
```

Exercise 1: Modifying the Stack

```
    0x400557 <fun>:
      400557: movq $13, 16(%rsp)
      40055a: ret

    0x40055b <main>:
%rip → 40055b: sub $8, %rsp
      40055f: pushq $47
      400560: callq 400557 <fun>
      400565: popq %rax
      400566: addq (%rsp), %rax
      40056a: addq $8, %rsp
      40056e: ret
```



%rax

What's the value in %rax immediately before the instruction at `0x40056e` is executed?
What's the value in %rsp immediately before the instruction at `0x40056e` is executed?

Procedure Calls (simplified)

Caller

- Before
  - Put arguments in place (if there are parameters)
  - Make call
- After
  - Use result (if non-void)

Callee

- Preamble
  - Allocate space on stack (if needed)
- Exit code
  - Put return value in place (if non-void function)
  - Deallocate space on stack (if allocated)
  - Return

Example: Procedure Calls

```
int example1(int x) {
  int a[4];
  a[3] = 10;
  return proc(a) + 1;
}
```

```
example1:
  subq   $16, %rsp             allocate
  movl   $10, 12(%rsp)
  movq   %rsp, %rdi            args
  call   0x400596 <proc>       call
  addl   $1, %rax              ret. val
  addq   $16, %rsp             dealloc.
  ret                          return
