## CS 105
## "Tour of the Black Holes of Computing"

# Machine-Level Programming III: Procedures

**Topics**

- x86-64 stack discipline
- Register-saving conventions
- Creating pointers to local variables

## Mechanisms in Procedures

**Passing control**

- To beginning of procedure code
- Back to calling point

**Passing data**

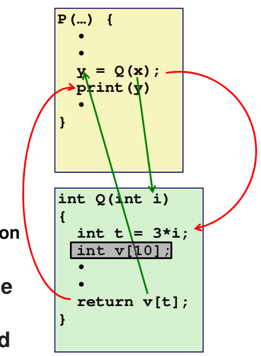
- Procedure arguments
- Return value

**Memory management**

- Allocate variables during procedure execution
- Deallocate upon return

**Mechanisms all implemented with machine instructions**

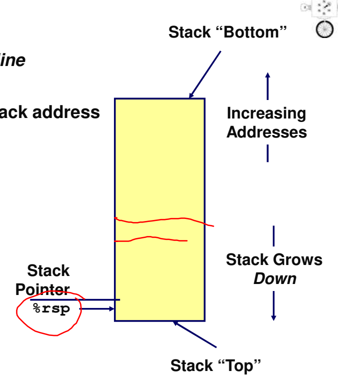
**x86-64 procedures use only what's needed**






## x86-64 Stack

- Region of memory managed with *stack discipline*
- Grows toward *lower* addresses
- Register `%rsp` indicates numerically *lowest* stack address
  - Always holds address of *"top"* element
  - Always changes by multiples of 8

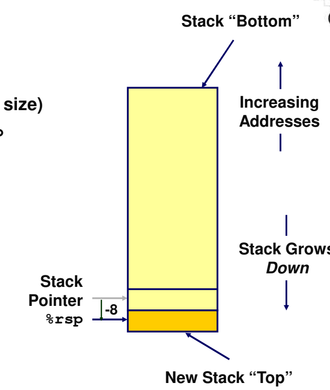





## x86-64 Stack Pushing

**Pushing:** `pushq` *Src*

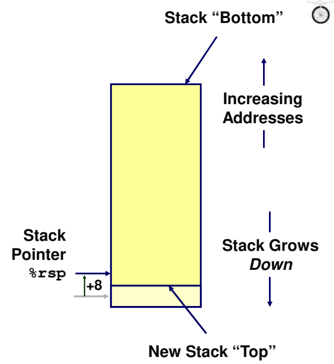
- Fetch operand at *Src*
- Decrement `%rsp` by 8 (regardless of operand size)
- Then write operand at address given by `%rsp`



# x86-64 Stack Popping

**Popping:** `popq` *Dest*

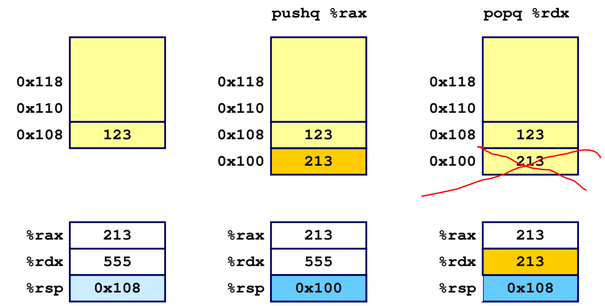
- Read memory data at address given by `%rsp`
- Increment `%rsp` by 8
- Write to *Dest*







# Stack Operation Examples







# Procedure Control Flow

- Use stack to support procedure call and return

**Procedure call:** `call` **or** `callq`

`call` ***label*** Push return address onto stack; jump to ***label***

**Return address value**

- Address of instruction *just beyond* `call`

**Procedure return:** `ret` **or** `retq` **(or** `rep; ret`**)**

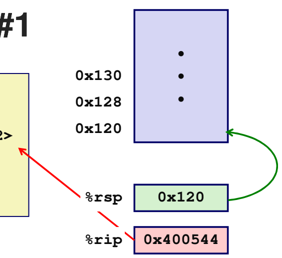
- Pop address (of instruction after corresponding `call`) from stack
- Jump to that address




