

# CSCI 2021: x86-64 Control Flow

Chris Kauffman

*Last Updated:  
Mon Feb 28 01:25:03 PM CST 2022*

# Logistics

## Reading Bryant/O'Hallaron

- ▶ Ch 3.6: Control Flow
- ▶ Ch 3.7: Procedure calls

## Goals

- ▶ Finish Assembly Basics
- ▶ Jumps and Control flow
- ▶ Comparison / Test Instructions
- ▶ Procedure calls
- ▶ Stack Manipulation

## Assignments

- ▶ Lab06 GDB / HW06 Assembly Basics, Due Tue 3/1
- ▶ Lab07 / HW07 this week on assembly

## Project 2: Due 3/1 2/28

- ▶ Problem 1: Thermometer C Functions (50%)
- ▶ Problem 2: Puzzlebox via GDB (50%)

## Project 3 later this week

# Control Flow in Assembly and the Instruction Pointer

- ▶ No high-level conditional or looping constructs in assembly
- ▶ Only `%rip`: Instruction Pointer or “Program Counter”: memory address of the next instruction to execute
- ▶ Don’t mess with `%rip` by hand: automatically increases as instructions execute so the next valid instruction is referenced
- ▶ Jump instructions modify `%rip` to go elsewhere
- ▶ Typically label assembly code with positions of instructions that will be the target of jumps
- ▶ **Unconditional Jump** Instructions always jump to a new location.
- ▶ **Comparison / Test** Instruction, sets EFLAGS bits indicating relation between registers/values
- ▶ **Conditional Jump** Instruction, jumps to a new location if certain bits of EFLAGS are set, ignored if bits not set

## Exercise: Loop Sum with Instruction Pointer (rip)

- ▶ Can see direct effects on rip in disassembled code
- ▶ rip increases corresponding to instruction length
- ▶ Jumps include address for next rip

```
// C Code equivalent
int sum=0, i=1, lim=100;
while(i<=lim){
    sum += i;
    i++;
}
return sum;
```

000000000000005fa <main>:

ADDR	HEX-OPCODES	ASSEMBLY	EFFECT ON RIP
5fa:	48 c7 c0 00 00 00 00	mov \$0x0,%rax	# rip = 5fa -> 601
601:	48 c7 c1 01 00 00 00	mov \$0x1,%rcx	# rip = 601 -> 608
608:	48 c7 c2 64 00 00 00	mov \$0x64,%rdx	# rip = 608 -> 60f

0000000000000060f <LOOP>:

60f:	48 39 d1	cmp %rdx,%rcx	# rip = 60f -> 612
612:	7f 08	jg 61c <END>	# rip = 612 -> 614 OR 61c
614:	48 01 c8	add %rcx,%rax	# rip = 614 -> 617
617:	48 ff c1	inc %rcx	# rip = 617 -> 61a
61a:	eb f3	jmp 60f <LOOP>	# rip = 61a -> 60f

0000000000000061c <END>:

61c:	c3	retq	# rip 61c -> return address
------	----	------	-----------------------------

# Disassembling Binaries

- ▶ Binaries hard to read on their own
- ▶ Many tools exist to work with them, notably objdump on Unix
- ▶ Can **disassemble** binary: show “readable” version of contents

```
> gcc -Og loop.s                                # COMPILE AND ASSEMBLE

> file a.out
a.out: ELF 64-bit LSB pie executable, x86-64, version 1 (SYSV),

> objdump -d a.out                             # DISASSEMBLE BINARY
a.out:      file format elf64-x86-64
...
Disassembly of section .text:
...
00000000000001119 <main>:
    1119:      48 c7 c0 00 00 00 00    mov     $0x0,%rax
    1120:      48 c7 c1 01 00 00 00    mov     $0x1,%rcx
    1127:      48 c7 c2 64 00 00 00    mov     $0x64,%rdx
0000000000000112e <LOOP>:
    112e:      48 39 d1                cmp     %rdx,%rcx
    1131:      7f 08                jg      113b <END>
    1133:      48 01 c8                add     %rcx,%rax
    1136:      48 ff c1                inc     %rcx
    1139:      eb f3                jmp     112e <LOOP>
0000000000000113b <END>:
    113b:      c3                    retq
```

