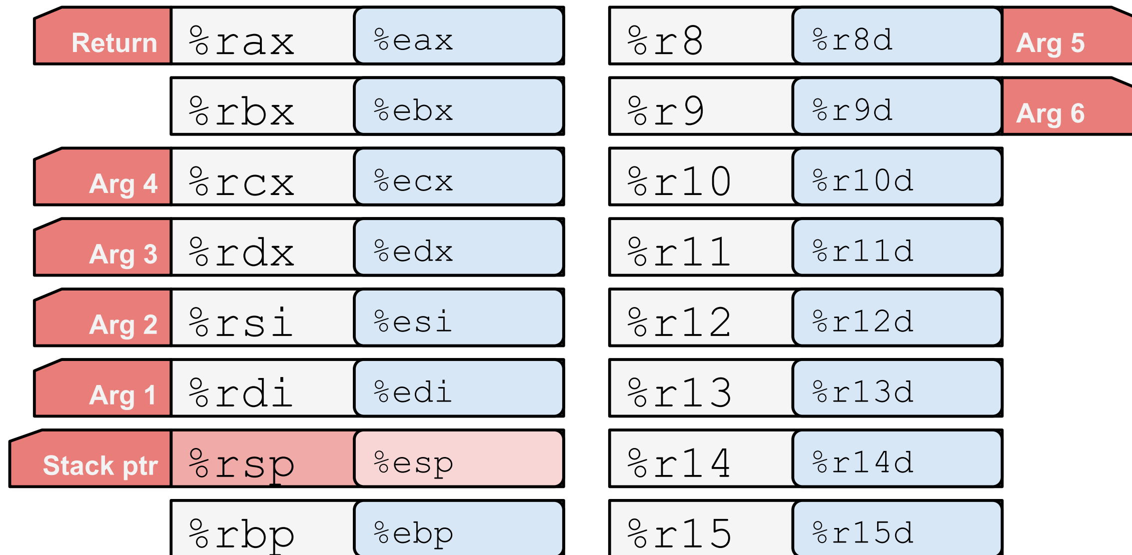
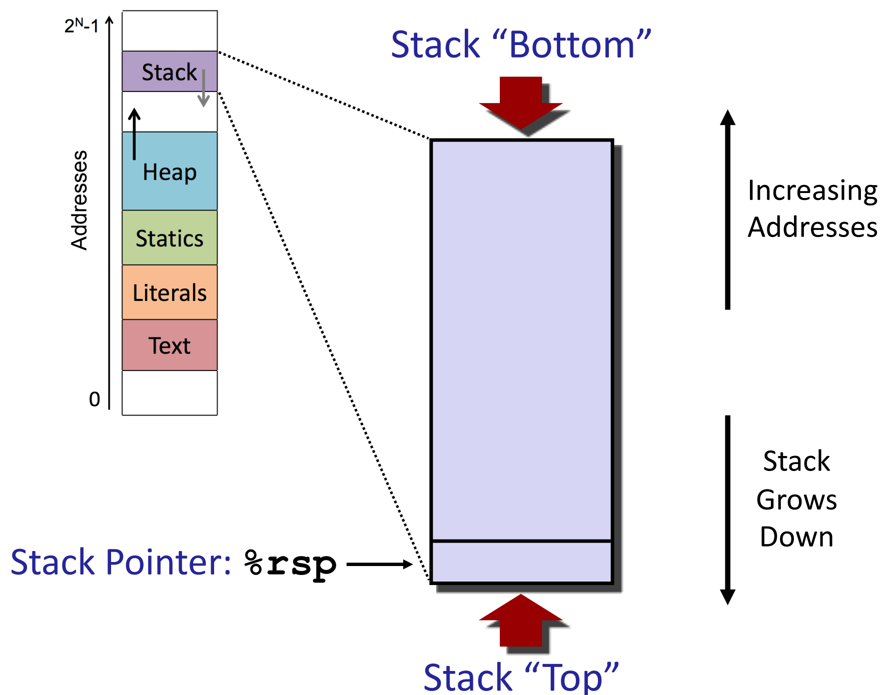
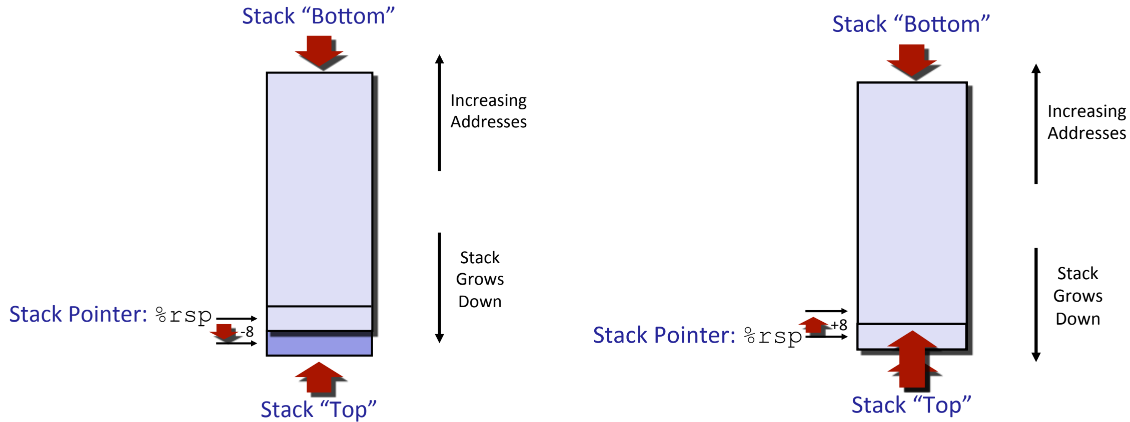
Machine Code: Procedures