# Control-Flow Example #1

```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

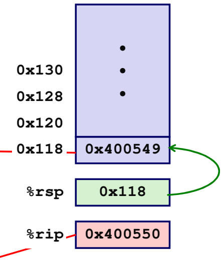
```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```



# Control-Flow Example #2

```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```

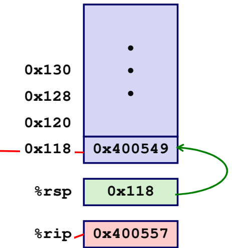





# Control-Flow Example #3

```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```

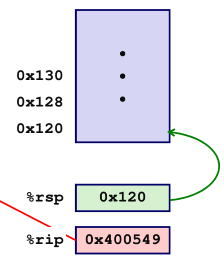





# Control-Flow Example #4

```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```



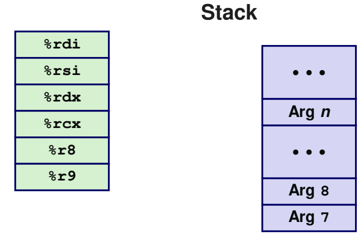



# Procedure Data Flow

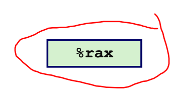
**Registers**

**First 6 arguments**

**Stack**




**Return value**




**Only allocate stack space when needed**

# Diane's Silk Dress Cost $89

## Registers

| |
|---|
| %rdi |
| %rsi |
| %rdx |
| %rcx |
| %r8 |
| %r9 |



# Data-Flow Example

```
void multstore(long x, long y, long *dest)
{
    long t = mult2(x, y);
    *dest = t;
}
```

```
0000000000400540 <multstore>:
  # x in %rdi, y in %rsi, dest in %rdx
  • • •
  400541: mov    %rdx,%rbx        # Save dest
  400544: callq  400550 <mult2>   # mult2(x,y)
  # t in %rax
  400549: mov    %rax,(%rbx)      # Save at dest
  • • •
```

```
long mult2(long a, long b)
{
  long s = a * b;
  return s;
}
```

```
0000000000400550 <mult2>:
  # a in %rdi, b in %rsi
  400550:  mov    %rdi,%rax # a
  400553:  imul   %rsi,%rax # a * b
  # s in %rax
  400557:  retq             # Return
```



# Stack-Based Languages

## Languages That Support Recursion

- E.g., C, Pascal, Java, Python, Racket, Haskell, …
- Code must be "*reentrant*"
  - Multiple simultaneous instantiations of single procedure
- ⇒Need some place to store state of each instantiation
  - Arguments
  - Local variables
  - Return pointer

## Stack Discipline

- State for given procedure needed for limited time
  - From when called to when return
- Callee returns before caller does

## Stack Allocated in *Frames*

- State for single procedure instantiation



# Call Chain Example

## Code Structure

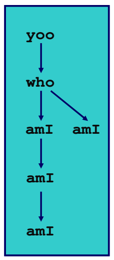
```
yoo(…)
{
  •
  •
  who();
  •
  •
}
```

