CS207: File Processing Term I/2018-19

Lecture 16:

A Pragmatic View of Computer Systems

x86-64 and friends II

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Recap: Everything is bits!

- Seen many data types so far:
  - Integers:
    - char/short/int/long (encoding as unsigned or two's complement signed)
  - Letters/punctutation/etc:
    - char (ASCII encoding)
  - Real numbers:
    - float/double (IEEE floating point encoding, didn't discuss)
  - Memory addresses:
    - pointer types (unsigned long encoding)
  - **the code itself!**
    - **Instructions**

Today's Topic

- More C to Assembly
  - Loops
  - The switch-case translation
  - Function calls

LOOPING: FOR, WHILE, DO-WHILE

"Do-While" Loop Example

C Code

```
long pcount_do
  (unsigned long x) {
  long result = 0;
  do {
    result += x & 0x1;
    x >>= 1;
  } while (x);
  return result;
}
```

Goto Version

```
long pcount_goto
  (unsigned long x) {
  long result = 0;
 loop:
  result += x & 0x1;
  x >>= 1;
  if(x) goto loop;
  return result;
}
```

- Count number of 1's in argument `x` ("popcount")
- Use conditional branch to either continue looping or to exit loop

"Do-While" Loop Compilation

Goto Version

```
long pcount_goto
  (unsigned long x) {
  long result = 0;
 loop:
  result += x & 0x1;
  x >>= 1;
  if(x) goto loop;
  return result;
}
```

Register	Use(s)
`%rdi`	Argument `x`
`%rax`	`result`

```
    movl    $0, %eax     #  result = 0
.L2:                     # loop:
    movq    %rdi, %rdx
    andl    $1, %edx     #  t = x & 0x1
    addq    %rdx, %rax   #  result += t
    shrq    %rdi         #  x >>= 1
    jne     .L2          #  if (x) goto loop
    rep; ret
```


General "Do-While" Translation

C Code

do
  Body
  while (*Test*);

Goto Version

loop:
  Body
  if (*Test*)
    goto loop

- Body: {

Statement$_1$;
Statement$_2$;
…
Statement$_n$;
}

General "While" Translation #1

- "Jump-to-middle" translation
- Used with **–Og** (optimized debugging experience)

While version

while (*Test*)
  Body

Goto Version

  goto test;
loop:
  Body
test:
  if (*Test*)
    goto loop;
done:

While Loop Example #1

C Code

```
long pcount_while
  (unsigned long x) {
  long result = 0;
  while (x) {
    result += x & 0x1;
    x >>= 1;
  }
  return result;
}
```

Jump to Middle

```
long pcount_goto_jtm
  (unsigned long x) {
  long result = 0;
  goto test;
 loop:
  result += x & 0x1;
  x >>= 1;
 test:
  if(x) goto loop;
  return result;
}
```

- Compare to do-while version of function
- Initial goto starts loop at test

General “While” Translation #2

While version

```
while (Test)
  Body
```

Do-While Version

```
  if (!Test)
    goto done;
  do
    Body
    while(Test);
done:
```

- “Do-while” conversion
- Used with `-O1`

Goto Version

```
  if (!Test)
    goto done;
loop:
  Body
  if (Test)
    goto loop;
done:
```


While Loop Example #2

C Code

```
long pcount_while
  (unsigned long x) {
  long result = 0;
  while (x) {
    result += x & 0x1;
    x >>= 1;
  }
  return result;
}
```

Do-While

```
long pcount_goto_dw
  (unsigned long x) {
  long result = 0;
  if (!x) goto done;
 loop:
  result += x & 0x1;
  x >>= 1;
  if(x) goto loop;
 done:
  return result;
}
```

- Compare to do-while version of function
- Initial conditional guards entrance to loop

“For” Loop Form

General Form

```
for (Init; Test; Update )

    Body
```

```
#define WSIZE 8*sizeof(int)
long pcount_for
  (unsigned long x)
{
  size_t i;
  long result = 0;
  for (i = 0; i < WSIZE; i++)
  {
    unsigned bit =
      (x >> i) & 0x1;
    result += bit;
  }
  return result;
}
```

Init

```
i = 0
```

Test

```
i < WSIZE
```

Update

```
i++
```

Body

```
{
  unsigned bit =
    (x >> i) & 0x1;
  result += bit;
}
```

"For" Loop → While Loop

For Version

```
for (Init; Test; Update )
    Body
```

While Version

```
Init;
while (Test ) {
    Body
    Update;
}
```


For-While Conversion

Init

```
i = 0
```

Test

```
i < WSIZE
```

Update

```
i++
```

Body

```
{
  unsigned bit =
     (x >> i) & 0x1;
  result += bit;
}
```

```
long pcount_for_while
  (unsigned long x)
{
  size_t i;
  long result = 0;
  i = 0;
  while (i < WSIZE)
  {
    unsigned bit =
      (x >> i) & 0x1;
    result += bit;
    i++;
  }
  return result;
}
```


"For" Loop Do-While Conversion

C Code

```
long pcount_for
  (unsigned long x)
{
  size_t i;
  long result = 0;
  for (i = 0; i < WSIZE; i++)
  {
    unsigned bit =
      (x >> i) & 0x1;
    result += bit;
  }
  return result;
}
```

- Initial test can be optimized away

Goto Version

```
long pcount_for_goto_dw
  (unsigned long x) {
  size_t i;
  long result = 0;
  i = 0;                    Init
  if (!(i < WSIZE))
    goto done;              ! Test
 loop:
  {
    unsigned bit =
      (x >> i) & 0x1;       Body
    result += bit;
  }
  i++;                      Update
  if (i < WSIZE)
    goto loop;              Test
 done:
  return result;
}
```


