Princeton University

Computer Science 217: Introduction to Programming Systems

Assembly Language: Function Calls

Goals of this Lecture

Help you learn:

- Function call problems
- x86-64 solutions
  - Pertinent instructions and conventions

Function Call Problems

(1) Calling and returning

- How does caller function **jump** to callee function?
- How does callee function **jump back** to the right place in caller function?

(2) Passing arguments

- How does caller function pass **arguments** to callee function?

(3) Storing local variables

- Where does callee function store its **local variables**?

(4) Returning a value

- How does callee function send **return value** back to caller function?
- How does caller function access the **return value**?

(5) Optimization

- How do caller and callee function minimize memory access?

Running Example

```
long absadd(long a, long b)
{
   long absA, absB, sum;
   absA = labs(a);
   absB = labs(b);
   sum = absA + absB;
   return sum;
}
```

Calls standard C `labs()` function

- Returns absolute value of given `long`

Agenda

Calling and returning

Passing arguments

Storing local variables

Returning a value

Optimization

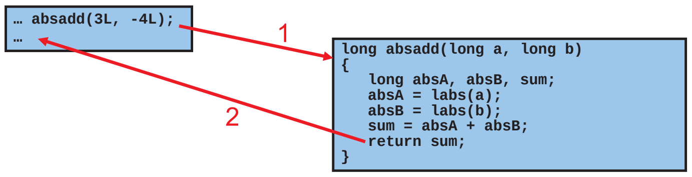
Problem 1: Calling and Returning

How does caller *jump* to callee?

- i.e., Jump to the address of the callee's first instruction

How does the callee *jump back* to the right place in caller?

- i.e., Jump to the instruction immediately following the most-recently-executed call instruction



```
… absadd(3L, -4L);
…
```

```
long absadd(long a, long b)
{
   long absA, absB, sum;
   absA = labs(a);
   absB = labs(b);
   sum = absA + absB;
   return sum;
}
```

Attempted Solution: `jmp` Instruction

Attempted solution: caller and callee use **`jmp`** instruction

```
f:
  …
  jmp g       # Call g
fReturnPoint:
  …
```

```
g:
  …
  jmp fReturnPoint   # Return
```

Attempted Solution: `jmp` Instruction

Problem: callee may be called by multiple callers

```
f1:
  …
  jmp g       # Call g
f1ReturnPoint:
  …
```

```
f2:
  …
  jmp g       # Call g
f2ReturnPoint:
  …
```

```
g:
  …
  jmp ???   # Return
```

Attempted Solution: Use Register

Attempted solution: Store return address in register

```
f1:
  movq $f1ReturnPoint, %rax
  jmp g       # Call g
f1ReturnPoint:
  …
```

```
f2:
  movq $f2ReturnPoint, %rax
  jmp g       # Call g
f2ReturnPoint:
  …
```

```
g:
  …
  jmp *%rax  # Return
```

Special form of **`jmp`** instruction

Attempted Solution: Use Register

Problem: Cannot handle nested function calls

```
f:
  movq $fReturnPoint, %rax
  jmp g       # Call g
fReturnPoint:
  …
```

```
g:
  movq $gReturnPoint, %rax
  jmp h       # Call h
gReturnPoint:
  …
  jmp *%rax  # Return
```

```
h:
  …
  jmp *%rax  # Return
```

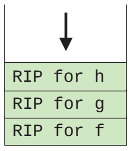
Problem if **`f()`** calls **`g()`**, and **`g()`** calls **`h()`**

Return address **`g()`** -> **`f()`** is lost

x86-64 Solution: Use the Stack

Observations:

- May need to store many return addresses
  - The number of nested function calls is not known in advance
  - A return address must be saved for as long as the invocation of this function is live, and discarded thereafter
- Stored return addresses are destroyed in reverse order of creation
  - **`f()`** calls **`g()`** ⇒ return addr for **g** is stored
  - **`g()`** calls **`h()`** ⇒ return addr for **h** is stored
  - **`h()`** returns to **`g()`** ⇒ return addr for **h** is destroyed
  - **`g()`** returns to **`f()`** ⇒ return addr for **g** is destroyed
- LIFO data structure (stack) is appropriate