Call Stack



Stack Operations



pushq Src

1. Decrement `%rsp` by 8
2. Write **Src** to `(%rsp)`

popq Dest

1. Read `(%rsp)` to **Dest**
2. Increment `%rsp` by 8

Procedure Call Example

```
long x = add(3, 5);
doSomething(x);
```

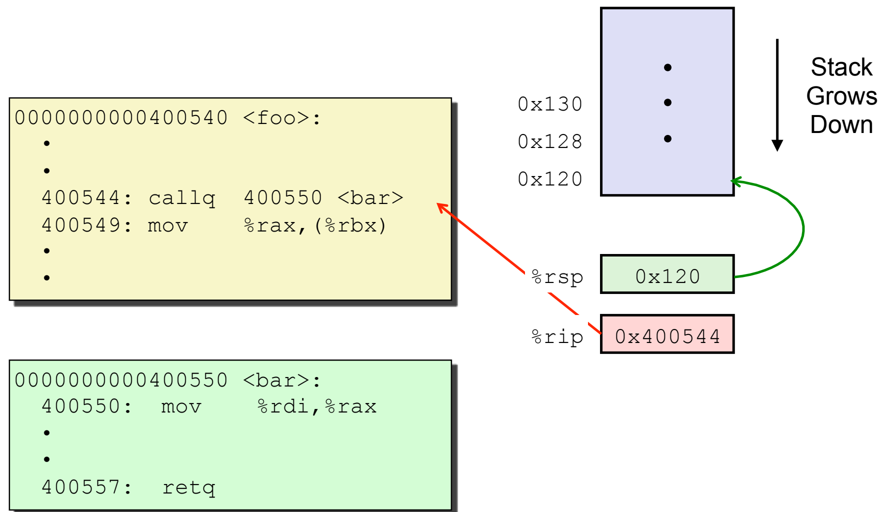
```
long add(long x, long y) {
  return x + y;
}
```

```
movq $3, %rdi
movq $5, %rsi
callq add          push retaddr
movq %rax, %rdi
callq doSomething
```

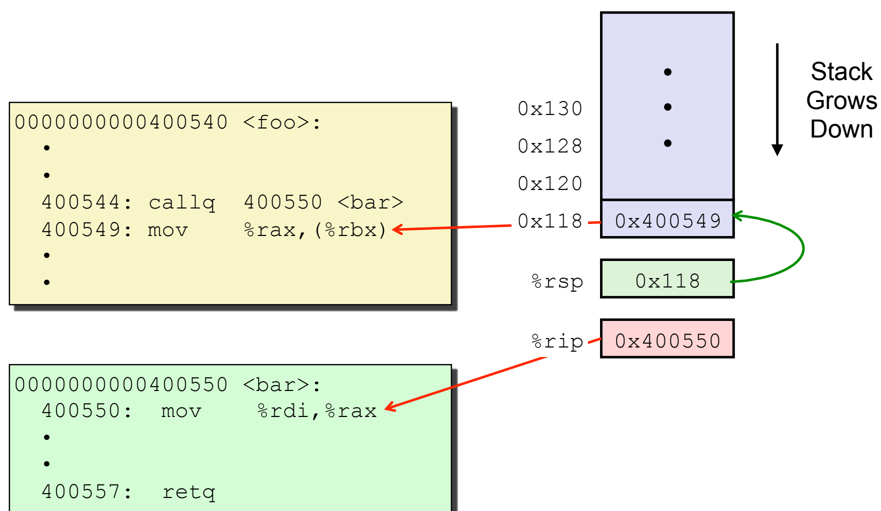
return address

```
add:
  movq %rdi, %rax
  addq %rsi, %rax
  retq             pop retaddr & jump
```

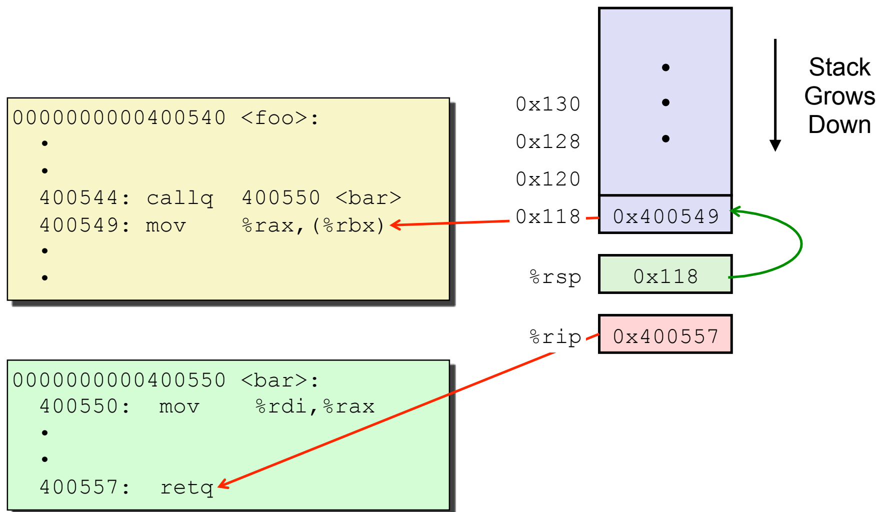
Procedure Call Return Addresses (1)



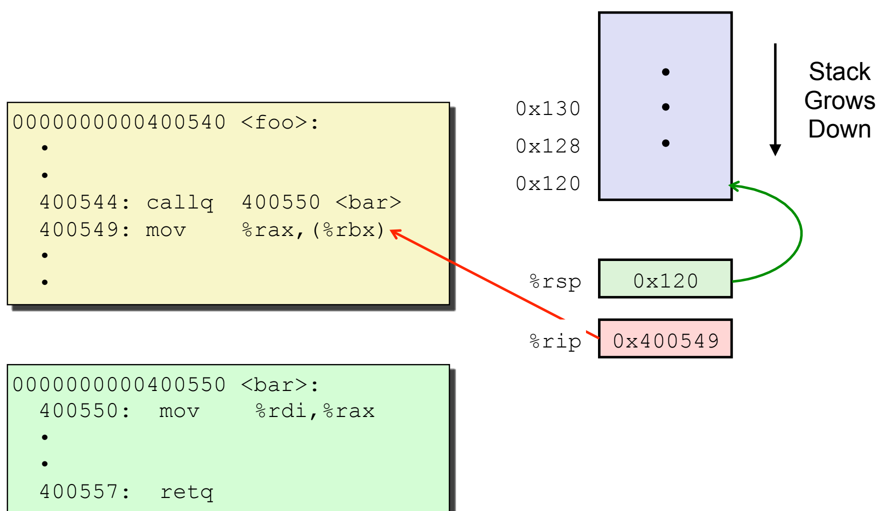
Procedure Call Return Addresses (2)



Procedure Call Return Addresses (3)



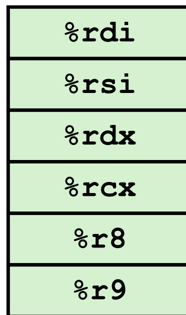
Procedure Call Return Addresses (4)



