CS429: Computer Organization and Architecture

Instruction Set Architecture IV

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Last updated: October 9, 2019 at 18:14

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

x86-64 implementation of a procedure uses only those mechanisms required.

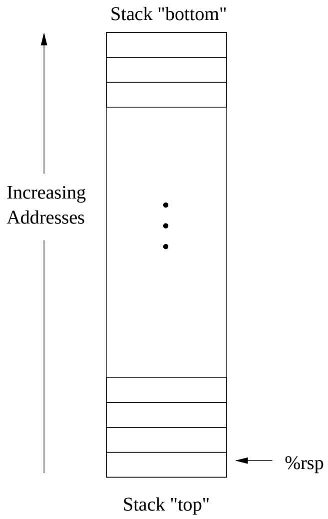
```
P(...) {
  ...
  y = Q(x);
  printf(y);
  ...
}
```

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

---

x86-64 Stack

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



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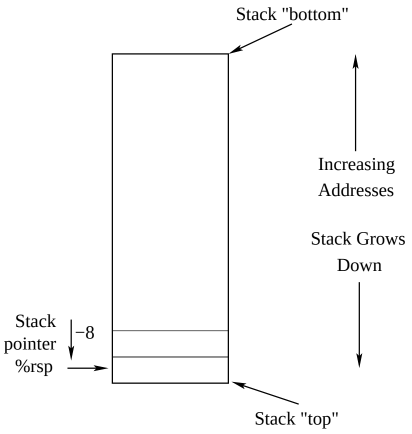
x86-64 Stack Pushing

Pushing

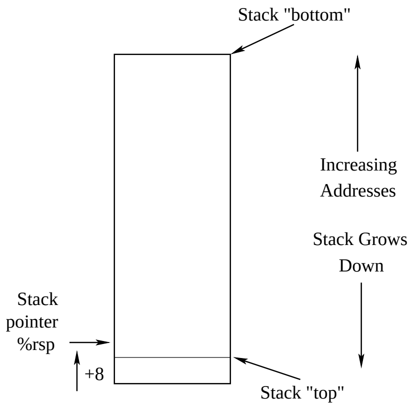
- `pushq Src`
- Decrement `%rsp` by 8
- Write operand at address given by `%rsp`



x86-64 Stack Popping

Popping

- `popq Dest`
- Read operand at address given by `%rsp`
- Increment `%rsp` by 8
- Write to Dest



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  400580 <mult2> # mult2(x, y)
  40054D:   mov    %rax, (%rbx)   # Save at dest
  400550:   pop    %rbx           # Restore %rbx
  400552:   retq                  # Return
```

Code Examples (2)

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

```
0000000000400580 <mult2>:
   400580:  mov  %rdi, %rax    # a
   400583:  imul %rsi, %rax    # a * b
   400587:  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 next instruction right after call

Procedure return: `ret`

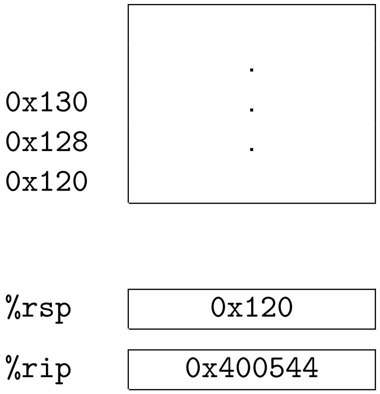
- Pop address from stack
- Jump to address

Control Flow Example #1

Poised to execute `call` in `multstore`.

```
0000000000400540 <multstore>:
          ...
  400544:   callq 400580 <mult2>
  40054D:   mov   %rax, (%rbx)
          ...
```

```
0000000000400580 <mult2>:
   400580:   mov   %rdi, %rax
          ...
   400587:   retq
```