Summarizing

- C Control
  - if-then-else
  - do-while
  - while, for
- Assembler Control
  - Conditional jump
  - Conditional move
  - Indirect jump (via jump tables)
  - Compiler generates code sequence to implement more complex control
- Standard Techniques
  - Loops converted to do-while or jump-to-middle form

Switch Statement Example

```
long switch_eg
    (long x, long y, long z)
{
    long w = 1;
    switch(x) {
    case 1:
        w = y*z;
        break;
    case 2:
        w = y/z;
        /* Fall Through */
    case 3:
        w += z;
        break;
    case 5:
    case 6:
        w -= z;
        break;
    default:
        w = 2;
    }
    return w;
}
```

- Multiple case labels
  - Here: 5 & 6
- Fall through cases
  - Here: 2
- Missing cases
  - Here: 4

Jump Table Structure

Switch Form

```
switch(x) {
  case val_0:
    Block 0
  case val_1:
    Block 1
    • • •
  case val_n-1:
    Block n-1
}
```

Jump Table

```
jtab: Targ0
      Targ1
      Targ2
      •
      •
      •
      Targn-1
```

Jump Targets

```
Targ0:   Code Block 0
Targ1:   Code Block 1
Targ2:   Code Block 2
   •
   •
   •
Targn-1: Code Block n-1
```

Translation (Extended C)

```
goto *JTab[x];
```


Switch Statement Example

```
long switch_eg(long x, long y, long z)
{
    long w = 1;
    switch(x) {
      . . .
    }
    return w;
}
```

Setup:

```
switch_eg:
    movq    %rdx, %rcx
    cmpq    $6, %rdi    # x:6
    ja      .L8
    jmp     *.L4(,%rdi,8)
```

What range of values takes default?

Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rdx	Argument z
%rax	Return value

Note that **w** not initialized here

Switch Statement Example

```
long switch_eg(long x, long y, long z)
{
    long w = 1;
    switch(x) {
      . . .
    }
    return w;
}
```

Jump table

```
.section    .rodata
  .align 8
.L4:
  .quad    .L8  # x = 0
  .quad    .L3  # x = 1
  .quad    .L5  # x = 2
  .quad    .L9  # x = 3
  .quad    .L8  # x = 4
  .quad    .L7  # x = 5
  .quad    .L7  # x = 6
```

Setup:

```
switch_eg:
    movq    %rdx, %rcx
    cmpq    $6, %rdi         # x:6
    ja      .L8              # Use default
    jmp     *.L4(,%rdi,8)    # goto *JTab[x]
```

Indirect jump

Assembly Setup Explanation

- Table Structure
  – Each target requires 8 bytes
  – Base address at **`.L4`**
- Jumping
  – **Direct:** **`jmp .L8`**
  – Jump target is denoted by label **`.L8`**

  – **Indirect:** **`jmp *.L4(,%rdi,8)`**
  – Start of jump table: **`.L4`**
  – Must scale by factor of 8 (addresses are 8 bytes)
  – Fetch target from effective Address **`.L4 + x*8`**
    - Only for $0 \le \mathbf{x} \le 6$

Jump table

```
.section    .rodata
  .align 8
.L4:
  .quad     .L8  # x = 0
  .quad     .L3  # x = 1
  .quad     .L5  # x = 2
  .quad     .L9  # x = 3
  .quad     .L8  # x = 4
  .quad     .L7  # x = 5
  .quad     .L7  # x = 6
```


Jump Table

Jump table

```
.section    .rodata
  .align 8
.L4:
  .quad     .L8  # x = 0
  .quad     .L3  # x = 1
  .quad     .L5  # x = 2
  .quad     .L9  # x = 3
  .quad     .L8  # x = 4
  .quad     .L7  # x = 5
  .quad     .L7  # x = 6
```

```
switch(x) {
case 1:         // .L3
    w = y*z;
    break;
case 2:         // .L5
    w = y/z;
    /* Fall Through */
case 3:         // .L9
    w += z;
    break;
case 5:
case 6:         // .L7
    w -= z;
    break;
default:        // .L8
    w = 2;
}
```


Finding Jump Table in Binary

```
00000000004005e0 <switch_eg>:
4005e0:     48 89 d1                mov    %rdx,%rcx
4005e3:     48 83 ff 06             cmp    $0x6,%rdi
4005e7:     77 2b                   ja     400614 <switch_eg+0x34>
4005e9:     ff 24 fd f0 07 40 00    jmpq   *0x4007f0(,%rdi,8)
4005f0:     48 89 f0                mov    %rsi,%rax
4005f3:     48 0f af c2             imul   %rdx,%rax
4005f7:     c3                      retq
4005f8:     48 89 f0                mov    %rsi,%rax
4005fb:     48 99                   cqto
4005fd:     48 f7 f9                idiv   %rcx
400600:     eb 05                   jmp    400607 <switch_eg+0x27>
400602:     b8 01 00 00 00          mov    $0x1,%eax
400607:     48 01 c8                add    %rcx,%rax
40060a:     c3                      retq
40060b:     b8 01 00 00 00          mov    $0x1,%eax
400610:     48 29 d0                sub    %rdx,%rax
400613:     c3                      retq
400614:     b8 02 00 00 00          mov    $0x2,%eax
400619:     c3                      retq
```