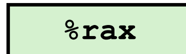
Passing Data

Registers

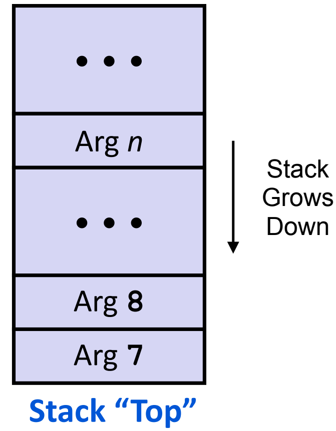
- **First 6 arguments**



- **Return value**

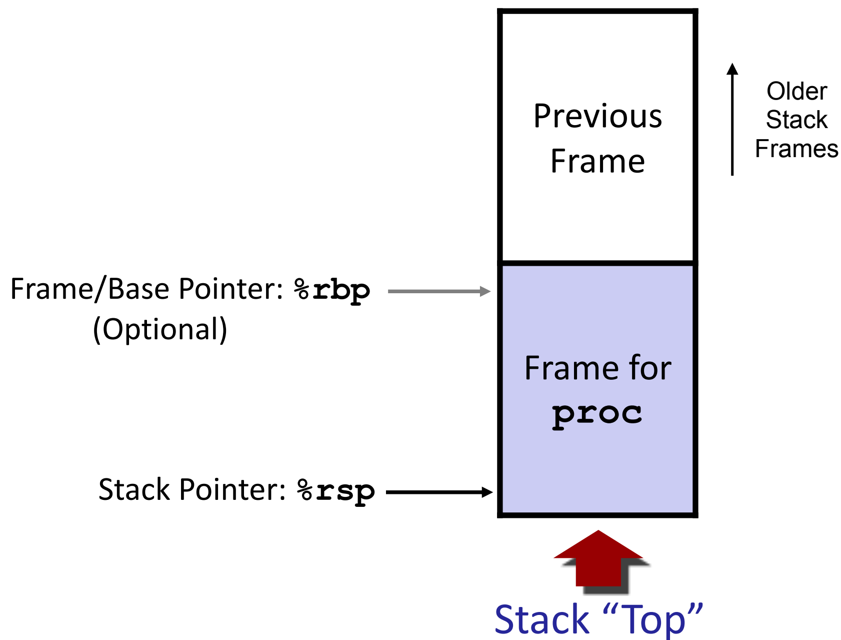


Stack

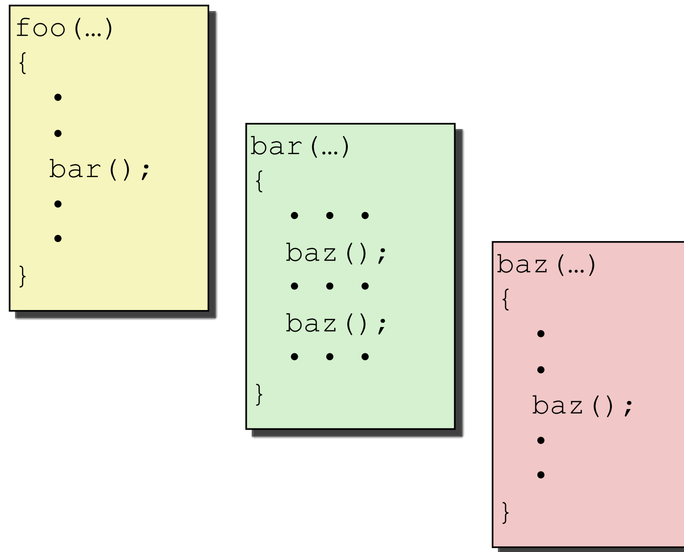


Stack "Top"

Stack Frames

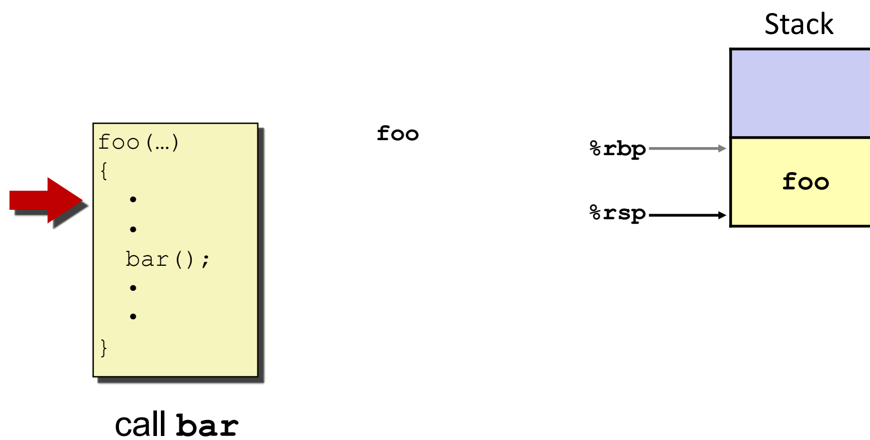


Call Chain Example

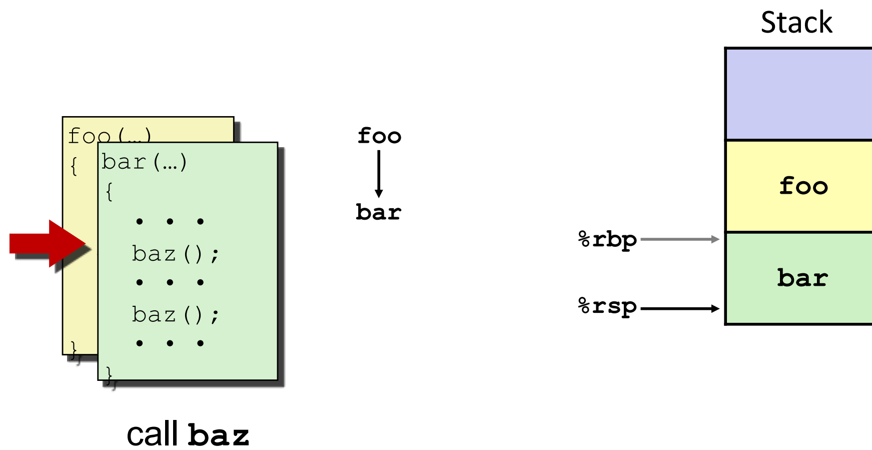


Procedure **baz()** is recursive

Stack Frame Allocation (1)