0x130
0x128
0x120

%rsp 0x120

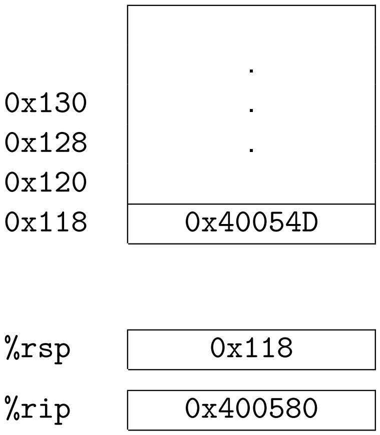
%rip 0x400544

Control Flow Example #2

After `call` in `multstore`. Now in `mult2`.

```
0000000000400540 <multstore>:
          ...
  400544:   callq 400580 <mult2>
  40054D:   mov   %rax, (%rbx)
          ...
```

```
0000000000400580 <mult2>:
   400580:   mov   %rdi, %rax
          ...
   400587:   retq
```



0x130
0x128
0x120
0x118 0x40054D

%rsp 0x118

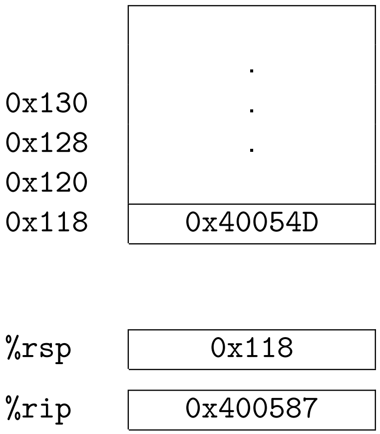
%rip 0x400580

Control Flow Example #3

Execute through `mult2` to `retq`.

```
0000000000400540 <multstore>:
          ...
  400544:   callq 400580 <mult2>
  40054D:   mov   %rax, (%rbx)
          ...
```

```
0000000000400580 <mult2>:
   400580:   mov   %rdi, %rax
          ...
   400587:   retq
```



0x130
0x128
0x120
0x118 0x40054D

%rsp 0x118

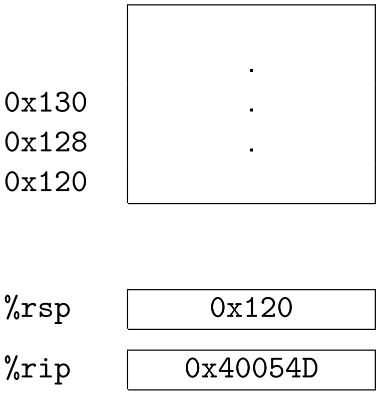
%rip 0x400587

Control Flow Example #4

After `retq` in `mult2`. Back in `multstore`.

```
0000000000400540 <multstore>:
          ...
  400544:   callq 400580 <mult2>
  40054D:   mov   %rax, (%rbx)
          ...
```

```
0000000000400580 <mult2>:
   400580:   mov   %rdi, %rax
          ...
   400587:   retq
```



0x130
0x128
0x120

%rsp 0x120

%rip 0x40054D

Procedure Data Flow

Registers: First 6 arguments

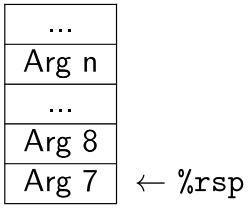
`%rdi`
`%rsi`
`%rdx`
`%rcx`
`%r8`
`%r9`

Mnemonic to remember the order: “Diane’s silk dress cost $89.” Args past 6 are pushed on the stack in reverse order.

Return value

`%rax`

Stack



Only allocate stack space when needed.

Stack-Based Languages

Languages that support recursion

- e.g., C, Pascal, 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 a limited time: from call to return
- Callee returns before caller does

Stack allocated in Frames

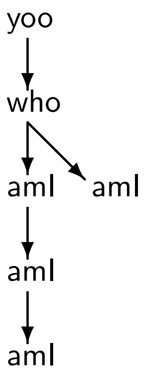
- State for a single procedure instantiation

Call Chain Example

Code Structure

```
yoo(...) {
  ...
  who();
  ...
}

who(...) {
  ...
  aml();
  ...
  aml();
  ...
}

aml(...) {
  ...
  aml();
  ...
}
```

Procedure aml is recursive.