Finding Jump Table in Binary (cont.)

```
00000000004005e0 <switch_eg>:
. . .
4005e9:     ff 24 fd f0 07 40 00    jmpq   *0x4007f0(,%rdi,8)
. . .
```

```
% gdb switch
(gdb) x /8xg 0x4007f0
0x4007f0:       0x0000000000400614      0x00000000004005f0
0x400800:       0x00000000004005f8      0x0000000000400602
0x400810:       0x0000000000400614      0x000000000040060b
0x400820:       0x000000000040060b      0x2c646c25203d2078
(gdb)
```

Code Blocks (x == 1)

```
switch(x) {
case 1:    // .L3
        w = y*z;
        break;
    . . .
}
```

```
.L3:
    movq     %rsi, %rax   # y
    imulq    %rdx, %rax   # y*z
    ret
```

Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rdx	Argument z
%rax	Return value

Handling Fall-Through

```
long w = 1;
 . . .
switch(x) {
 . . .
case 2:
       w = y/z;
       /* Fall Through */
case 3:
       w += z;
       break;
 . . .
}
```

```
case 2:
       w = y/z;
       goto merge;
```

```
case 3:
            w = 1;

merge:
            w += z;
```


Code Blocks (x == 2, x == 3)

```
long w = 1;
 . . .
switch(x) {
 . . .
case 2:
      w = y/z;
      /* Fall Through */
case 3:
      w += z;
      break;
 . . .
}
```

```
.L5:                        # Case 2
    movq     %rsi, %rax
    cqto
    idivq    %rcx           #  y/z
    jmp      .L6            #  goto merge
.L9:                        # Case 3
    movl     $1, %eax       #  w = 1
.L6:                        # merge:
    addq     %rcx, %rax #  w += z
    ret
```

Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rdx	Argument z
%rax	Return value

Code Blocks (x == 5, x == 6, default)

```
switch(x) {
  . . .
  case 5:  // .L7
  case 6:  // .L7
      w -= z;
      break;
  default: // .L8
      w = 2;
}
```

```
.L7:                     # Case 5,6
  movl  $1, %eax     #  w = 1
  subq  %rdx, %rax #  w -= z
  ret
.L8:                     # Default:
  movl  $2, %eax     #  2
  ret
```

Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rdx	Argument z
%rax	Return value

Techniques for Switches

- Large switch statements use jump tables
- Sparse switch statements may use decision trees (if-else..if-else..if-else)

MUIC: File Pro.

FUNCTION CALLS

MUIC: File Pro.

Mechanisms in Procedures

- Passing control
  - To beginning of procedure code
  - Back to return point
- Passing data
  - Procedure arguments
  - Return value
- Memory management
  - Allocate during procedure execution
  - Deallocate upon return
- Mechanisms all implemented with machine instructions

```
P(…) {
  •
  •
  y = Q(x);
  print(y)
  •
}
```

```
int Q(int i)
{
  int t = 3*i;
  int v[10];
  •
  •
  return v[t];
}
```

MUIC: File Pro.

Mechanisms in Procedures

- Passing control
  - To beginning of procedure code
  - Back to return point
- Passing data
  - Procedure arguments
  - Return value
- Memory management
  - Allocate during procedure execution
  - Deallocate upon return
- Mechanisms all implemented with machine instructions

```
P(…) {
  •
  •
  y = Q(x);
  print(y)
  •
}
```

```
int Q(int i)
{
  int t = 3*i;
  int v[10];
  •
  •
  return v[t];
}
```

Mechanisms in Procedures

- Passing control
  - To beginning of procedure code
  - Back to return point
- Passing data
  - Procedure arguments
  - Return value
- Memory management
  - Allocate during procedure execution
  - Deallocate upon return
- Mechanisms all implemented with machine instructions

```
P(…) {
  •
  •
  y = Q(x);
  print(y)
  •
}
```

```
int Q(int i)
{
  int t = 3*i;
  int v[10];
  •
  •
  return v[t];
}
```


Mechanisms in Procedures

Machine instructions implement the mechanisms, but the choices are determined by designers. These choices make up the **Application Binary Interface (ABI).**

- Memory management
  - Allocate during procedure execution
  - Deallocate upon return
- Mechanisms all implemented with machine instructions

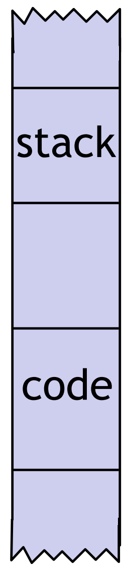
```
{
  int t = 3*i;
  int v[10];
  •
  •
  return v[t];
}
```

Today

- **Procedures**
  - **Stack Structure**
  - Calling Conventions
    - Passing control
    - Passing data
    - Managing local data

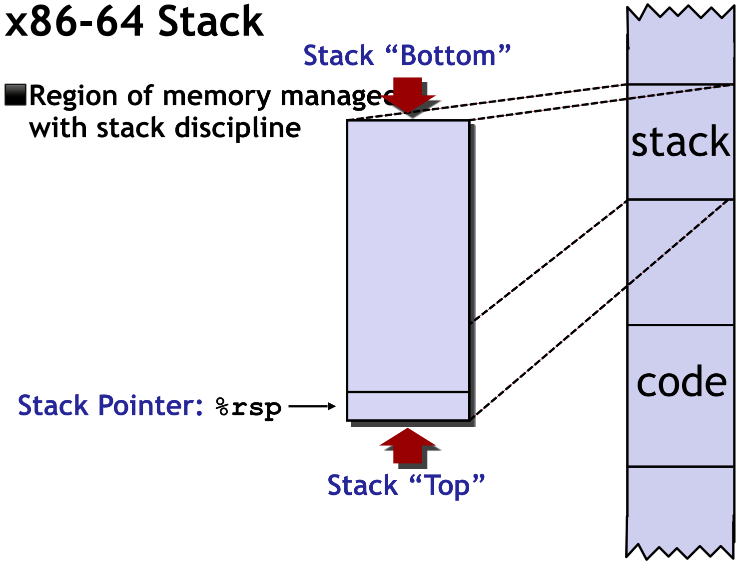
x86-64 Stack

- **Region of memory managed with stack discipline**
  - Memory viewed as array of bytes.
  - Different regions have different purposes.
  - (Like ABI, a policy decision)