```
who(…)
{
  • • •
  amI();
  • • •
  amI();
  • • •
}
```

```
amI(…)
{
  •
  •
  amI();
  •
  •
}
```

- Procedure `amI` is recursive

## Call Chain



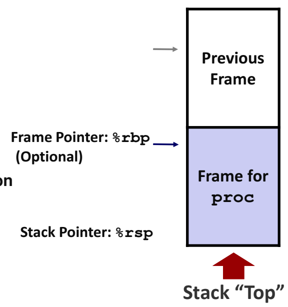
# Stack Frames

## Contents

- Return information
- Local storage (if needed)
- Temporary space (if needed)

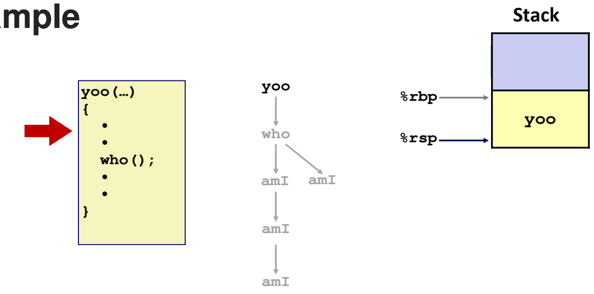
## Management

- Space allocated when procedure entered
  - "Set-up" code
  - Frame includes push done by `call` instruction
- Deallocated upon return
  - "Finish" code
  - Includes pop done by `ret` instruction



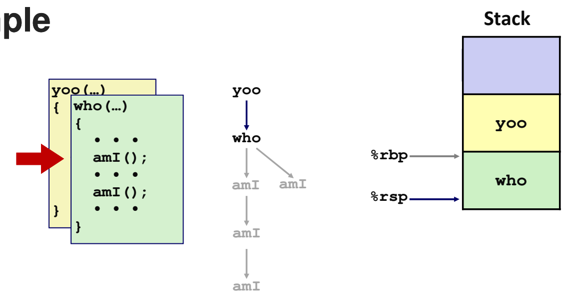



# Example



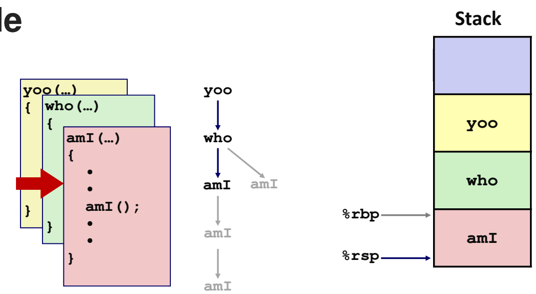



# Example

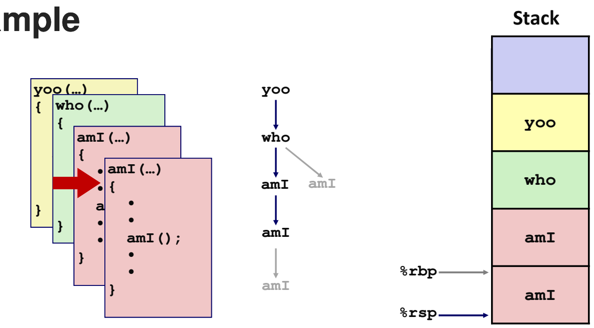





# Example



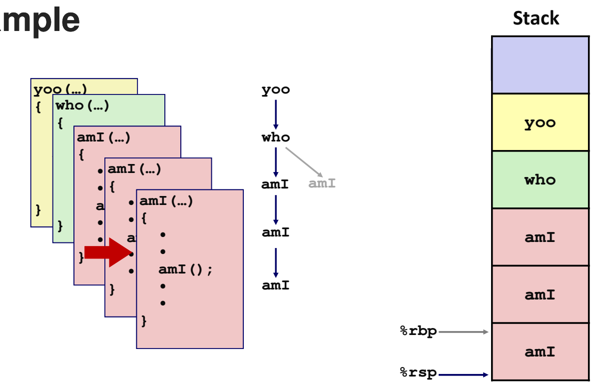