Stack Frames

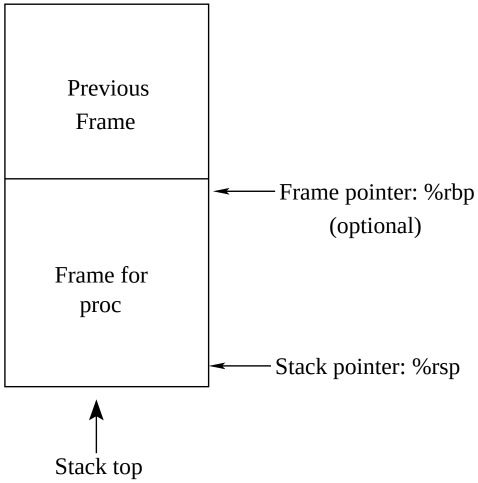
In IA32, almost every procedure call generated a stack frame. In x86-64, most calls do not generate an explicit frame.

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 returning
  - “Finish” code
  - Includes pop by `ret` instruction

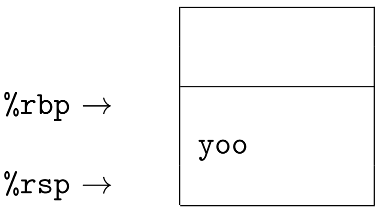


Example (1)

yoo

```
/* Executing
   here: */
yoo(...)
{
  ...
  who();
  ...
}
```

Stack

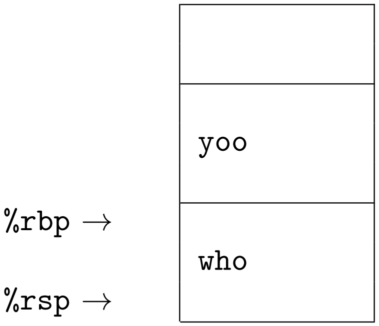


Example (2)

```
yoo(...)
{
  ...
  who();
  ...
}

/* Executing
   here: */
who(...)
{
  ...
  amI();
  ...
}
```

yoo
↓
who

Stack

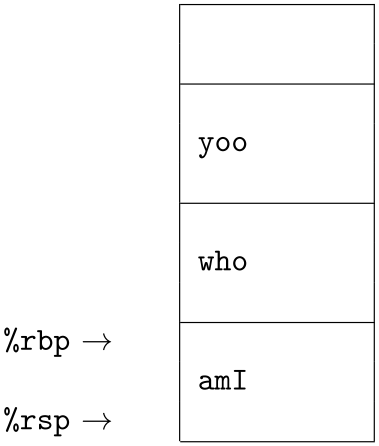


Example (3)

```
yoo(...)
{
  ...
}

who(...)
{
  ...
}

/* Executing
   here: */
amI(...)
{
  ...
  amI();
  ...
}
```

yoo
↓
who
↓
amI

Stack

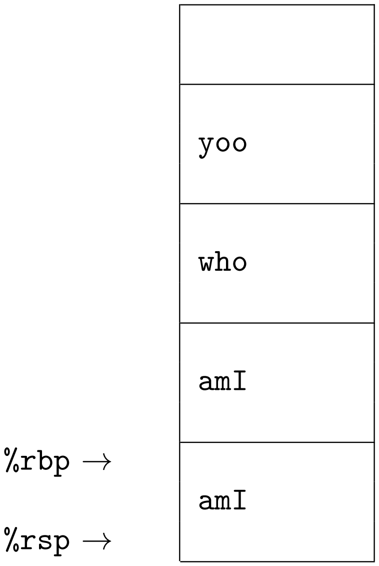


Example (4)

```
yoo(...)
{
  ...
}

who(...)
{
  ...
}

/* Executing
   here: */
amI(...)
{
  ...
  amI();
  ...
}
```