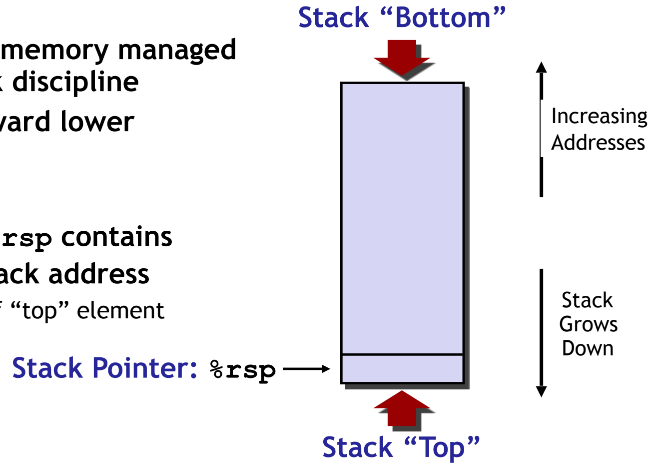
x86-64 Stack

- Region of memory managed with stack discipline



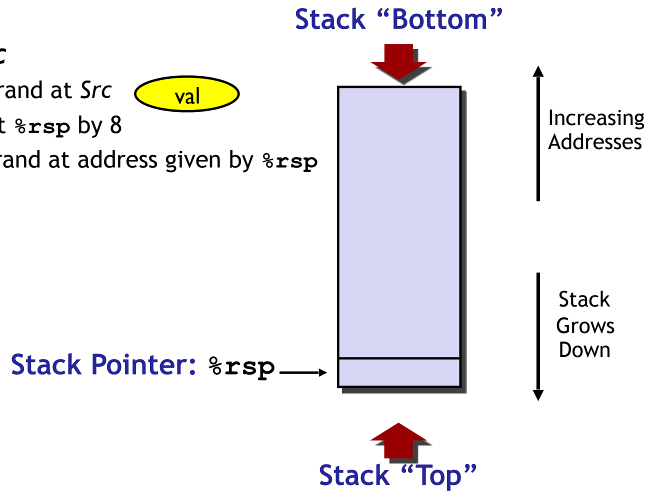
x86-64 Stack

- Region of memory managed with stack discipline
- Grows toward lower addresses
- Register `%rsp` contains lowest stack address
  - address of “top” element



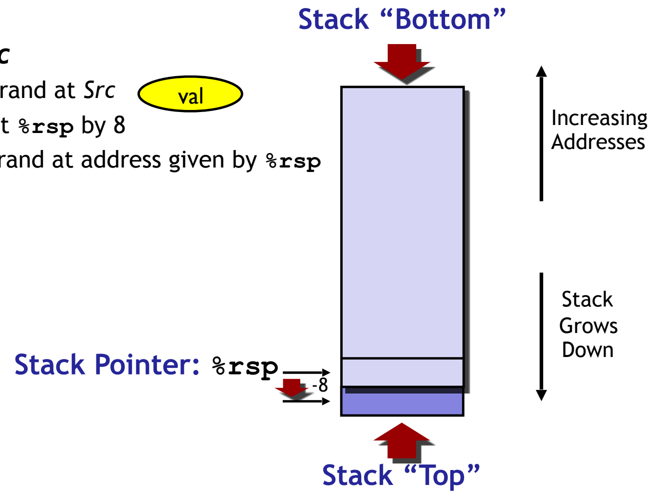
x86-64 Stack: Push

- **`pushq`** *Src*
  - Fetch operand at *Src* (val)
  - Decrement `%rsp` by 8
  - Write operand at address given by `%rsp`



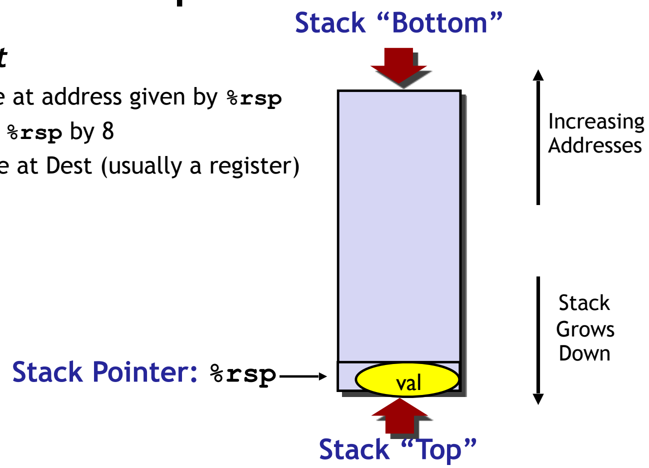
x86-64 Stack: Push

- **`pushq`** *Src*
  - Fetch operand at *Src* (val)
  - Decrement `%rsp` by 8
  - Write operand at address given by `%rsp`