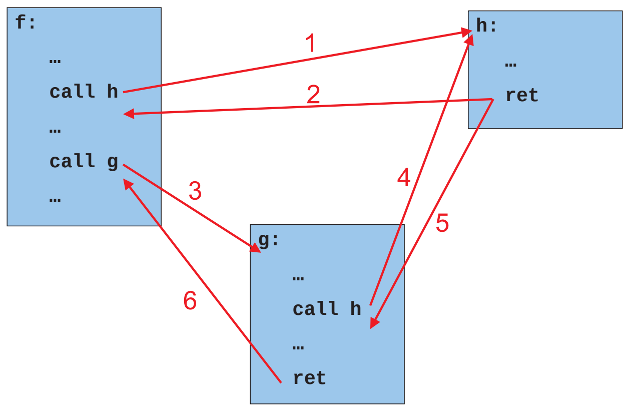


x86-64 solution:

- Use the STACK section of memory, usually accsesed via RSP
- Via **`call`** and **`ret`** instructions

`call` and `ret` Instructions

`ret` instruction "knows" the return address



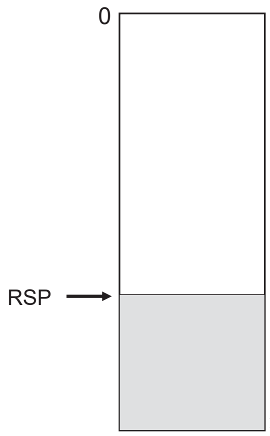
Stack operations

RSP (stack pointer) register
points to top of stack

Instruction	Equivalent to

`pushq src`	`subq $8, %rsp`
	`movq src, (%rsp)`

`popq dest`	`movq (%rsp), dest`
	`addq $8, %rsp`



Implementation of `call`

RIP (instruction pointer) register
points to next instruction
to be executed

Instruction	Equivalent to

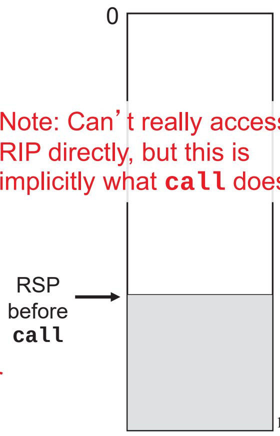
`pushq src`	`subq $8, %rsp`
	`movq src, (%rsp)`

`popq dest`	`movq (%rsp), dest`
	`addq $8, %rsp`

`call addr`	`pushq %rip`
	`jmp addr`

Note: Can't really access RIP directly, but this is implicitly what `call` does

`call` instruction pushes return addr (old RIP) onto stack, then jumps



Implementation of `call`

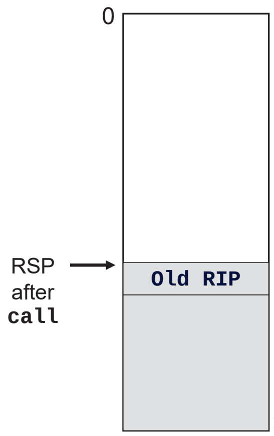
RIP (instruction pointer) register
points to next instruction
to be executed

Instruction	Equivalent to

`pushq src`	`subq $8, %rsp`
	`movq src, (%rsp)`

`popq dest`	`movq (%rsp), dest`
	`addq $8, %rsp`

`call addr`	`pushq %rip`
	`jmp addr`



Implementation of `ret`

RIP (instruction pointer) register
points to next instruction
to be executed

Instruction	Equivalent to

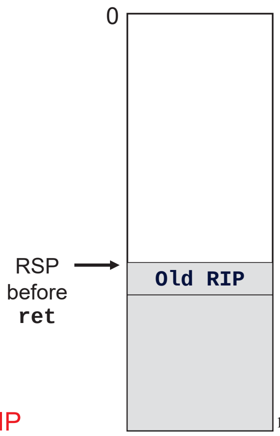
`pushq src`	`subq $8, %rsp`
	`movq src, (%rsp)`

`popq dest`	`movq (%rsp), dest`
	`addq $8, %rsp`

`call addr`	`pushq %rip`
	`jmp addr`

`ret`	`popq %rip`

`ret` instruction pops stack, thus placing return addr (old RIP) into RIP



Implementation of `ret`

RIP (instruction pointer) register
points to next instruction
to be executed

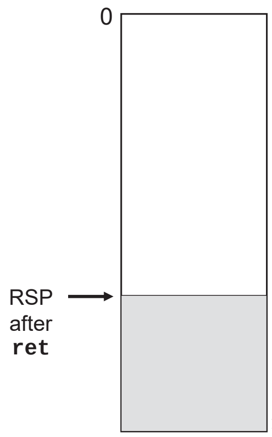
Instruction	Equivalent to

`pushq src`	`subq $8, %rsp`
	`movq src, (%rsp)`

`popq dest`	`movq (%rsp), dest`
	`addq $8, %rsp`

`call addr`	`pushq %rip`
	`jmp addr`

`ret`	`popq %rip`



Running Example

```
# long absadd(long a, long b)
absadd:
   # long absA, absB, sum
   …
   # absA = labs(a)
   …
   call labs
   …
   # absB = labs(b)
   …
   call labs
   …
   # sum = absA + absB
   …
   # return sum
   …
   ret
```