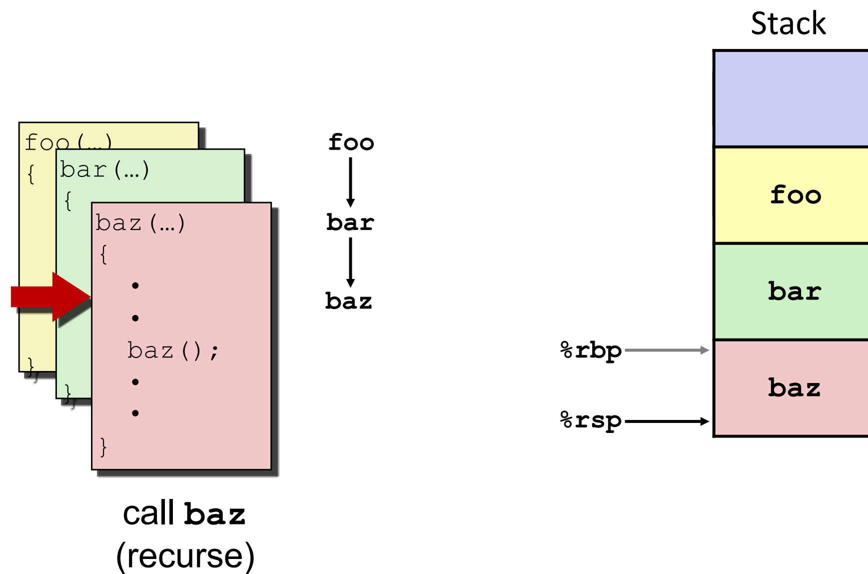


Stack Frame Allocation (2)



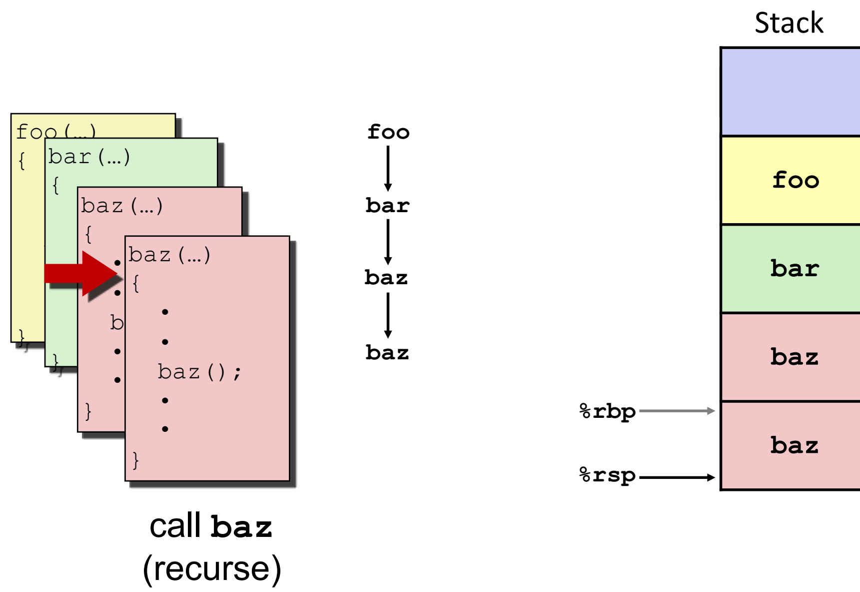
call **baz**

Stack Frame Allocation (3)



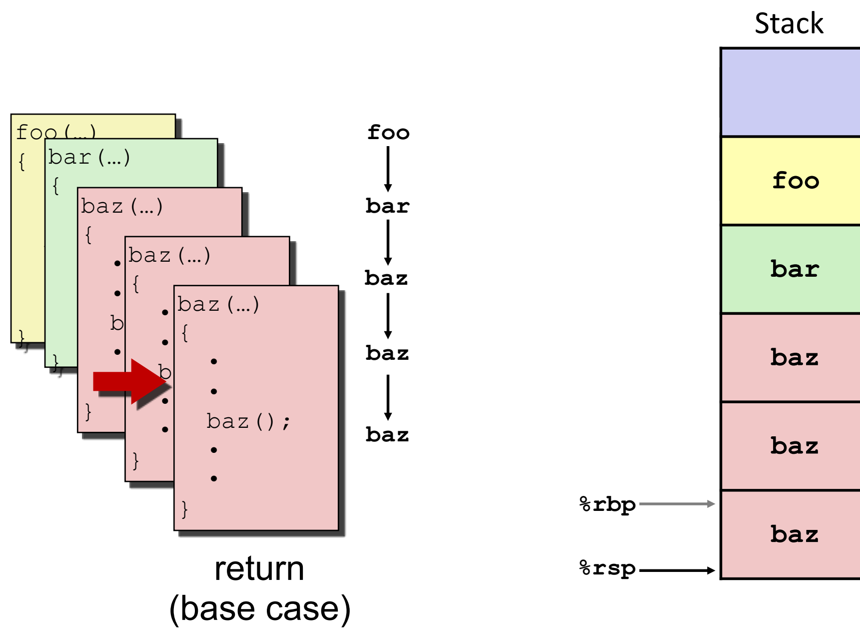
call **baz**
(recurse)

Stack Frame Allocation (4)



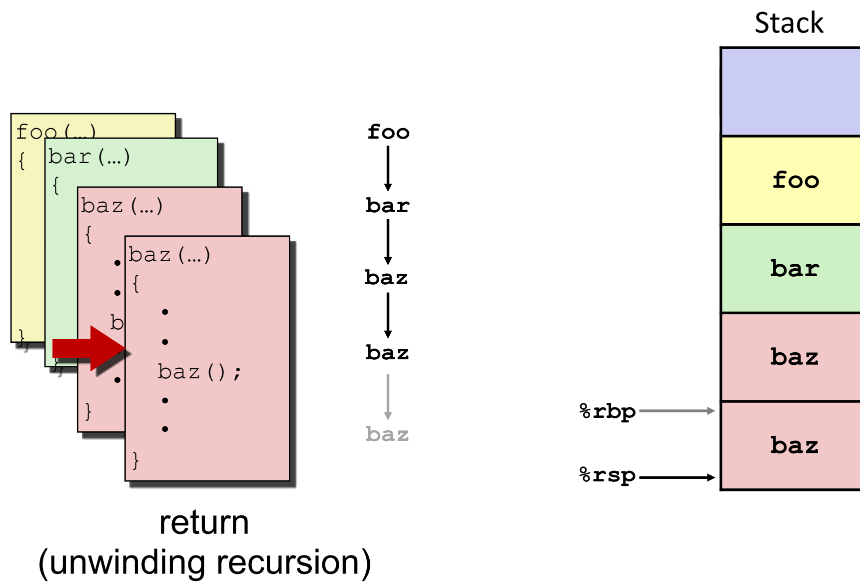
call **baz**
(recurse)

Stack Frame Allocation (5)