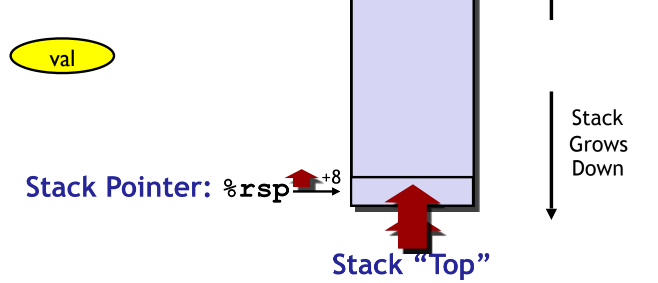
x86-64 Stack: Pop

- **popq** ***Dest***
  - Read value at address given by `%rsp`
  - Increment `%rsp` by 8
  - Store value at Dest (usually a register)



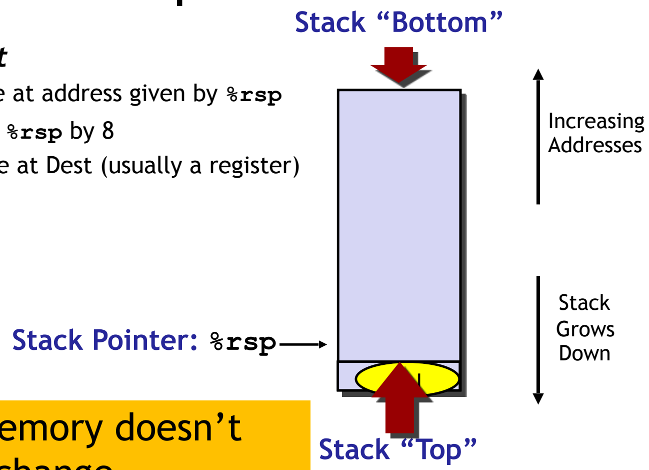
x86-64 Stack: Pop

- **popq** ***Dest***
  - Read value at address given by `%rsp`
  - Increment `%rsp` by 8
  - Store value at Dest (usually a register)



x86-64 Stack: Pop

- **popq** ***Dest***
  - Read value at address given by `%rsp`
  - Increment `%rsp` by 8
  - Store value at Dest (usually a register)



(The memory doesn’t change,
only the value of `%rsp`)

Today

- **Procedures**
  - Stack Structure
  - Calling Conventions
    - **Passing control**
    - Passing data
    - Managing local data
  - Illustration of Recursion

Code Examples

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

```
0000000000400540 <multstore>:
  400540: push   %rbx              # Save %rbx
  400541: mov    %rdx,%rbx         # Save dest
  400544: callq  400550 <mult2>    # mult2(x,y)
  400549: mov    %rax,(%rbx)       # Save at dest
  40054c: pop    %rbx              # Restore %rbx
  40054d: retq                     # Return
```

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

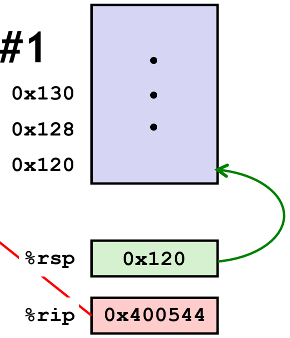
```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax        # a
  400553:  imul   %rsi,%rax        # a * b
  400557:  retq                    # Return
```


Procedure Control Flow

- **Use stack to support procedure call and return**
- **Procedure call: `call label`**
  - Push return address on stack
  - Jump to *label*
- **Return address:**
  - Address of the next instruction right after call
- **Procedure return: `ret`**
  - Pop address from stack
  - Jump to address

Control Flow Example #1

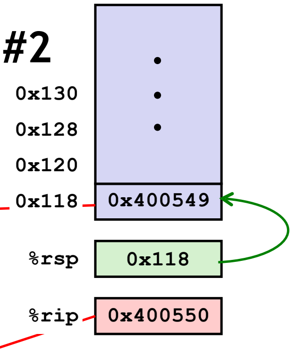
```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```




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


Control Flow Example #2

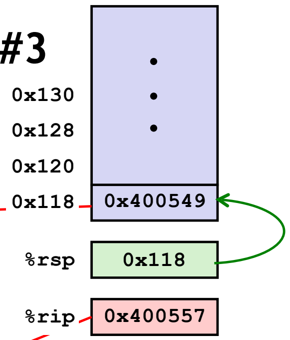
```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```




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

Control Flow Example #3

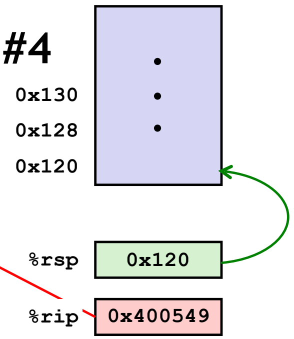
```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```




```
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
```

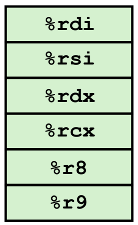

Today

- Procedures
  - Stack Structure
  - Calling Conventions
    - Passing control
    - Passing data
    - Managing local data

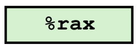
Procedure Data Flow

Registers

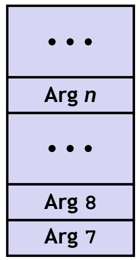
- First 6 arguments



- Return value



Stack



- Only allocate stack space when needed

Data Flow Examples