## FLAGS: Condition Codes Register

- ▶ Most CPUs have a special register with “flags” for various conditions
- ▶ In x86-64 this register goes by the following names

Name	Width	Notes
FLAGS	16-bit	Most important bits in first 16
EFLAGS	32-bit	Name shown in gdb
RFLAGS	64-bit	Not used normally

- ▶ Bits in FLAGS register are **automatically** set based on results of other operations
- ▶ Pertinent examples with conditional execution

Bit	Abbrev	Name	Description
0	<b>CF</b>	Carry flag	Set if last op caused unsigned overflow
6	<b>ZF</b>	Zero flag	Set if last op yielded a 0 result
7	<b>SF</b>	Sign flag	Set if last op yielded a negative
8	TF	Trap flag	Used by gdb to stop after one ASM instruction
9	IF	Interrupt flag	1: handle hardware interrupts, 0: ignore them
11	<b>OF</b>	Overflow flag	Set if last op caused signed overflow/underflow

# Comparisons and Tests

Set the EFLAGS register by using comparison instructions

Name	Instruction	Examples	Notes
Compare	cmpX B, A	cmpl \$1,%eax	Like if(eax > 1){...}
	Like: A - B	cmpq %rsi,%rdi	Like if(rdi > rsi){...}
Test	testX B, A	testq %rcx,%rdx	Like if(rdx & rcx){...}
	Like: A & B	testl %rax,%rax	Like if(rax){...}

- ▶ Immediates like \$2 must be the first argument B
- ▶ B, A are NOT altered with cmp/test instructions
- ▶ EFLAGS register IS changed by cmp/test to indicate less than, greater than, 0, etc.

### EXAMPLES:

```
movl $5, %eax      # 5 = 0b0101
cmpl $1, %eax      # [      ] 5-1=4 : No flags
cmpl $5, %eax      # [ZF   ] 5-5=0 : Zero flag
cmpl $8, %eax      # [  SF] 5-8=-3 : Sign flag
```

```
testl $0b0110, %eax # [      ] 0101 & 0110 = 0100
testl $0b1010, %eax # [ZF   ] 0101 & 1010 = 0000
```

## Jump Instruction Summary

All control structures implemented using combination of Compare/Test + Jump instructions.

<i>Instruction</i>	<i>Jump Condition</i>	<i>FLAGS</i>
jmp LAB	Unconditional jump	-
je LAB	Equal / zero	ZF
jz LAB		ZF
jne LAB	Not equal / non-zero	!ZF
jnz LAB		!ZF
js LAB	Negative ("signed")	SF
jns LAB	Nonnegative	!SF
jg LAB	Greater-than signed	!SF & !ZF
jge LAB	Greater-than-equal signed	!SF
jl LAB	Less-than signed	SF & !ZF
jle LAB	Less-than-equal signed	SF
ja LAB	Above unsigned	!CF & !ZF
jae LAB	Above-equal unsigned	!CF
jb LAB	Below unsigned	CF & !ZF
jbe LAB	Below-equal unsigned	CF
jmp *OPER	Unconditional jump to variable address	-



## Examine: Compiler Comparison Inversion

- ▶ Often compiler inverts comparisons
- ▶  $i < n$  becomes `cmpX / jge` (jump greater/equal)
- ▶  $i == 0$  becomes `cmpX / jne` (jump not equal)
- ▶ This allows “true” case to fall through immediately
- ▶ Depending on structure, may have additional jumps
  - ▶ `if(){ .. }` usually has a single jump
  - ▶ `if(){} else {}` may have a couple

```
## Assembly translation of
## if(rbx >= 2){
##   rdx = 10;
## }
## else{
##   rdx = 5;
## }
## return rdx;
    cmpq    $2,%rbx      # compare: rbx-0
    jl     .LESSTHAN     # goto less than
    ## if(rbx >= 2){
    movq    $10,%rdx     # greater/equal
    ## }
    jmp     .AFTER
.LESSTHAN:
    ## else{
    movq    $5,%rdx      # less than
    ## }
.AFTER:
    ## rdx is 10 if rbx >= 2
    ## rdx is 5 otherwise
    movq    %rdx,%rax
    ret
```