```

Maintaining Variable state

```
int function(){
  int x = 47;
  int y = 13;
  mystery(y);

  // what is x?
  // what is y?
}
```

```
function:
  movl   $47, %rbx
  movl   $13, %rdi
  call   0x40042a <mystery>

# what is in %rbx?
# what is in %rdi?
  ret
```

X86-64 Register Usage Conventions

`%rax` (function result)	`%r8` (fifth argument)
`%rbx`	`%r9` (sixth argument)
`%rcx` (fourth argument)	`%r10`
`%rdx` (third argument)	`%r11`
`%rsi` (second argument)	`%r12`
`%rdi` (first argument)	`%r13`
`%rsp` (stack pointer)	`%r14`
`%rbp`	`%r15`

Callee-saved registers are shaded

Procedure Calls, Division of Labor

Caller

- Before
  - Save caller-saved registers to stack (if used after call)
  - Put arguments in place (if there are parameters)
  - Make call
- After
  - Restore caller-saved register (if used after call)
  - Use result (if non-void)

Callee

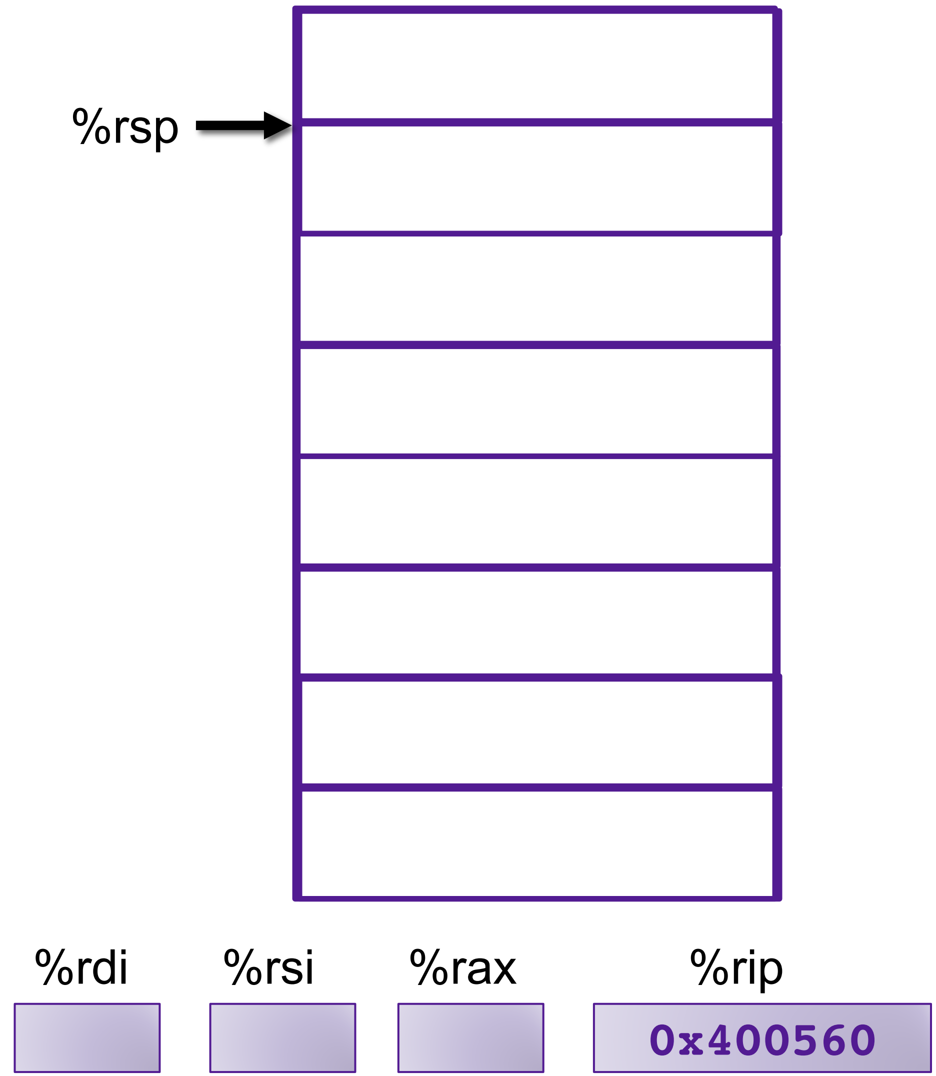
- Preamble
  - Save callee-saved registers (if will use)
  - Allocate space on stack (if needed)
- Exit code
  - Put return value in place (if non-void function)
  - Restore callee-saved registers (if used)
  - Deallocate space on stack (if allocated)
  - Return

Exercise 2: Value Passing