Agenda

Calling and returning

Passing arguments

Storing local variables

Returning a value

Optimization

Problem 2: Passing Arguments

Problem:
- How does caller pass *arguments* to callee?
- How does callee accept *parameters* from caller?

```
long absadd(long a, long b)
{
   long absA, absB, sum;
   absA = labs(a);
   absB = labs(b);
   sum = absA + absB;
   return sum;
}
```

x86-64 Solution 1: Use the Stack

Observations (déjà vu):
- May need to store many arg sets
  - The number of arg sets is not known in advance
  - Arg set must be saved for as long as the invocation of this function is live, and discarded thereafter
- Stored arg sets are destroyed in reverse order of creation
- LIFO data structure (stack) is appropriate

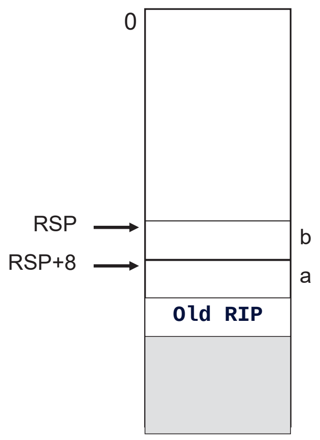
x86-64 Solution 2: Use Registers

x86-64 solution:
- Pass first 6 (integer or address) arguments in registers for efficiency
  - RDI, RSI, RDX, RCX, R8, R9
- More than 6 arguments ⇒
  - Pass arguments 7, 8, … on the stack
  - (Beyond scope of COS 217)
- Arguments are structures ⇒
  - Pass arguments on the stack
  - (Beyond scope of COS 217)

Callee function then saves arguments to stack
- Or maybe not!
  - See “optimization” later this lecture
- Callee accesses arguments as positive offsets vs. RSP

Running Example

```
# long absadd(long a, long b)
absadd:
   pushq %rdi # Push a
   pushq %rsi # Push b

   # long absA, absB, sum
   …
   # absA = labs(a)
   movq 8(%rsp), %rdi
   call labs
   …
   # absB = labs(b)
   movq 0(%rsp), %rdi
   call labs
   …
   # sum = absA + absB
   …
   # return sum
   …
   addq $16, %rsp
   ret
```



Agenda

Calling and returning

Passing arguments

Storing local variables

Returning a value

Optimization

Problem 3: Storing Local Variables

Where does callee function store its *local variables?*

```
long absadd(long a, long b)
{
   long absA, absB, sum;
   absA = labs(a);
   absB = labs(b);
   sum = absA + absB;
   return sum;
}
```

x86-64 Solution: Use the Stack

Observations (déjà vu again!):

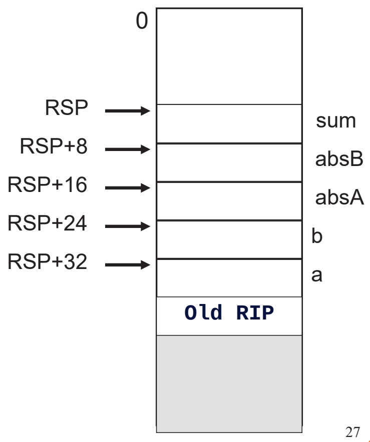
- May need to store many local var sets
  - The number of local var sets is not known in advance
  - Local var set must be saved for as long as the invocation of this function is live, and discarded thereafter
- Stored local var sets are destroyed in reverse order of creation
- LIFO data structure (stack) is appropriate

x86-64 solution:

- Use the STACK section of memory
- Or maybe not!
  - See later this lecture

Running Example

```
# long absadd(long a, long b)
absadd:
   pushq %rdi # Push a
   pushq %rsi # Push b

   # long absA, absB, sum
   subq $24, %rsp

   # absA = labs(a)
   movq 32(%rsp), %rdi
   call labs
   …
   # absB = labs(b)
   movq 24(%rsp), %rdi
   call labs
   …
   # sum = absA + absB
   movq 16(%rsp), %rax
   addq 8(%rsp), %rax
   movq %rax, 0(%rsp)
   …
   # return sum
   …
   addq $40, %rsp
   ret
```



Agenda

Calling and returning

Passing arguments

Storing local variables

Returning a value

Optimization

Problem 4: Return Values

Problem:

- How does callee function send return value back to caller function?
- How does caller function access return value?

```
long absadd(long a, long b)
{
   long absA, absB, sum;
   absA = labs(a);
   absB = labs(b);
   sum = absA + absB;
   return sum;
}
```

x86-64 Solution: Use RAX

In principle

- Store return value in stack frame of caller

Or, for efficiency

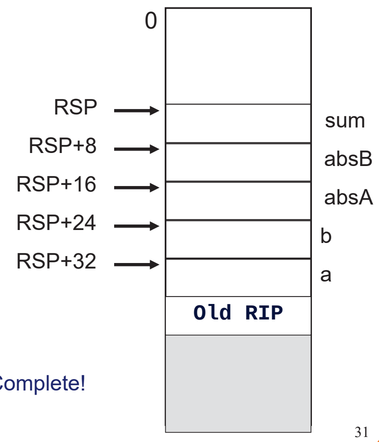
- Known small size ⇒ store return value in register
- Other ⇒ store return value in stack

x86-64 convention

- Integer or address:
  - Store return value in RAX
- Floating-point number:
  - Store return value in floating-point register
  - (Beyond scope of COS 217)
- Structure:
  - Store return value on stack
  - (Beyond scope of COS 217)

Running Example

```
# long absadd(long a, long b)
absadd:
   pushq %rdi # Push a
   pushq %rsi # Push b

   # long absA, absB, sum
   subq $24, %rsp

   # absA = labs(a)
   movq 32(%rsp), %rdi
   call labs
   movq %rax, 16(%rsp)

   # absB = labs(b)
   movq 24(%rsp), %rdi
   call labs
   movq %rax, 8(%rsp)

   # sum = absA + absB
   movq 16(%rsp), %rax
   addq 8(%rsp), %rax
   movq %rax, 0(%rsp)

   # return sum
   movq 0(%rsp), %rax
   addq $40, %rsp
   ret
```



Complete!

Agenda

Calling and returning

Passing arguments

Storing local variables

Returning a value

Optimization

Problem 5: Optimization

Observation: Accessing memory is expensive
- More expensive than accessing registers
- For efficiency, want to store parameters and local variables in registers (and not in memory) when possible

Observation: Registers are a finite resource
- In principle: Each function should have its own registers
- In reality: All functions share same small set of registers

Problem: How do caller and callee use same set of registers without interference?
- Callee may use register that the caller also is using
- When callee returns control to caller, old register contents may have been lost
- Caller function cannot continue where it left off

x86-64 Solution: Register Conventions

Callee-save registers
- RBX, RBP, R12, R13, R14, R15
- Callee function ***must preserve*** contents
- If necessary…
  - Callee saves to stack near beginning
  - Callee restores from stack near end

Caller-save registers
- RDI, RSI, RDX, RCX, R8, R9, RAX, R10, R11
- Callee function ***can change*** contents
- If necessary…
  - Caller saves to stack before call
  - Caller restores from stack after call

Running Example

Local variable handling in *unoptimized* version:
- At beginning, **absadd()** allocates space for local variables (**absA**, **absB**, **sum**) on stack
- Body of **absadd()** uses stack
- At end, **absadd()** pops local variables from stack

Local variable handling in *optimized* version:
- **absadd()** keeps local variables in R13, R14, R15
- Body of **absadd()** uses R13, R14, R15
- Must be careful:
  - **absadd()**cannot change contents of R13, R14, or R15
  - So **absadd()** must save R13, R14, and R15 near beginning, and restore near end

Running Example

```
# long absadd(long a, long b)
absadd:
   pushq %r13 # Save R13, use for absA
   pushq %r14 # Save R14, use for absB
   pushq %r15 # Save R15, use for sum

   # absA = labs(a)
   pushq %rsi # Save RSI
   call labs
   movq %rax, %r13
   popq %rsi  # Restore RSI

   # absB += labs(b)
   movq %rsi, %rdi
   call labs
   movq %rax, %r14

   # sum = absA + absB
   movq %r13, %r15
   addq %r14, %r15

   # return sum
   movq %r15, %rax
   popq %r15 # Restore R15
   popq %r14 # Restore R14
   popq %r13 # Restore R13
   ret
```

absadd() stores local vars in R13, R14, R15, not in memory

absadd() cannot destroy contents of R13, R14, R15

So **absadd()** must save R13, R14, R15 near beginning and restore near end

Running Example

Parameter handling in *unoptimized* version:

- **`absadd()`** accepts parameters (**a** and **b**) in RDI and RSI
- At beginning**,** **`absadd()`** copies contents of RDI and RSI to stack
- Body of **`absadd()`** uses stack
- At end, **`absadd()`** pops parameters from stack

Parameter handling in *optimized* version:

- **`absadd()`** accepts parameters (**a** and **b**) in RDI and RSI
- Body of **`absadd()`** uses RDI and RSI
- Must be careful:
  - Call of **`labs()`** could change contents of RDI and/or RSI
  - **`absadd()`** must save contents of RDI and/or RSI before call of **`labs()`**, and restore contents after call

Running Example

```
# long absadd(long a, long b)
absadd:
   pushq %r13 # Save R13, use for absA
   pushq %r14 # Save R14, use for absB
   pushq %r15 # Save R15, use for sum

   # absA = labs(a)
   pushq %rsi # Save RSI
   call labs
   movq %rax, %r13
   popq %rsi  # Restore RSI

   # absB += labs(b)
   movq %rsi, %rdi
   call labs
   movq %rax, %r14

   # sum = absA + absB
   movq %r13, %r15
   addq %r14, %r15

   # return sum
   movq %r15, %rax
   popq %r15 # Restore R15
   popq %r14 # Restore R14
   popq %r13 # Restore R13
   ret
```

`absadd()` keeps a and b in RDI and RSI, not in memory

`labs()` can change RDI and/or RSI

`absadd()` must retain contents of RSI (value of b) across 1st call of labs()

So **`absadd()`** must save RSI before call and restore RSI after call

Non-Optimized vs. Optimized Patterns

Unoptimized pattern

- Parameters and local variables strictly in memory (stack) during function execution
- **Pro**: Always possible
- **Con**: Inefficient
- gcc compiler uses when invoked without –O option

Optimized pattern

- Parameters and local variables mostly in registers during function execution
- **Pro**: Efficient
- **Con**: Sometimes impossible
  - More than 6 local variables
  - Local variable is a structure or array
  - Function computes address of parameter or local variable
- gcc compiler uses when invoked with –O option, when it can!

Hybrid Patterns

Hybrids are possible

- Example
  - Parameters in registers
  - Local variables in memory (stack)

Hybrids are error prone for humans

- Example (continued from previous)
  - Step 1: Access local variable ← local var is at stack offset X
  - Step 2: Push caller-save register
  - Step 3: Access local variable ← local var is at stack offset X+8!!!
  - Step 4: Call **`labs()`**
  - Step 6: Access local variable ← local var is at stack offset X+8!!!
  - Step 7: Pop caller-save register
  - Step 8: Access local variable ← local var is at stack offset X

Avoid hybrids for Assignment 4

Summary

Function calls in x86-64 assembly language

Calling and returning

- **`call`** instruction pushes RIP onto stack and jumps
- **`ret`** instruction pops from stack to RIP

Passing arguments

- Caller copies args to caller-saved registers (in prescribed order)
- Unoptimized pattern:
  - Callee pushes args to stack
  - Callee uses args as positive offsets from RSP
  - Callee pops args from stack
- Optimized pattern:
  - Callee keeps args in caller-saved registers
  - Be careful!

Summary (cont.)

Storing local variables

- Unoptimized pattern:
  - Callee pushes local vars onto stack
  - Callee uses local vars as positive offsets from RSP
  - Callee pops local vars from stack
- Optimized pattern:
  - Callee keeps local vars in callee-saved registers
  - Be careful!

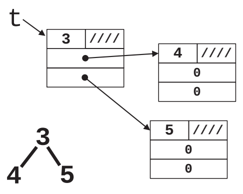
Returning values

- Callee places return value in RAX
- Caller accesses return value in RAX

Putting it all together

Add up the keys of a tree

```
struct tree {
    int key;
    struct tree *left;
    struct tree *right;
};

int sum (struct tree *t) {
  if (t==NULL)
       return 0;
  else return t->key +
              sum(t->left) +
              sum(t->right);
}
```



```
          .text
          .globl    sum
sum:
# LOCAL VARIABLES:
#  %r12=t, %r13d=partial sum
          pushq     %r12
          pushq     %r13
          movq      %rdi, %r12
          cmpq      $0, %r12
          jne       .L2
          movl      $0, %eax
          jmp       .L3
.L2:
          movl      0(%r12), %r13d
          movq      8(%r12), %rdi
          call      sum
          addl      %eax, %r13d
          movq      16(%r12), %rdi
          call      sum
          addl      %eax, %r13d
          movl      %r13d, %eax
.L3:
          popq      %r13
          popq      %r12
          ret
```