## Exercise: The test Instruction

```
1  main:
2      movl    $0,%eax
3      movl    $5,%edi
4      movl    $3,%esi
5      movq    $0,%rdx
6      movl    $-4,%ecx
7
8      testl   %edi,%edi
9      jnz     .NONZERO
10     addl    $20,%eax
11
12     .NONZERO:
13         testl   %esi,%esi
14         jz      .FALSEY
15         addl    $30,%eax
16
17     .FALSEY:
18         testq   %rdx,%rdx
19         je      .ISNULL
20         addl    $40,%eax
21
22     .ISNULL:
23         testl   %ecx,%ecx
24         jns     .NONNEGATIVE
25         addl    $50,%eax
26
27     .NONNEGATIVE:
28         ret
```

- ▶ `testl %eax,%eax` uses bitwise AND to examine a register
- ▶ Selected by compiler to check for zero, NULL, negativity, etc.
- ▶ Followed by `je` / `jz` / `jne` / `jnz` / `js` / `jns`
- ▶ Demoed in `jmp_tests_asm.s`
- ▶ Trace the execution
- ▶ Determine final value in `%eax`

# Answers: The test Instruction

```
1  ### From jmp_tests_asm_commented.s
2  main:
3      movl    $0,%eax        # eax is 0
4      movl    $5,%edi        # set initial vals
5      movl    $3,%esi        # for registers to
6      movl    $0,%edx        # use in tests
7      movl    $-4,%ecx
8
9      ## eax=0, edi=5, esi=3, edx=NULL, ecx=-4
10     testl   %edi,%edi      # any bits set?
11     jnz     .NONZERO       # jump on !ZF (zero flag), same as jne
12     ## if(edi == 0){
13     addl    $20,%eax
14     ## }
15 .NONZERO:
16     testl   %esi,%esi      # any bits set?
17     jz      .FALSEY        # jump on ZF same as je
18     ## if(esi){
19     addl    $30,%eax
20     ## }
21 .FALSEY:
22     testq   %rdx,%rdx      # any bits set
23     je      .ISNULL        # same as jz: jump on ZF
24     ## if(rdx != NULL){
25     addl    $40,%eax
26     ## }
27 .ISNULL:
28     testl   %ecx,%ecx      # sign flag set on test to indicate negative results
29     jns     .NONNEGATIVE    # jump on !SF (not signed; e.g. positive)
30     ## if(ecx < 0){
31     addl    $50,%eax
32     ## }
33 .NONNEGATIVE:
34     ret                ## eax is return value
```

## cmov Family: Conditional Moves

- ▶ A family of instructions allows conditional movement of data into registers
- ▶ Can limit jumping in simple assignments

```
cmpq    %r8,%r9
cmovge   %r11,%r10  # if(r9 >= r8) { r10 = r11 }
cmovg    %r13,%r12  # if(r9 >  r8) { r12 = r13 }
```

- ▶ Note that condition flags are set on arithmetic operations
- ▶ cmpX is like subQ: both set FLAG bits the same
- ▶ Greater than is based on the SIGN flag indicating subtraction would be negative allowing the following:

```
subq     %r8,%r9      # r9 = r9 - r8
cmovge    %r11,%r10   # if(r9 >= 0) { r10 = r11 }
cmovg     %r13,%r12   # if(r9 >  0) { r12 = r13 }
```

# Procedure Calls

Have seen basics so far:

```
main:
    ...
    call my_func # call a function
    ## arguments in %rdi, %rsi, %rdx, etc.
    ## control jumps to my_func, returns here when done
    ...

my_func:
    ## arguments in %rdi, %rsi, %rdx, etc.
    ...
    movl $0,%eax # set up return value
    ret          # return from function
    ## return value in %rax
    ## returns control to wherever it came from
```