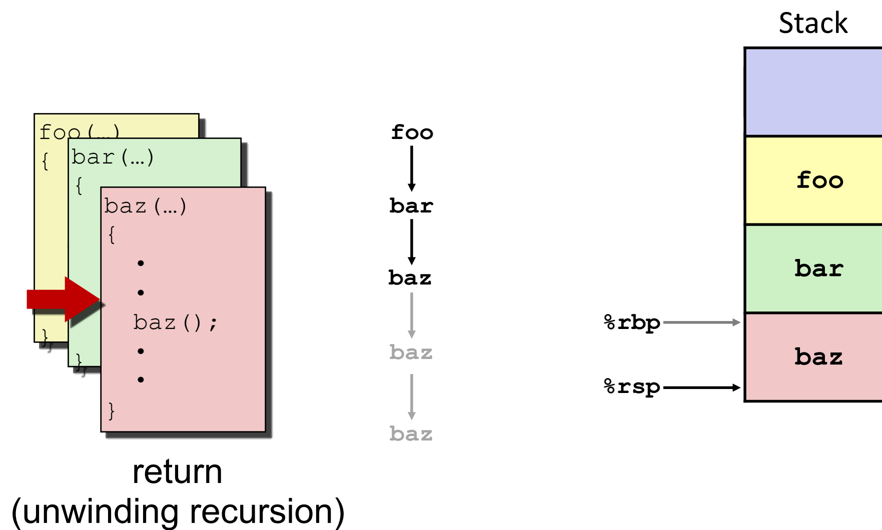
return
(base case)

Stack Frame Allocation (6)



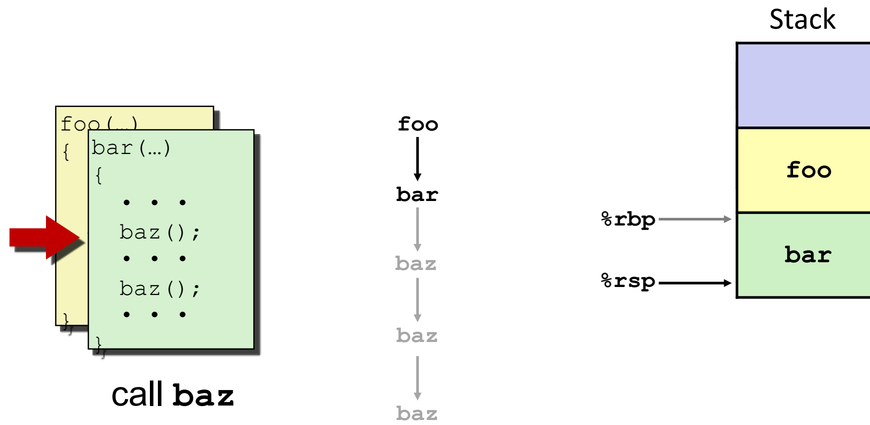
return
(unwinding recursion)

Stack Frame Allocation (7)

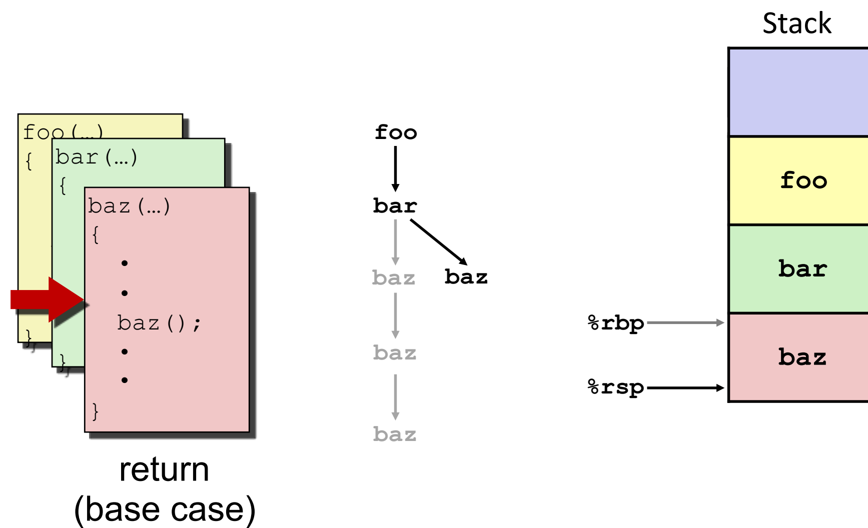


return
(unwinding recursion)

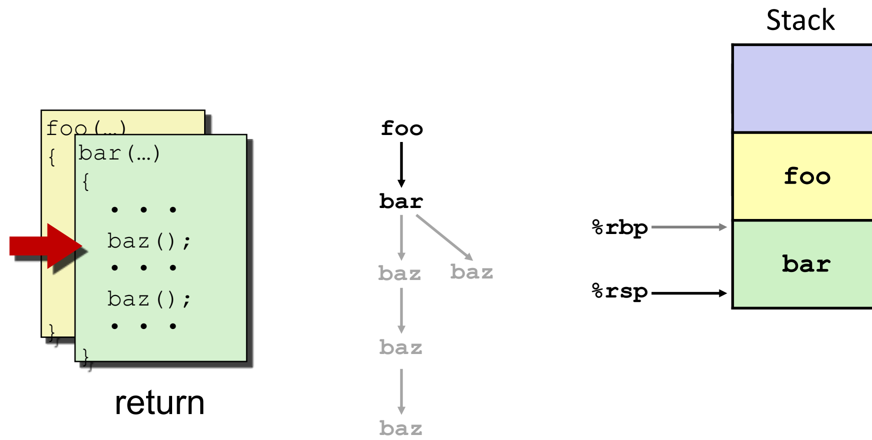
Stack Frame Allocation (8)



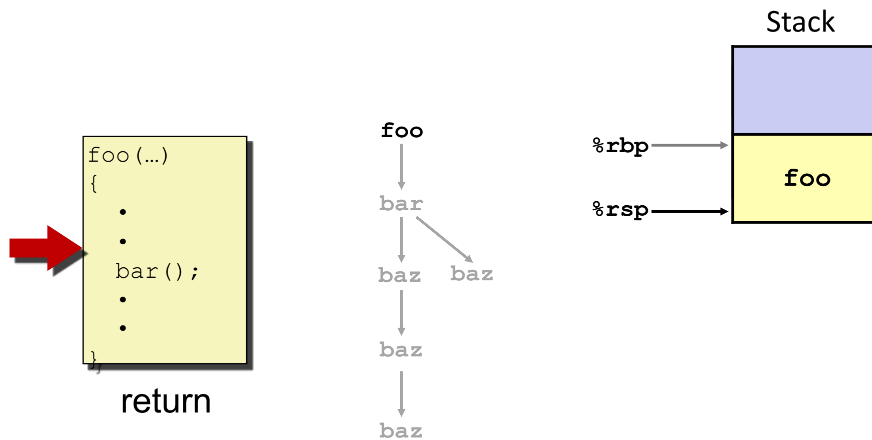
Stack Frame Allocation (9)