# Example








# Example





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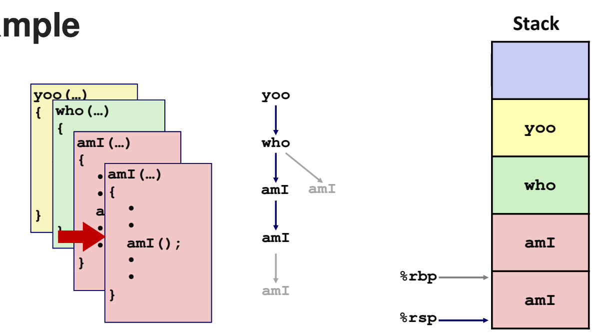






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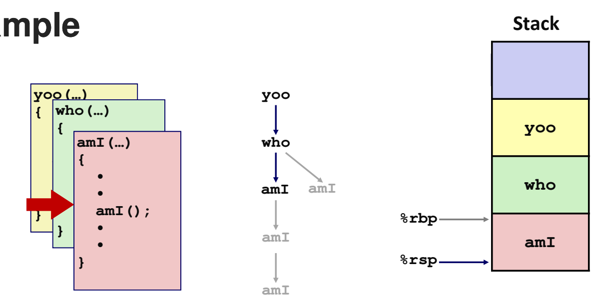
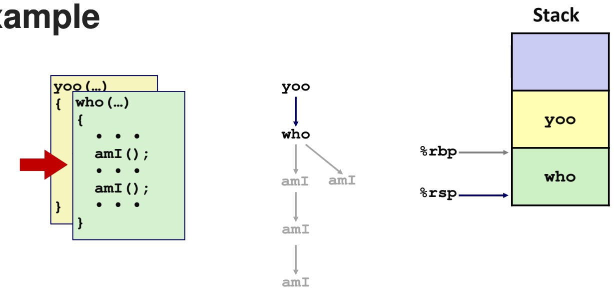
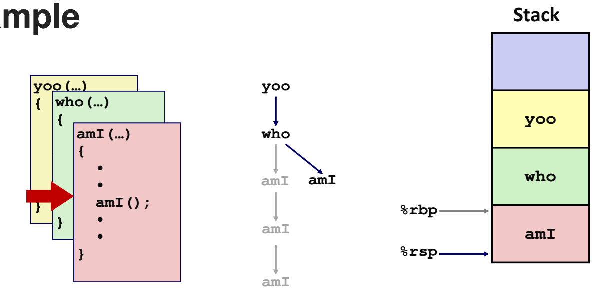


# Example



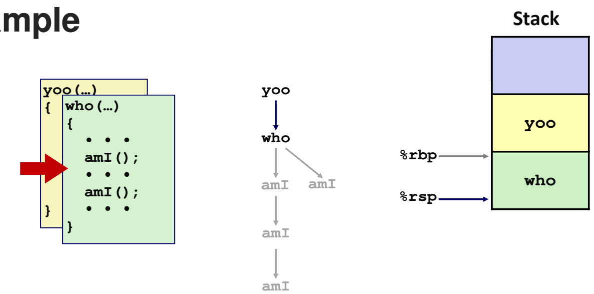



# Example



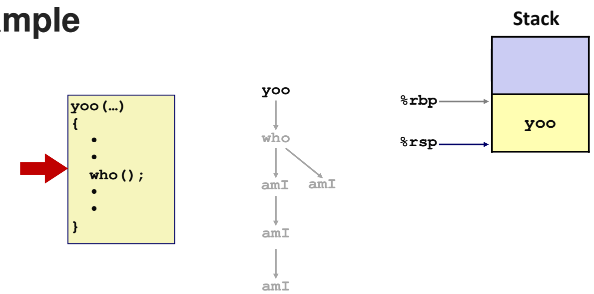



# Example






# Example



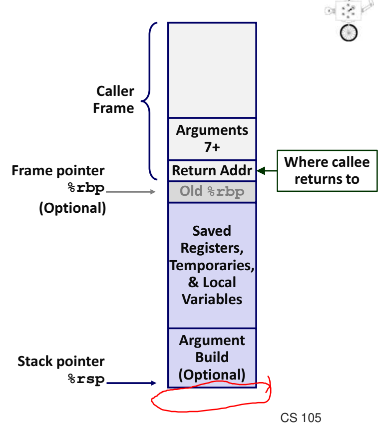
# x86-64/Linux Stack Frame

## Current Stack Frame ("Top" to Bottom)

- "Argument build:"
  Parameters for function about to be called
- Local variables (if can't keep in registers)
- Saved register context
- Old frame pointer (optional)

## Caller Stack Frame

- Return address
  - Pushed by `call` instruction
- Arguments 7+ for this call






# Example: `incr`