Need several additional notions

- ▶ Control Transfer to called function?
- ▶ Return back to calling function?
- ▶ Stack alignment and conventions
- ▶ Register conventions

# Procedure Calls Return to Arbitrary Locations

- ▶ call instructions always transfer control to start of return\_seven at line 4/5, like jmp instruction which modifies %rip
- ▶ ret instruction at line 6 must transfer control to **different locations**
  1. call-ed at line 11  
ret to line 12
  2. call-ed at line 17  
ret to line 18ret cannot be a normal jmp
- ▶ To enable return to multiple places, record a **Return Address** when call-ing, use it when ret-urning

```
1  ### return_seven_asm.s
2  .text
3  .global return_seven
4  return_seven:
5      movl    $7, %eax
6      ret     ## jump to line 12 OR 18??
7  .global main
8  main:
9      subq    $8, %rsp
10
11     call    return_seven  ## to line 5
12     leaq    .FORMAT_1(%rip), %rdi
13     movl    %eax, %esi
14     movl    $0, %eax
15     call    printf@PLT
16
17     call    return_seven  ## to line 5
18     leaq    .FORMAT_2(%rip), %rdi
19     movl    %eax, %esi
20     movl    $0, %eax
21     call    printf@PLT
22
23     addq    $8, %rsp
24     movl    $0, %eax
25     ret
26 .data
27 .FORMAT_1: .asciz "first: %d\n"
28 .FORMAT_2: .asciz "second: %d\n"
```

# call / ret with Return Address in Stack

## call Instruction

1. Push the “caller” **Return Address** onto the stack  
Return address is for instruction after call
2. Change rip to first instruction of the “callee” function

## ret Instruction

1. Set rip to Return Address at top of stack
2. Pop the Return Address off the stack shrinking stack

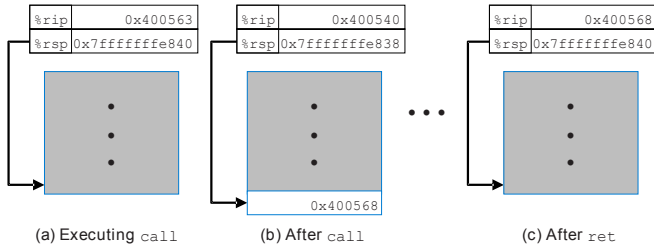


Figure: Bryant/O'Hallaron Fig 3.26 demonstrates call/return in assembly

## return\_seven\_asm.s 1/2: Control Transfer with call

### BEFORE CALL

return\_seven:

```
0x55555555139 <return_seven>  mov    $0x7,%eax
0x5555555513e <return_seven+5> retq
```

main: ...

```
0x5555555513f <main>          sub    $0x8,%rsp
=> 0x55555555143 <main+4>      callq  0x55555555139 <return_seven>
0x55555555148 <main+9>      lea    0x2ee1(%rip),%rdi
0x5555555514f <main+16>     mov    %eax,%esi
```

(gdb) stepi

```
rsp = 0x7fffffff450 -> call -> 0x7fffffff448    # push on return address
rip = 0x55555555143 -> call -> 0x55555555139    # jump control to procedure
```

### AFTER CALL

return\_seven:

```
=> 0x55555555139 <return_seven>  mov    $0x7,%eax
    0x5555555513e <return_seven+5> retq
```

main: ...

```
0x5555555513f <main>          sub    $0x8,%rsp
0x55555555143 <main+4>      callq  0x55555555139 <return_seven>
0x55555555148 <main+9>      lea    0x2ee1(%rip),%rdi
0x5555555514f <main+16>     mov    %eax,%esi
```

```
(gdb) x/gx $rsp          # stack grew 8 bytes with call
0x7fffffff448: 0x000055555555148    # return address in main on stack
```