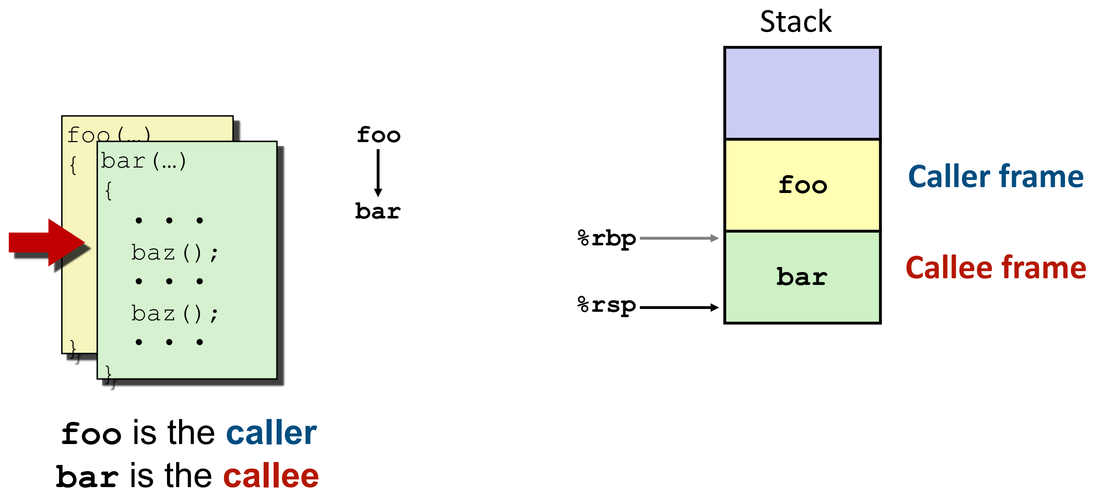
Stack Frame Allocation (10)



Stack Frame Allocation (11)

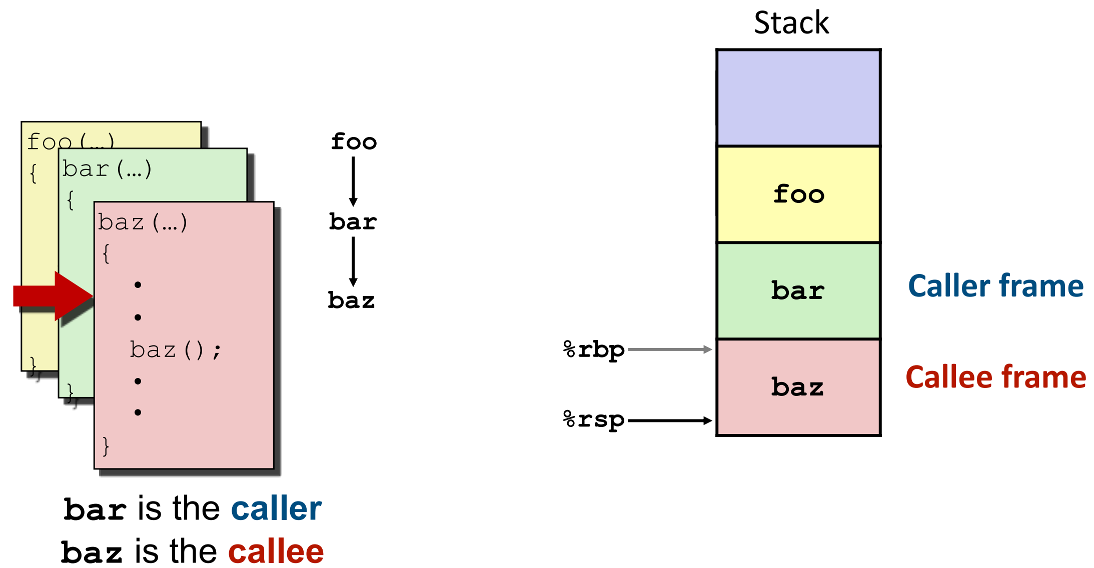


Caller vs. Callee (1)



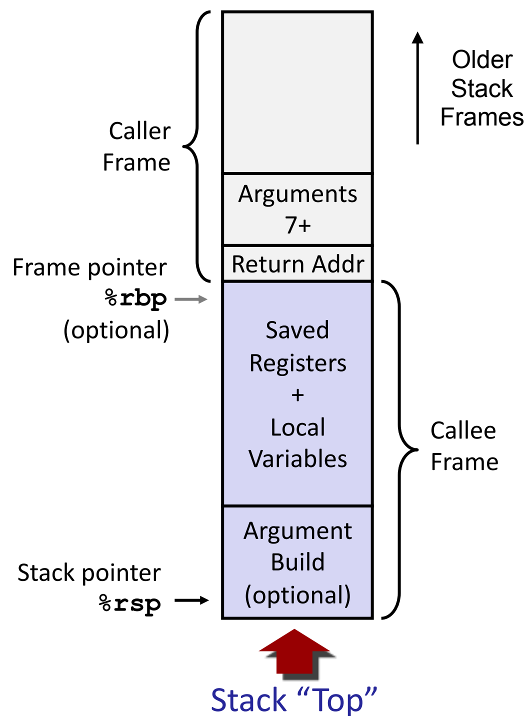
foo is the **caller**
bar is the **callee**

Caller vs. Callee (2)



bar is the **caller**
baz is the **callee**

Stack Frame Components



Stack “Top”

Using the Stack (1)

```
long incr(long* p, long val) {
    long x = *p;
    long y = x + val;
    *p = y;
    return x;
}
```

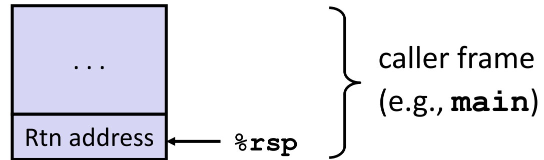
```
incr:
  movq    (%rdi), %rax
  addq    %rax, %rsi
  movq    %rsi, (%rdi)
  ret
```

Register	Use(s)
`%rdi`	Argument **p**
`%rsi`	Argument **val**, **y**
`%rax`	**x**, Return value

Using the Stack (2)

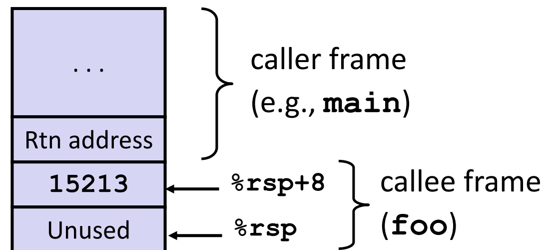
```
long foo() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

Initial Stack Structure




```
foo:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Resulting Stack Structure