```
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
```


Today

- **Procedures**
  - Stack Structure
  - Calling Conventions
    - Passing control
    - Passing data
    - **Managing local data**

Stack-Based Languages

- **Languages that support recursion**
  - e.g., C, Java
  - 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

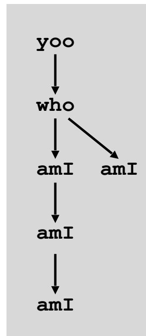
Call Chain Example

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

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

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

Example Call Chain

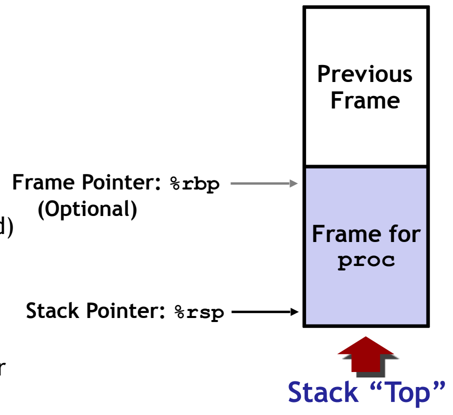


Procedure `amI()` is recursive

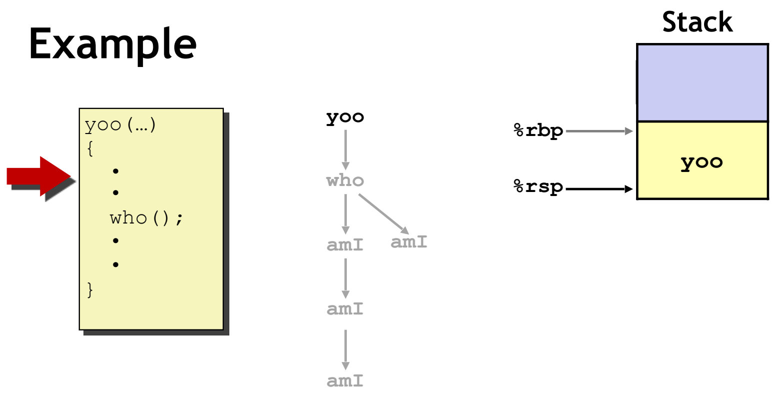
Stack Frames

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

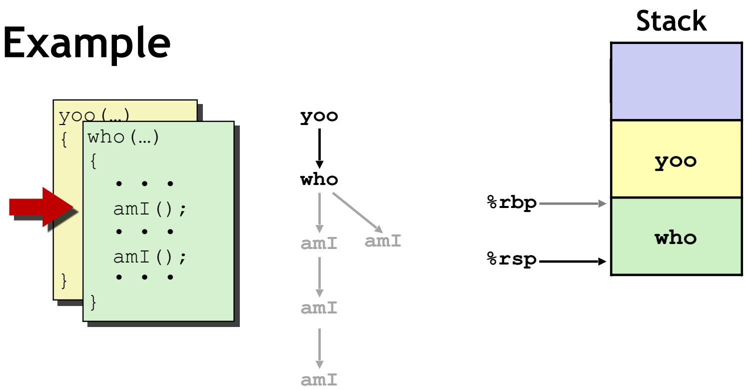
■Management
- Space allocated when enter procedure
  - "Set-up" code
  - Includes push by `call` instruction
- Deallocated when return
  - "Finish" code
  - Includes pop by `ret` instruction



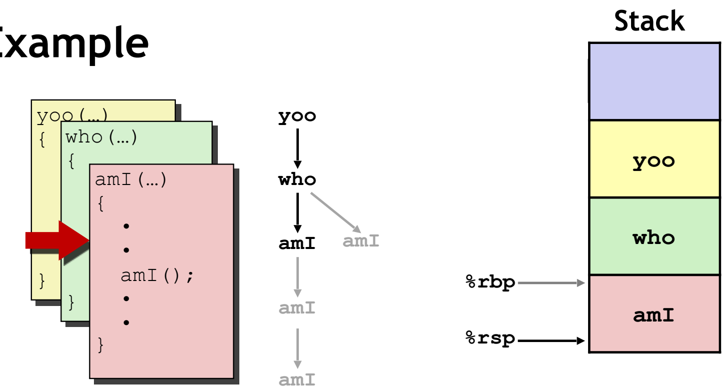
Example