```
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 |

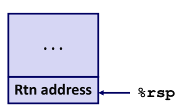


# Example: Calling `incr` #1

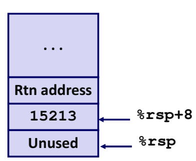
```
long call_incr()
{
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1 + v2;
}
```

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

Initial Stack Structure




Resulting Stack Structure



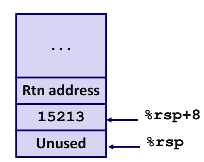



# Example: Calling `incr` #2

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

```
call_incr:
  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` |

## Example: Calling `incr` #3

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

```
call_incr:
  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**

| |
|---|
| ... |
| Rtn address |
| 18213 ← %rsp+8 |
| Unused ← %rsp |

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



## Example: Calling `incr` #4

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

```
call_incr:
  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**

| |
|---|
| ... |
| Rtn address |
| 18213 ← %rsp+8 |
| Unused ← %rsp |

| Register | Use(s) |
|---|---|
| %rax | Return value |

**Updated Stack Structure**

| |
|---|
| ... |
| Rtn address ← %rsp |



## Example: Calling `incr` #5

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

```
call_incr:
  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**

| |
|---|
| ... |
| Rtn address ← %rsp |

| Register | Use(s) |
|---|---|
| %rax | Return value |

**Final Stack Structure**

| |
|---|
| ... ← %rsp |



## Register Saving Conventions

**When procedure `yoo` calls `who`:**

- `yoo` is the *caller*
- `who` is the *callee*

**Can register *x* be used for temporary storage?**

```
yoo:
   • • •
   movq $15213, %rdx
   call who
   addq %rdx, %rax
   • • •
   ret
```

```
who:
   • • •
   subq $18213, %rdx
   • • •
   ret
```

- Contents of register `%rdx` overwritten by `who`
- This could be trouble → something should be done!
  - Need some coordination

# Register Saving Conventions

## When procedure `yoo` calls `who`:

- `yoo` is the *caller*
- `who` is the *callee*

## Can register *x* be used for temporary storage?

## Conventions

- *"Caller Saved"*
  - Caller saves temporary values in its frame before the call
- *"Callee Saved"*
  - Callee saves temporary values in its frame before using
  - Callee restores them before returning to caller



# x86-64 Linux Register Usage #1

## `%rax`

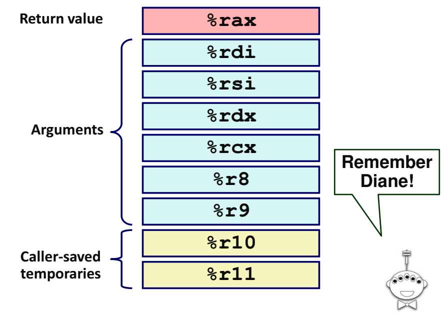
- Return value
- Caller-saved
- Can be modified by procedure

## `%rdi`, ..., `%r9`

- Arguments (Diane's silk dress)
- Caller-saved
- Can be modified by procedure

## `%r10`, `%r11`

- Caller-saved
- Can be modified by procedure






# x86-64 Linux Register Usage #2

## `%rbx`, `%r12`, `%r13`, `%r14`

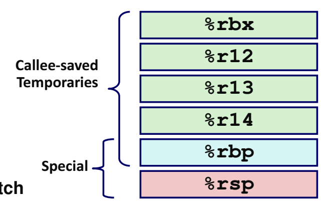
- Callee-saved
- Callee must save & restore