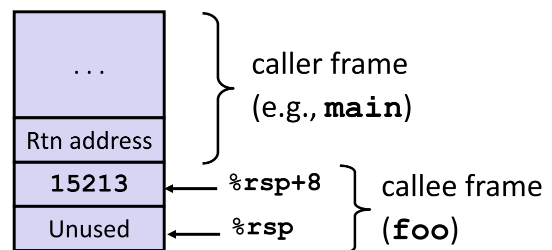


Using the Stack (3)

```
long foo() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

```
foo:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Stack Structure

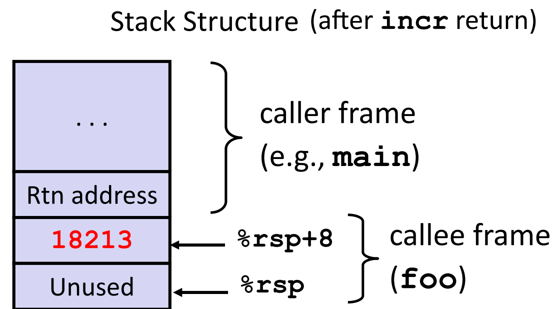


Register	Use(s)
%rdi	&v1
%rsi	3000

Using the Stack (4)

```
long foo() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

Stack Structure (after **incr** return)




```
foo:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

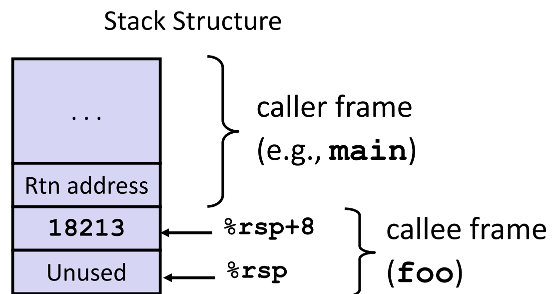
Register	Use(s)
%rdi	&v1
%rsi	3000

```
incr:
  movq    (%rdi), %rax
  addq    %rax, %rsi
  movq    %rsi, (%rdi)
  ret
```


Using the Stack (5)

```
long foo() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

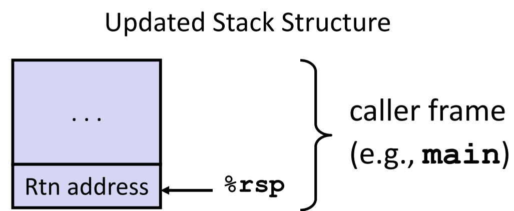
Stack Structure




```
foo:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Register	Use(s)
%rax	Return value

Updated Stack Structure

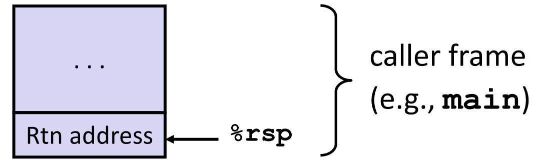


Using the Stack (6)

```
long foo() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

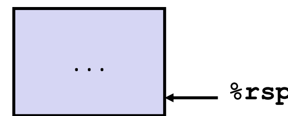
```
foo:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Updated Stack Structure

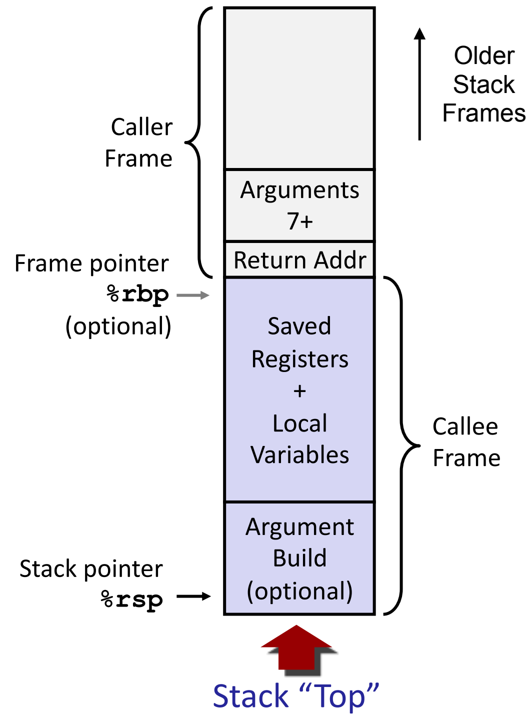


Register	Use(s)
%rax	Return value

Final Stack Structure



Stack Frame Components



Saved Registers

```
alice:
   movq X, %reg    # compute X
   callq bob
   movq %reg, ... # use X
```

Could overwrite %reg!

Caller-Saved %reg

```
alice:
   movq X, %reg # compute X
   pushq %reg   # save X
   callq bob    # might change X
   popq %reg    # restore X
   movq %reg, ... # use X
```

Callee-Saved %reg

```
alice:
   pushq %reg    # save caller's
   movq X, %reg # compute X
   callq bob     # preserves X
   movq %reg, ... # use X
   popq %reg     # restore caller
```


Caller-Saved vs. Callee-Saved (1)

```
alice:
   movq X, %reg    # compute X
   callq bob
   ...    # don't need X again
```

Caller-Saved %reg

```
alice:
   movq X, %reg # compute X
   callq bob    # might change X
   ...    # don't need X again
```

Skip save/restore!

Callee-Saved %reg

```
alice:
   pushq %reg    # save caller's
   movq X, %reg # compute X
   callq bob     # preserves X
   ...
   popq %reg     # restore caller
```

Caller-Saved vs. Callee-Saved (2)

```
alice:
   movq X, %reg   # compute X
   callq bob
   movq %reg, ... # use X
   callq charlie
   movq %reg, ... # use X
```