yoo
↓
who
↓
amI
↓
amI

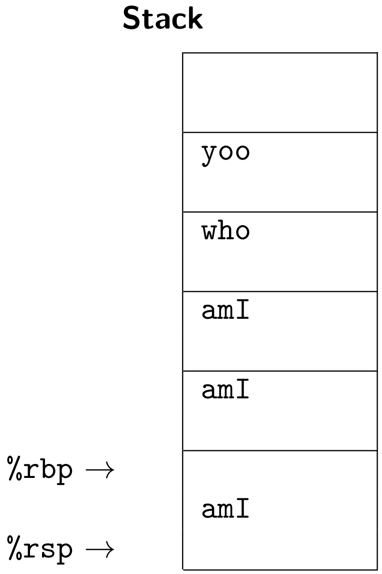
Stack



Example (5)

```
yoo(...)
{
   ...
}

who(...)
{
   ...
}

/* Executing
   here: */
amI(...)
{
   ...
   amI();
   ...
}
```

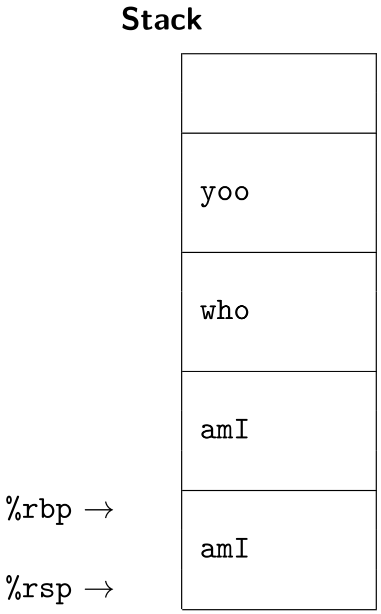
yoo
↓
who
↓
amI
↓
amI
↓
amI



Example (6)

```
yoo(...)
{
   ...
}

who(...)
{
   ...
}

/* Executing
   here: */
amI(...)
{
   ...
   amI();
   ...
}
```

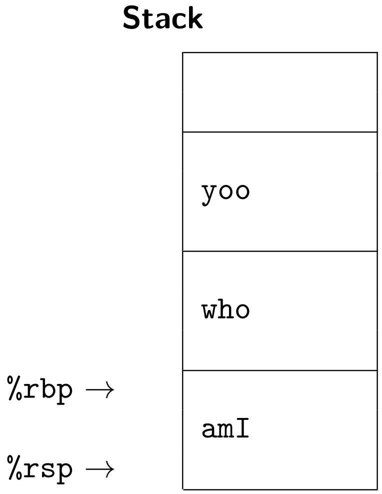
yoo
↓
who
↓
amI
↓
amI



Example (7)

```
yoo(...)
{
   ...
}

who(...)
{
   ...
}

/* Executing
   here: */
amI(...)
{
   ...
   amI();
   ...
}
```

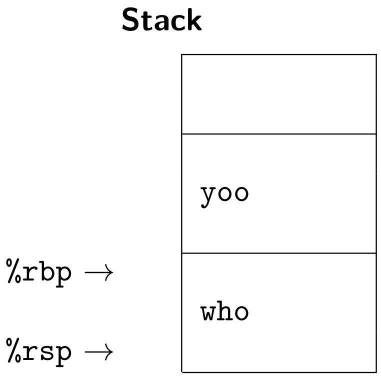
yoo
↓
who
↓
amI



Example (8)

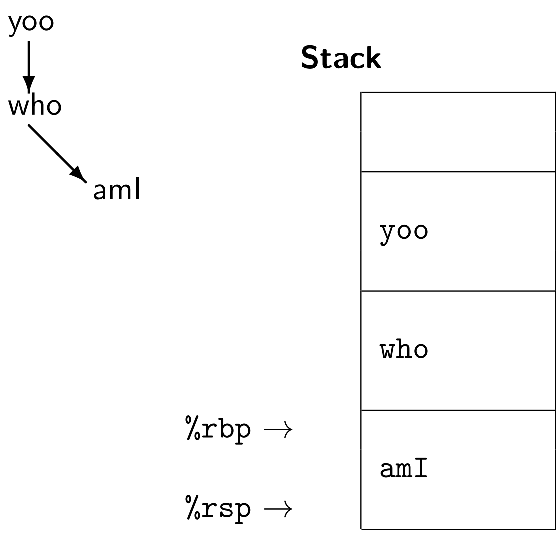
```
yoo(...)
{
   ...
   who();
   ...
}

/* Executing
   here: */
who(...)
{
   ...
   amI();
   ...
}
```