## `%rbp`

- Callee-saved
- Callee must save & restore
- May be used as frame pointer or as scratch
- Can mix & match

## `%rsp`

- Special form of callee save
- Restored to original value upon exit from procedure

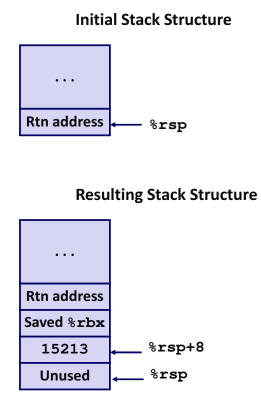





# Callee-Saved Example #1

```
long call_incr2(long x)
{
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x + v2;
}
```

```
call_incr2:
  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
```

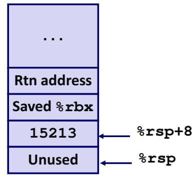


# Callee-Saved Example #2

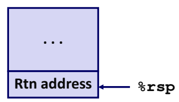
```
long call_incr2(long x)
{
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x + v2;
}
```

```
call_incr2:
  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 Function

```
/* Recursive popcount */
long pcount_r(unsigned long x)
{
  if (x == 0)
    return 0;
  else
    return (x & 1)
           + pcount_r(x >> 1);
}
```

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



# Recursive Function Terminal Case

```
/* Recursive popcount */
long pcount_r(unsigned long x)
{
  if (x == 0)
    return 0;
  else
    return (x & 1)
           + pcount_r(x >> 1);
}
```

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

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

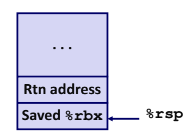


# Recursive Function Register Save

```
/* Recursive popcount */
long pcount_r(unsigned long x)
{
  if (x == 0)
    return 0;
  else
    return (x & 1)
           + pcount_r(x >> 1);
}
```

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

| Register | Use(s) | Type |
|---|---|---|
| %rdi | x | Argument |



# Recursive Function Call Setup

```
/* Recursive popcount */
long pcount_r(unsigned long x)
{
  if (x == 0)
    return 0;
  else
    return (x & 1)
           + pcount_r(x >> 1);
}
```

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

| Register | Use(s) | Type |
|---|---|---|
| %rdi | x >> 1 | Rec. argument |
| %rbx | x & 1 | Callee-saved |



# Recursive Function Call

```
/* Recursive popcount */
long pcount_r(unsigned long x)
{
  if (x == 0)
    return 0;
  else
    return (x & 1)
           + pcount_r(x >> 1);
}
```

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

| Register | Use(s) | Type |
|---|---|---|
| %rbx | x & 1 | Callee-saved |
| %rax | Recursive call return value | |



# Recursive Function Result

```
/* Recursive popcount */
long pcount_r(unsigned long x)
{
  if (x == 0)
    return 0;
  else
    return (x & 1)
           + pcount_r(x >> 1);
}
```

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

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

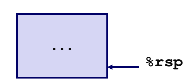


# Recursive Function Completion

```
/* Recursive popcount */
long pcount_r(unsigned long x)
{
  if (x == 0)
    return 0;
  else
    return (x & 1)
           + pcount_r(x >> 1);
}
```

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

| Register | Use(s) | Type |
|---|---|---|
| %rax | Return value | Return value |



# Observations About 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 (e.g., buffer overflow in future lecture)
- 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



# x86-64 Procedure Summary

## Important Points

- Stack is the right data structure for procedure call & return
  - If P calls Q, then Q returns before P

## Recursion (& mutual recursion) handled by normal calling conventions

- Can safely store values in local stack frame and in callee-saved registers
- Put function arguments at top of stack
- Result return in `%rax`

Pointers are addresses of values

- On stack or global