```
0x400540 <last>:
  400540: mov %rdi, %rax
  400543: imul %rsi, %rax
  400547: ret

0x400548 <first>:
  400548: lea 0x1(%rdi),%rsi
  40054c: sub $0x1, %rdi
  400550: callq 400540 <last>
  400555: rep; ret

0x400556 <main>:
  400560: mov $4, %rdi
  400563: callq 400548 <first>
  400568: addq  $0x13, %rax
  40056c: ret
```



What value gets returned by main?

Exercise 2: Value Passing

```
0x400540 <last>:
  400540: mov %rdi, %rax
  400543: imul %rsi, %rax
  400547: ret

0x400548 <first>:
  400548: lea 0x1(%rdi),%rsi
  40054c: sub $0x1, %rdi
  400550: callq 400540 <last>
  400555: rep; ret

0x400556 <main>:
  400560: mov $4, %rdi
  400563: callq 400548 <first>
  400568: addq  $0x13, %rax
  40056c: ret
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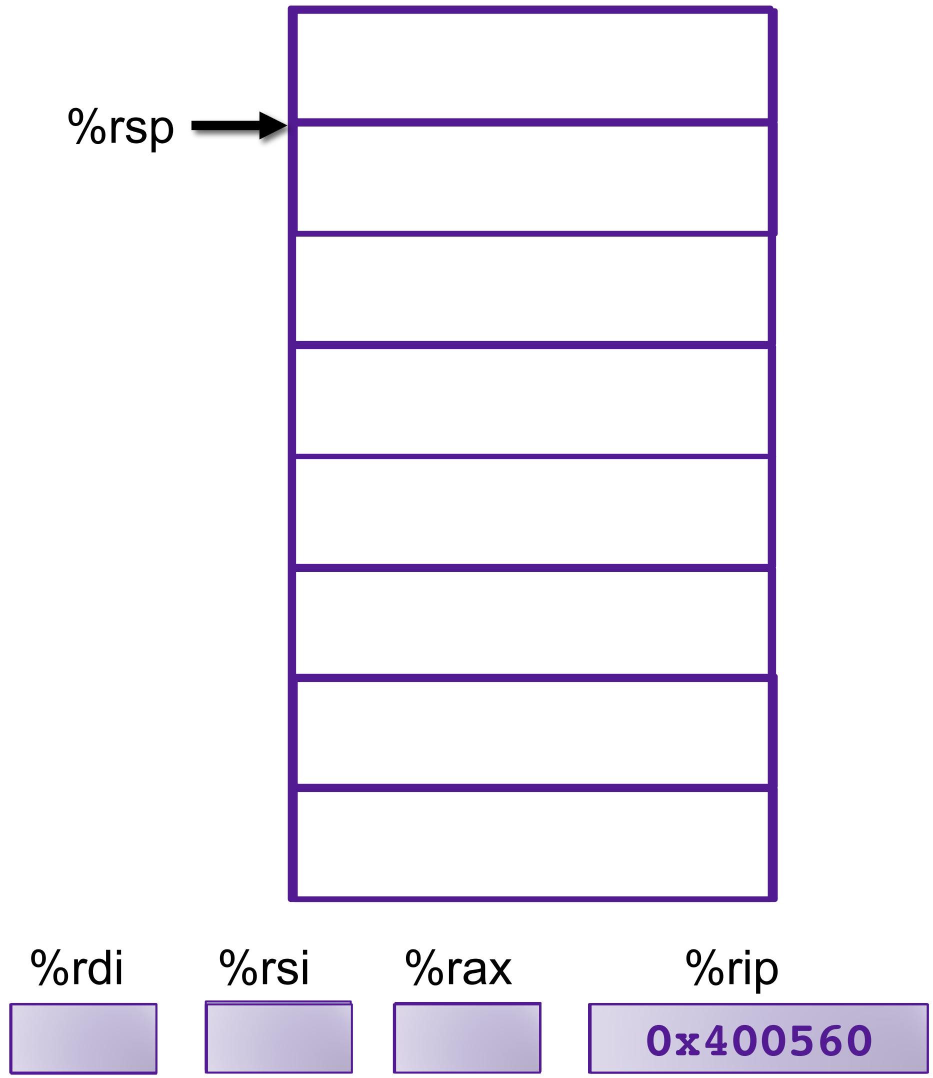


What value gets returned by main?

Handling Extra Parameters

- Conventions define 6 registers for storing arguments
- If function has more than 6 parameters, additional arguments go on the stack