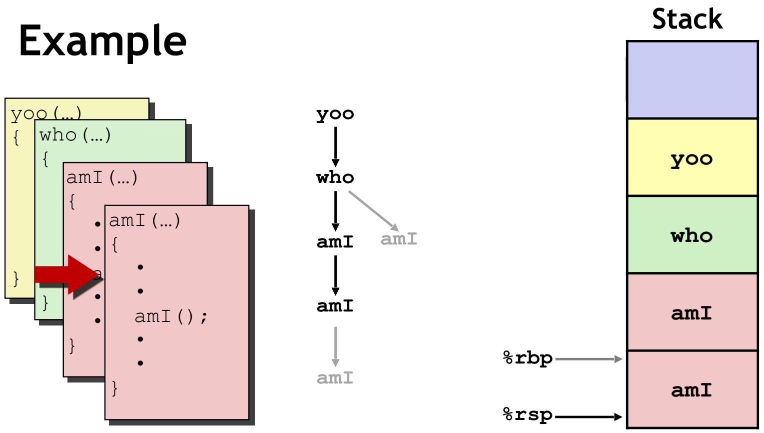
Example



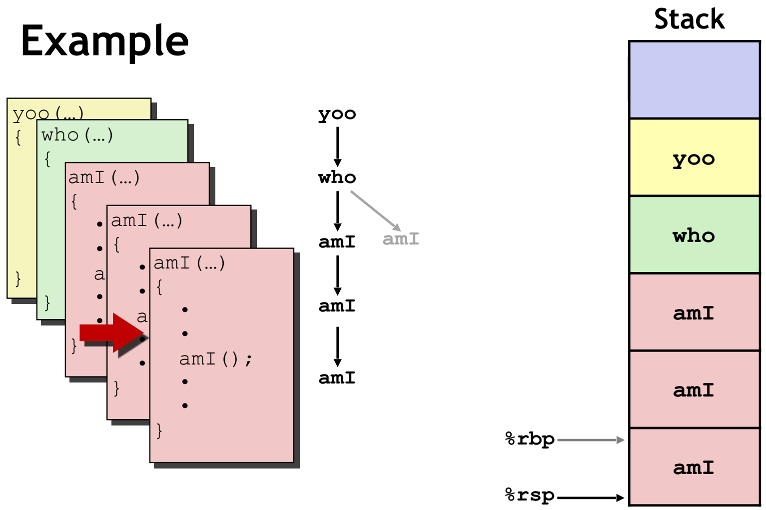
Example



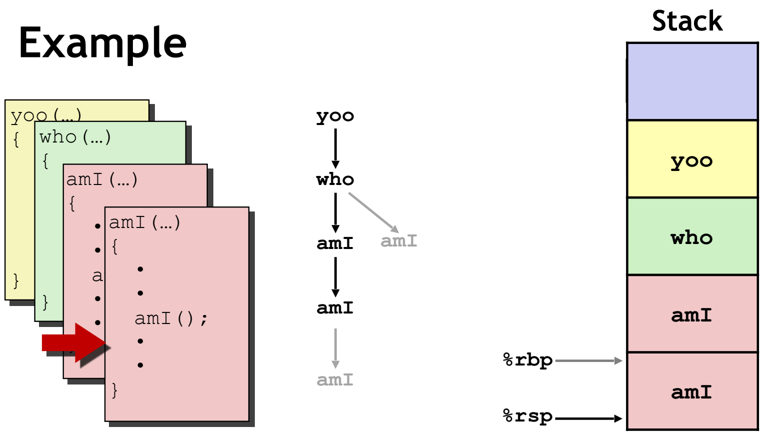
Example



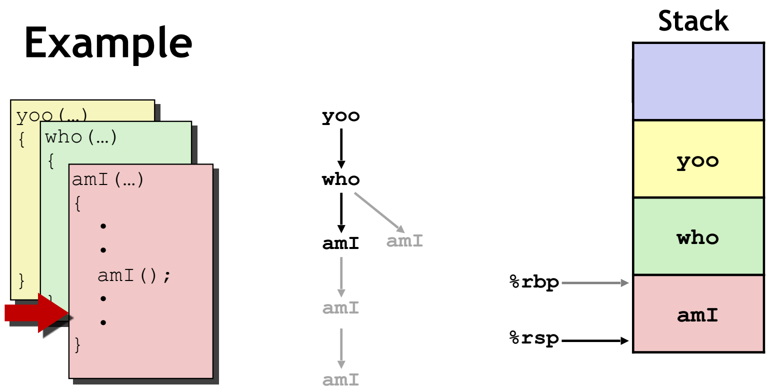
Example



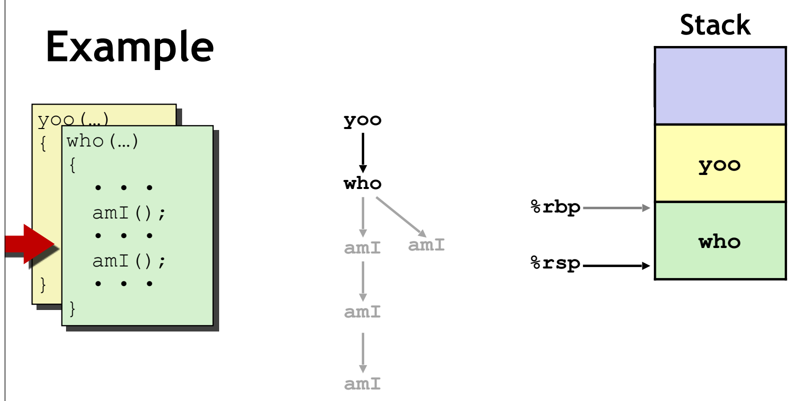
Example



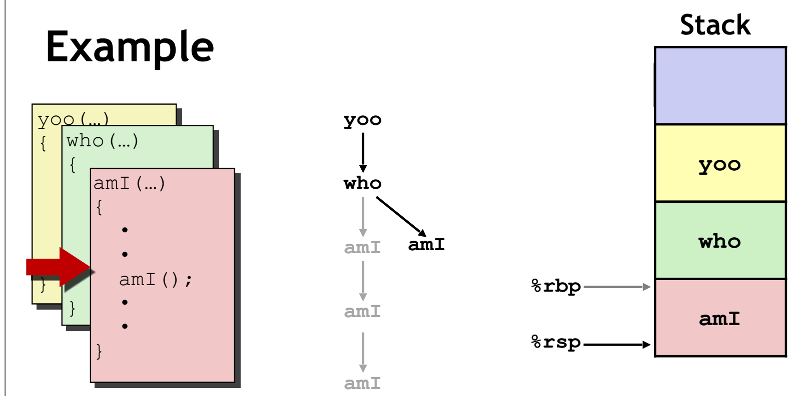
Example



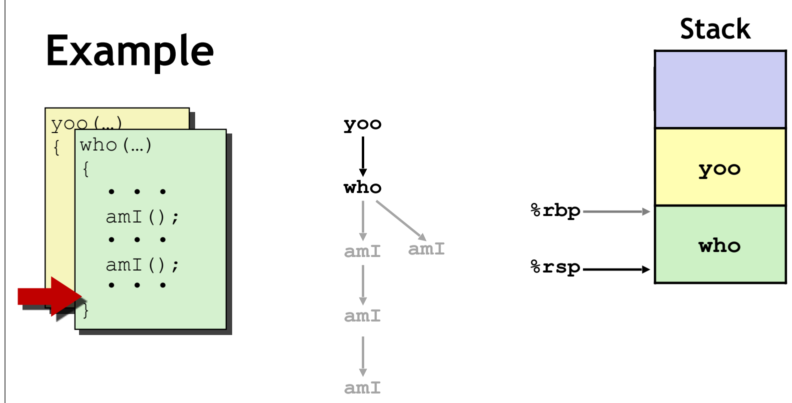
Example



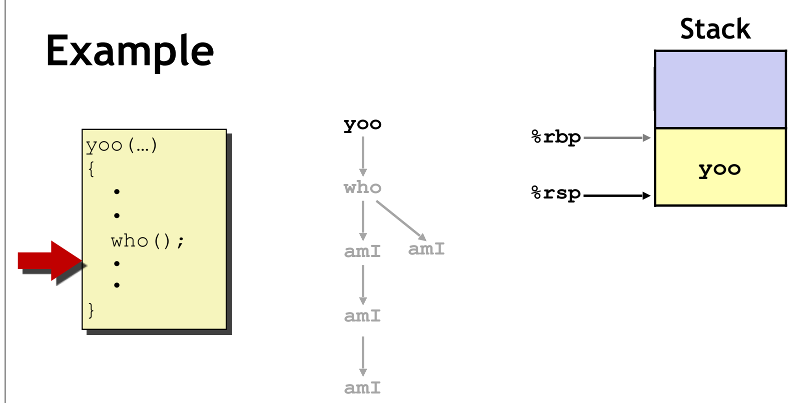
Example



Example

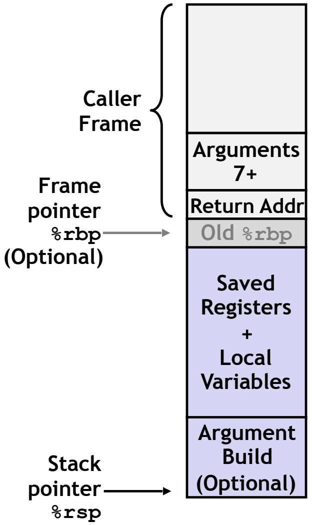


Example



x86-64/Linux Stack Frame

- **Current Stack Frame ("Top" to Bottom)**
  - "Argument build:"
    Parameters for function about to call
  - 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 for this call



Example: `incr`

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

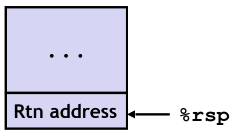
```
incr:
  movq    (%rdi), %rax
  addq    %rax, %rsi
  movq    %rsi, (%rdi)
  ret
```

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

Example: Calling `incr` #1

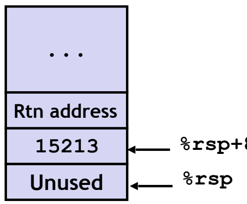
```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