yoo
↓
who



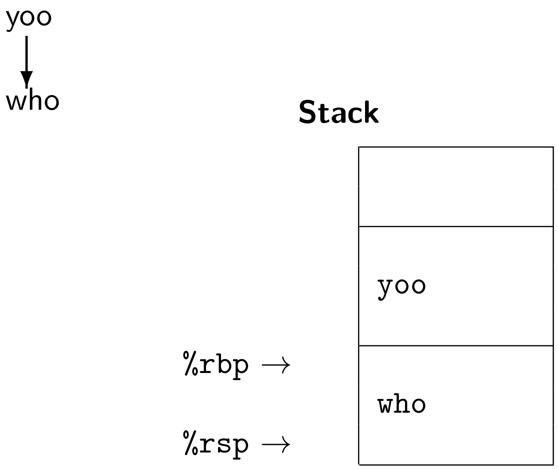
Example (9)

```
yoo(...)
{
   ...
}

who(...)
{
   ...
}

/* Executing
     here: */
amI(...)
{
   ...
   amI();
   ...
}
```



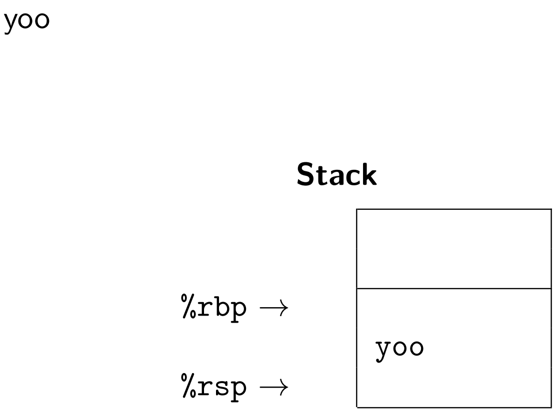
Example (10)

```
yoo(...)
{
   ...
   who();
   ...
}

/* Executing
     here: */
who(...)
{
   ...
   amI();
   ...
}
```



Example (11)

```
/* Executing
     here: */
yoo(...)
{
   ...
   who();
   ...
}
```



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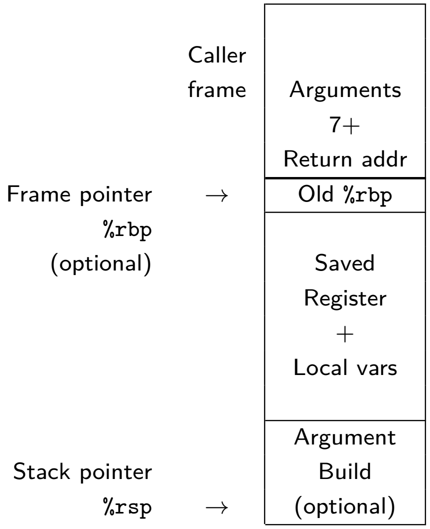
x86-64/Linux Stack Frame

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

Building a Stack Frame

IA32 routines almost always constructed an explicit stack frame; x86-64 routines usually don't.

If you do build a stack frame:

```
proc:
     pushq %rbp            # save caller's frame base
     movq  %rsp, %rbp      # set callee's frame base

       ...                 # body of routine proc

     movq  %rbp, %rsp      # discard callee's frame
     popq  %rbp            # reset caller's frame base
     ret
```

Reserve %rbp for this purpose if you're doing this.

What does this do?