Procedure Call Example: Arguments

```
int func1(int x1, int x2, int x3,
          int x4, int x5, int x6,
          int x7, int x8){
  int l1 = x1+x2;
  int l2 = x3+x4;
  int l3 = x5+x6;
  int l4 = x7+x8;
  int l5 = 4;
  int l6 = 13;
  int l7 = 47;
  int l8 = l1 + l2 + l3 + l4 + l5
              + l6 + l7;
  return l8;
}

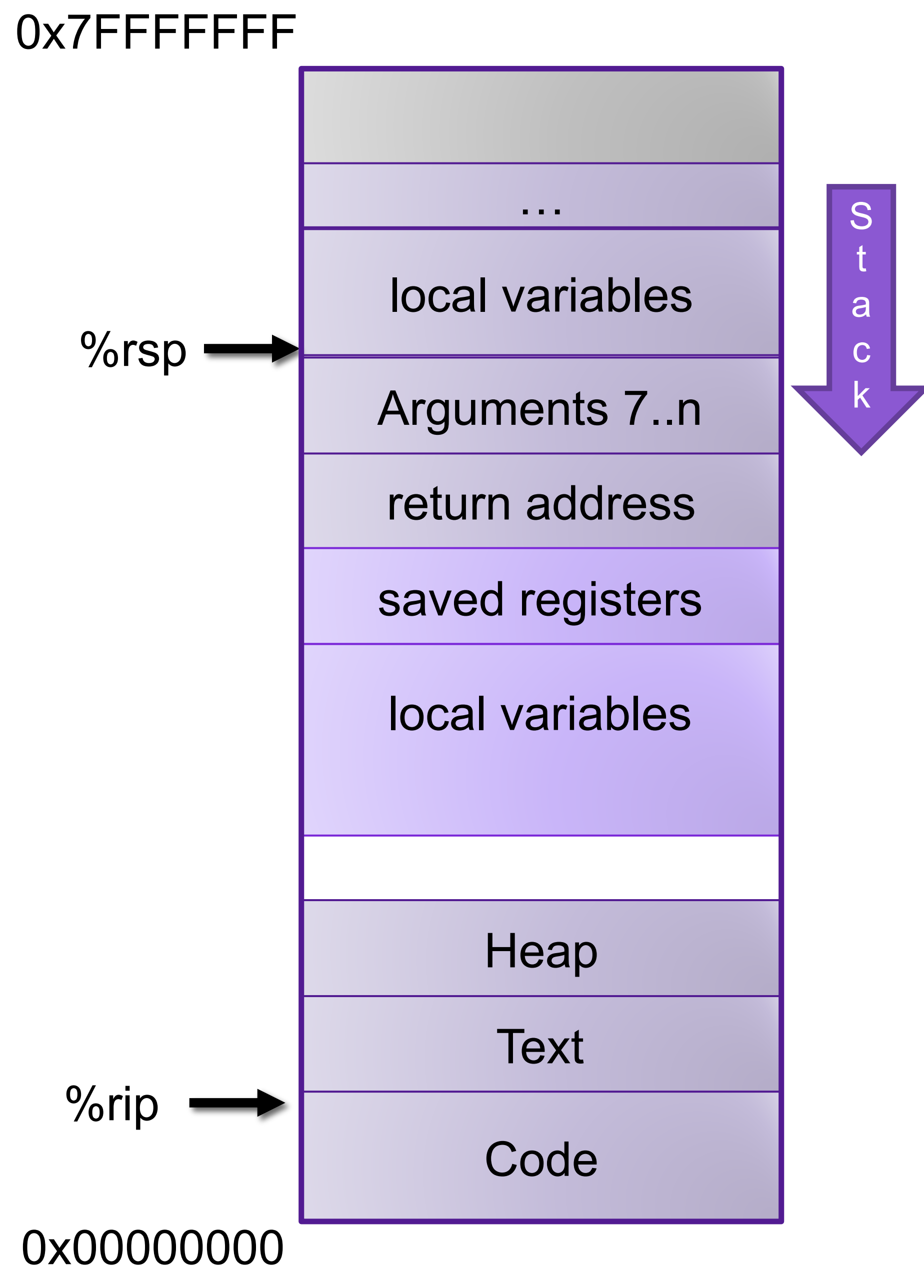
int main(int argc, char *argv[]){
  int x = func1(1,2,3,4,5,6,7,8);
  return x;
}
```

```
func1:
  addl    %edi, %esi
  addl    %ecx, %edx
  addl    %r9d, %r8d
  movl    16(%rsp), %eax
  addl    8(%rsp), %eax
```

```
main:
        movl    $1, %edi
        movl    $2, %esi
        movl    $3, %edx
        movl    $4, %ecx
        movl    $5, %r8d
        movl    $6, %r9d
        pushq   $8
        pushq   $7
        callq   _function1
        addq    $16, %rsp
        retq
```

Stack Frames

- Each function called gets a stack frame
- Passing data:
  - calling procedure P uses registers (and stack) to provide parameters to Q.
  - Q uses register %rax for return value
- Passing control:
  - **`call <proc>`**
    - Pushes return address (current **`%rip`**) onto stack
    - Sets **`%rip`** to first instruction of proc
  - **`ret`**
    - Pops return address from stack and places it in **`%rip`**
- Local storage:
  - allocate space on the stack by decrementing stack pointer, deallocate by incrementing