Initial Stack Structure




```
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
```

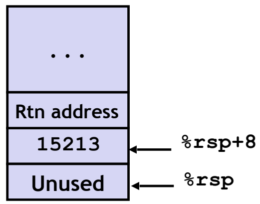
Resulting Stack Structure



Example: Calling `incr` #2

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

Stack Structure




```
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
```

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

Example: Calling `incr` #2

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

Stack Structure

. . .
Rtn address
15213 ← %rsp+8

Aside 1: `movl $3000, %esi`

- Remember, movl -> %exx zeros out high order 32 bits.
- Why use movl instead of movq? Maybe? 1 byte shorter.

```
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

%rdi	&v1
%rsi	3000

Example: Calling `incr` #2

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

Stack Structure

. . .
Rtn address
15213 ← %rsp+8
← %rsp

Aside 2: `leaq 8(%rsp), %rdi`

- Computes %rsp+8
- Actually, used for what it is meant!

```
ca
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

	e(s)
	&v1
%rsi	3000

Example: Calling `incr` #2

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

Stack Structure

. . .
Rtn address
15213 ← %rsp+8
Unused ← %rsp

```
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
```

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;
}
```

Stack Structure

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

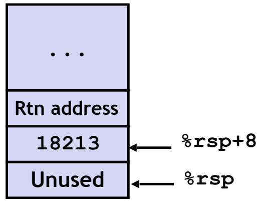
```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

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

Example: Calling `incr` #4

Stack Structure

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



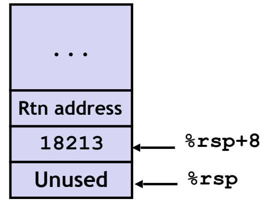

```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Register	Use(s)
`%rax`	Return value

Example: Calling `incr` #5a

Stack Structure

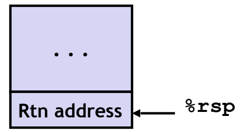
```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```




```
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
```

Register	Use(s)
`%rax`	Return value

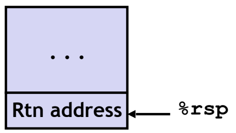
Updated Stack Structure



Example: Calling `incr` #5b

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

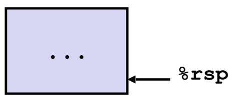
Updated Stack Structure




```
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
```

Register	Use(s)
`%rax`	Return value

Final Stack Structure



Today

- **Procedures**
  - Stack Structure
  - Calling Conventions
    - Passing control
    - Passing data
    - Managing local data

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**