Example: `incr`

This example doesn't use explicit frames!

```
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
```

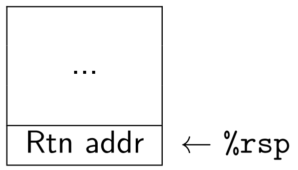
Register	Use(s)
%rdi	Argument p
%rsi	Argument val, y
%rax	x, return value

Example: Calling `incr` #1

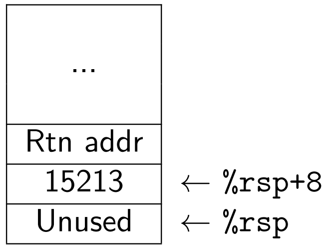
```
long call_incr() {

   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

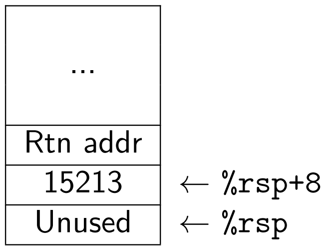


Example: Calling `incr` #2

```
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



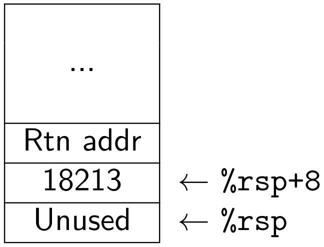
Register	Use(s)
%rdi	&v1
%rsi	3000

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 addr
18213 ← %rsp+8
Unused ← %rsp

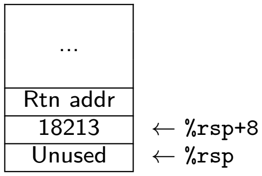
Register	Use(s)
%rdi	&v1
%rsi	3000

Example: Calling `incr` #4

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

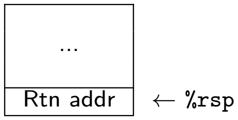
```
call_incr:
   subq   $16, %rsp
   movq   $15213, 8(%rsp)
   movl   $3000, %esi
   leaq   8(%rsp), %rdi
   call   incr

   addq   8(%rsp), %rax
   addq   $16, %rsp

   ret
```

Stack Structure


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

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

Updated Stack Structure

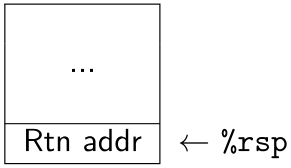

...
Rtn addr ← %rsp

Example: Calling `incr` #5

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

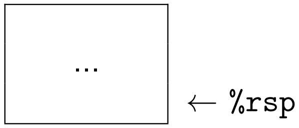
```
call_incr:
   subq   $16, %rsp
   movq   $15213, 8(%rsp)
   movl   $3000, %esi
   leaq   8(%rsp), %rdi
   call   incr
   addq   8(%rsp), %rax
   addq   $16, %rsp

   ret
```

Updated Stack Structure


...
Rtn addr ← %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 be used for temporary storage?

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

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

- Contents of register `%rdx` are overwritten by `who`
- This could be trouble; something should be done!
- Need to coordinate between caller and callee.

Register Saving Conventions

When procedure `yoo` calls `who`:

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

Can register 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 Caller-saved Registers

`%rax`

- Return value
- Also caller-saved
- Can be modified by procedure

`%rdi,%rsi,%rdx,%rcx,%r8,%r9`

- Arguments
- Also caller-saved
- Can be modified by procedure

`%r10, %r11`

- Caller-saved
- Can be modified by procedure

Return value	%rax
Argument 1	%rdi
Argument 2	%rsi
Argument 3	%rdx
Argument 4	%rcx
Argument 5	%r8
Argument 6	%r9
Caller-saved temporaries	%r10
	%r11

---

x86-64 Linux Callee-saved Registers

`%rbx, %r12, %r13, %r14, %r15`

- Callee-saved
- Callee must save and restore

`%rbp`

- Callee-saved
- Callee must save and restore
- May be used as frame pointer
- Can mix and match

`%rsp`

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

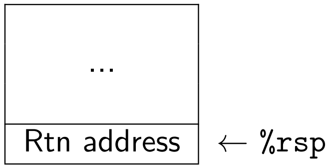
Callee-saved Temporaries	%rbx
	%r12
	%r13
	%r14
	%r15
Special	%rbp
Special	%rsp