Recursion

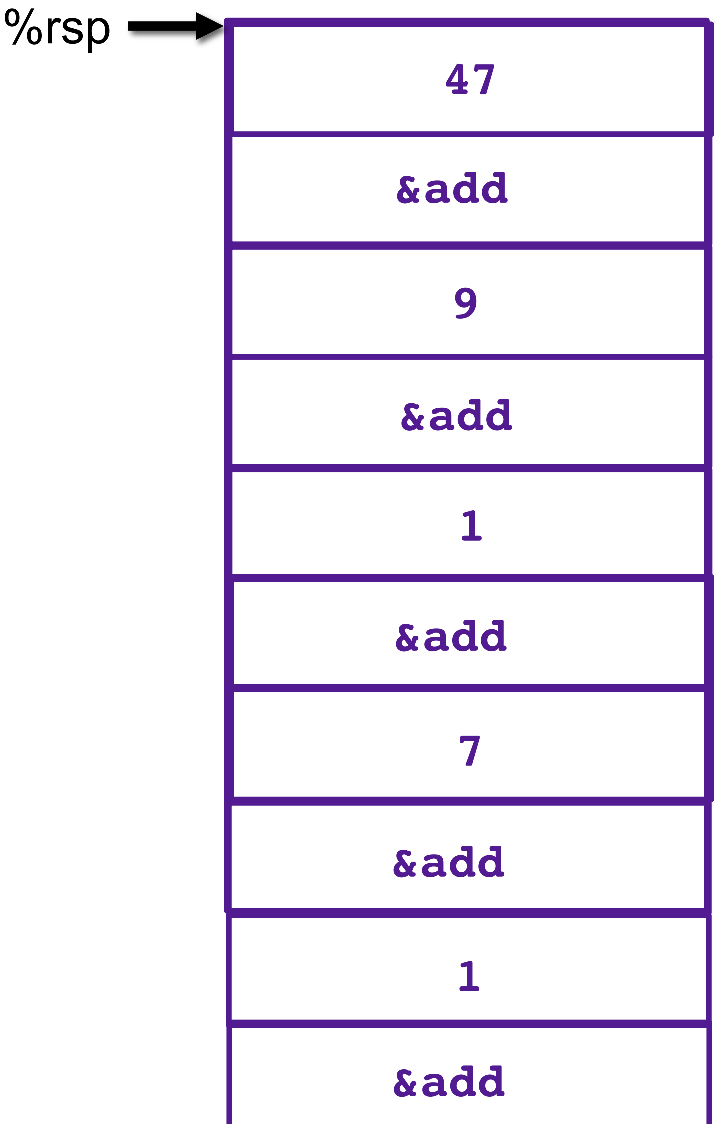
- Handled Without Special Consideration
  - Stack frames mean that each function call has private storage
    - Saved registers & local variables
    - Saved return pointer
  - Register saving conventions prevent one function call from corrupting another's data
    - Unless the C code explicitly does so (more later!)
  - Stack discipline follows call / return pattern
    - If P calls Q, then Q returns before P
    - Last-In, First-Out
- Also works for mutual recursion
  - P calls Q; Q calls P

Array Recursion

```c
int sum_digits_r(int* z, int i){

  if(i >= 5){
    return 0;
  }


  int val = z[i];

  int sum_r = sum_digits_r(z,i+1);

  return sum + val;
}
```

```
sum_digits_r:
  cmp     $4, %rsi
  jle       L2
  mov      $0, %rax
  ret
L2:
  push    %rbx
  mov     (%rdi,%rsi,4), %ebx
  incr     $1, %rsi
  call    sum_digits_r
  add     %ebx, %eax
  pop     %rbx
  ret
```

Example: Array Recursion




```
sum_digits_r:
   cmp     $4, %rsi
   jle       L2
   mov      $0, %rax
   ret
L2:
   push    %rbx
   mov     (%rdi,%rsi,4), %ebx
   incr     $1, %rsi
   call    sum_digits_r
   add     %ebx, %eax
   pop     %rbx
   ret
```