Caller-Saved %reg

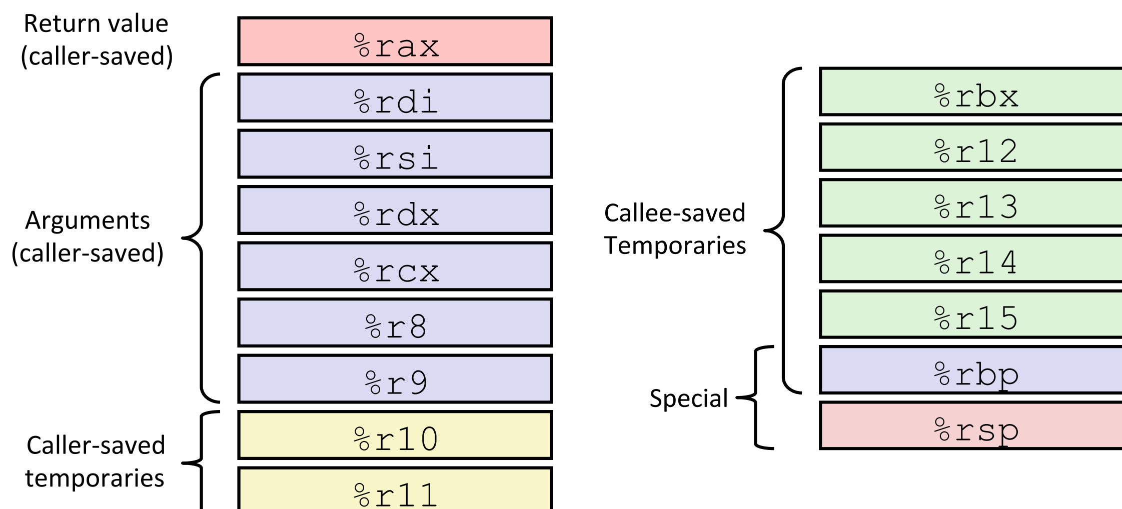
```
alice:
   movq X, %reg # compute X
   pushq %reg    # save X
   callq bob     # might change X
   popq %reg     # restore X
   movq %reg, ... # use X
   pushq %reg    # save X
   callq charlie # might change
   popq %reg     # restore X
   movq %reg, ... # use X
```

Callee-Saved %reg

```
alice:
   pushq %reg    # save caller's
   movq X, %reg # compute
   callq bob     # preserves X
   movq %reg, ... # use X
   callq charlie  # preserves X
   movq %reg, ... # use X
   popq %reg     # restore caller
```

Only one save/restore!

Register Saving Conventions

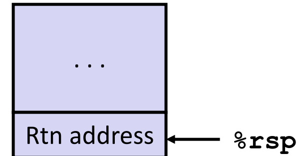


Callee-Saved Example (1)

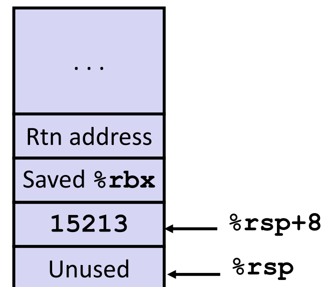
```
long foo2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
foo2:
  pushq   %rbx
  subq    $16, %rsp
  movq    %rdi, %rbx
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    %rbx, %rax
  addq    $16, %rsp
  popq    %rbx
  ret
```

Initial Stack Structure



Resulting Stack Structure

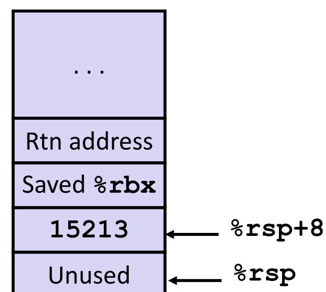


Callee-Saved Example (2)

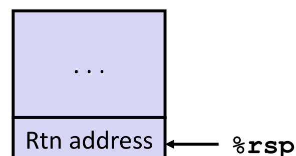
```
long foo2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
foo2:
  pushq   %rbx
  subq    $16, %rsp
  movq    %rdi, %rbx
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    %rbx, %rax
  addq    $16, %rsp
  popq    %rbx
  ret
```

Resulting Stack Structure



Pre-return Stack Structure



Recursive Example

```
/* recursive bitcount */
long bitcount_r(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    long bit = x & 1;
    long rest = bitcount_r(x >> 1);
    return bit + rest;
  }
}
```

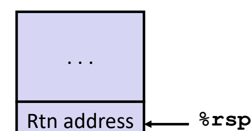
```
bitcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi
  call    bitcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  ret
```


Recursive Base Case

```
/* recursive bitcount */
long bitcount_r(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    long bit = x & 1;
    long rest = bitcount_r(x >> 1);
    return bit + rest;
  }
}
```

```
bitcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi
  call    bitcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  ret
```

Register	Use(s)	Type
%rdi	x	Argument
%rax	Return value	Return value



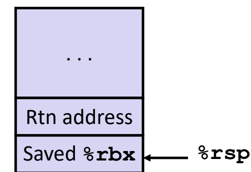
Recursive Register Save

```
/* recursive bitcount */
long bitcount_r(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    long bit = x & 1;
    long rest = bitcount_r(x >> 1);
    return bit + rest;
  }
}
```

```
bitcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi
  call    bitcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  ret
```

Register	Use(s)	Type
%rbx	Caller's value	Callee-saved

Caller's value!

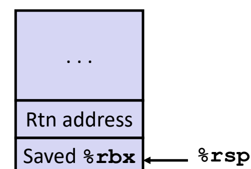


Recursive Call Setup

```
/* recursive bitcount */
long bitcount_r(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    long bit = x & 1;
    long rest = bitcount_r(x >> 1);
    return bit + rest;
  }
}
```

```
bitcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi
  call    bitcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  ret
```

Register	Use(s)	Type
%rbx	x & 1	Callee-saved
%rdi	x >> 1	Recursive arg

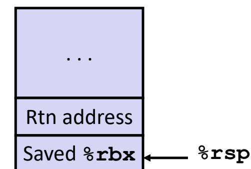


Recursive Call

```
/* recursive bitcount */
long bitcount_r(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    long bit = x & 1;
    long rest = bitcount_r(x >> 1);
    return bit + rest;
  }
}
```

```
bitcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi
  call    bitcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  ret
```

Register	Use(s)	Type
%rbx	x & 1	Callee-saved
%rax	Subcall result	Return value

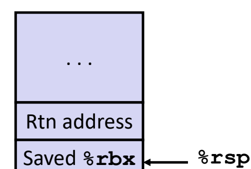


Recursive Result

```
/* recursive bitcount */
long bitcount_r(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    long bit = x & 1;
    long rest = bitcount_r(x >> 1);
    return bit + rest;
  }
}
```

```
bitcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi
  call    bitcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  ret
```

Register	Use(s)	Type
%rbx	x & 1	Callee-saved
%rax	Combined result	Return value

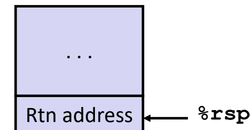


Recursive Completion

```
/* recursive bitcount */
long bitcount_r(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    long bit = x & 1;
    long rest = bitcount_r(x >> 1);
    return bit + rest;
  }
}
```

```
bitcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi
  call    bitcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  ret
```

Register	Use(s)	Type
%rax	Combined result	Return value



Caller/Callee-Saved Example

```
void compute() {
  int x = 5;
  int y = do_work(x);
  do_work(y);
  do_work(y);
  do_work(y);
}
```

Register for x? **Caller-saved**

Register for y? **Callee-saved**

Saved by compute? **just y register**

Stack Frame Components