Callee-Saved Example #1

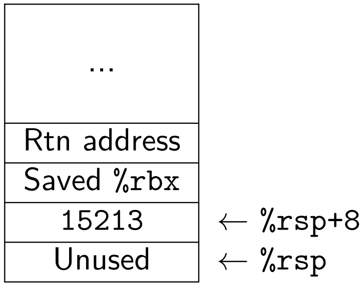
```
long call_incr2( long x ) {
  long v1 = 15213;
  long v2 = incr( &v1, 3000 )
    ;
  return x + v2;
}
```

```
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
```

Initial Stack Structure



Resulting Stack Structure



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

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

Pre-return Stack Structure

...	
Rtn address	← %rsp

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    $1, %rdi
   call    pcount_r
   addq    %rbx, %rax
   popq    %rbx
.L6:
   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);
}
```

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

```
pcount_r:

   movl    $0, %eax
   testq   %rdi, %rdi
   je      .L6

   pushq   %rbx
   movq    %rdi, %rbx
   andl    $1, %ebx
   shrq    $1, %rdi
   call    pcount_r
   addq    %rbx, %rax
   popq    %rbx
.L6:
   ret
```

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);
}
```

...	
Rtn address	
Saved %rbx	← %rsp

```
pcount_r:
   movl    $0, %eax
   testq   %rdi, %rdi
   je      .L6

   pushq   %rbx

   movq    %rdi, %rbx
   andl    $1, %ebx
   shrq    $1, %rdi
   call    pcount_r
   addq    %rbx, %rax
   popq    %rbx
.L6:
   ret
```

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

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);
}
```

Register	Use(s)	Type
%rdi	x >> 1	Rec. argument
%rax	x & 1	Caller-saved

```
pcount_r:
   movl     $0, %eax
   testq    %rdi, %rdi
   je       .L6
   pushq    %rbx

   movq     %rdi, %rbx
   andl     $1, %ebx
   shrq     $1, %rdi

   call     pcount_r
   addq     %rbx, %rax
   popq     %rbx
.L6:
   ret
```

Recursive Function Call

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

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

```
pcount_r:
   movl     $0, %eax
   testq    %rdi, %rdi
   je       .L6
   pushq    %rbx
   movq     %rdi, %rbx
   andl     $1, %ebx
   shrq     $1, %rdi

   call     pcount_r

   addq     %rbx, %rax
   popq     %rbx
.L6:
   ret
```

Recursive Function Result

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

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

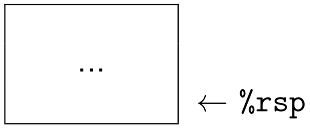
```
pcount_r:
   movl     $0, %eax
   testq    %rdi, %rdi
   je       .L6
   pushq    %rbx
   movq     %rdi, %rbx
   andl     $1, %ebx
   shrq     $1, %rdi
   call     pcount_r

   addq     %rbx, %rax

   popq     %rbx
.L6:
   ret
```

Recursive Function Completion

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

Register	Use(s)	Type
%rax		Return value

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

   popq     %rbx
.L6:
   ret
```



Observations About Recursion

Handled without Special Consideration

- Stack frames mean that each function call has private storage
    - Saved registers and 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)
- 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

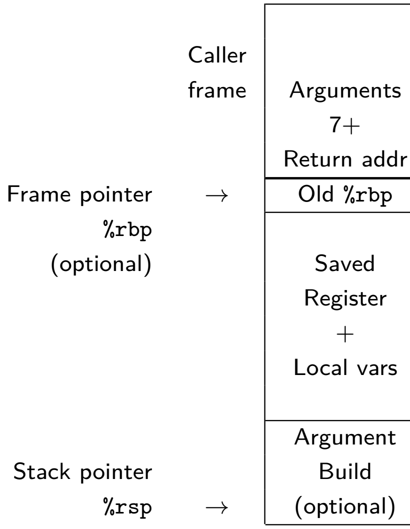
Important Points

- Stack is the right data structure for procedure call / return; if P calls Q, then Q returns before P

Recursion (and mutual recursion) are 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)



Caller frame

Arguments 7+

Return addr

Frame pointer `%rbp` (optional) →

Old `%rbp`

Saved Register + Local vars

Argument Build (optional)

Stack pointer `%rsp` →