## return\_seven\_asm.s 2/2: Control Transfer with ret

### BEFORE RET

return\_seven:

```
0x55555555139 <return_seven>  mov    $0x7,%eax
=> 0x5555555513e <return_seven+5>  retq
```

main: ...

```
0x5555555513f <main>          sub    $0x8,%rsp
0x55555555143 <main+4>        callq  0x55555555139 <return_seven>
0x55555555148 <main+9>        lea     0x2ee1(%rip),%rdi
0x5555555514f <main+16>       mov     %eax,%esi
```

(gdb) x/gx \$rsp

0x7fffffff448: 0x000055555555148 # return address pointed to by %rsp

(gdb) stepi

# EXECUTE RET INSTRUCTION

rsp = 0x7fffffff448 -> ret -> 0x7fffffff450 # pops return address off

rip = 0x5555555513e -> ret -> 0x55555555148 # sets %rip to return address

### AFTER RET

return\_seven:

```
0x55555555139 <return_seven>  mov    $0x7,%eax
0x5555555513e <return_seven+5>  retq
```

main: ...

```
0x5555555513f <main>          sub    $0x8,%rsp
0x55555555143 <main+4>        callq  0x55555555139 <return_seven>
=> 0x55555555148 <main+9>        lea     0x2ee1(%rip),%rdi
0x5555555514f <main+16>       mov     %eax,%esi
```

(gdb) print \$rsp --> \$3 = 0x7fffffff450

## Warning: `%rsp` is important for returns

- ▶ When a function is about to return `%rsp` MUST refer to the memory location of the return address
- ▶ `ret` uses value pointed to `%rsp` as the return address
- ▶ Major problems arise if this is not so
- ▶ Using `pushX` / `subq` instructions to extend stack during a function MUST be coupled with `popX` / `addq` instructions
- ▶ There are computer security issues associated stack-based return value we will discuss later

# Messing up the Return Address

```
### return_seven_buggy_asm.s
.text
.global return_seven
return_seven:
    pushq    $0x42        # push but no pop before returning
    movl     $7, %eax
    ret                # %rsp points to a 0x42 return address - BAD!
                    #
```

REG	VALUE	ADDRESS	VALUE	NOTE
rax	7	0x77128	0x554210	Ret Address
rsp	0x77120	---> 0x77120	0x42	Pushed Val

#

```
> gcc return_seven_buggy_asm.s
```

```
> ./a.out
```

```
Segmentation fault (core dumped)    ## definitely a memory problem
```

```
> valgrind ./a.out                    ## get help from Valgrind
```

```
...
```

```
==2664132== Jump to the invalid address stated on the next line
```

```
==2664132==    at 0x42: ???                ## execute instruction at address 0x42??
```

```
==2664132==    by 0x109149: ??? (in a.out)
```

```
==2664132== Address 0x42 is not stack'd, malloc'd or (recently) free'd
```

*Valgrind output is not obvious but most reports like this indicate clobbering a return address as happened here through unbalanced push/pop instructions.*

# Stack Alignment

- ▶ According to the strict x86-64 ABI, must align `rsp` (stack pointer) to 16-byte boundaries when calling functions
- ▶ Will often see arbitrary pushes or subtractions to align
  - ▶ Always enter a function with 8-byte Return Address on the stack
  - ▶ Means that it is aligned to 8-byte boundary
- ▶ `rsp` changes must be undone prior to return

```
main:                                # enter with at 8-byte boundary
    subq    $8, %rsp                 # align stack for func calls
    ...
    call    sum_range                # call function
    ...
    addq    $8, %rsp                 # remove rsp change
    ret
```

- ▶ Failing to align the stack may work but may break
- ▶ Failing to “undo” stack pointer changes will likely result in return to the wrong spot : major problems

## x86-64 Register/Procedure Convention

- ▶ Used by Linux/Mac/BSD/General Unix
- ▶ Params and return in registers if possible

### Parameters and Return

- ▶ First 6 arguments are put into
  1. rdi / edi / di (arg 1)
  2. rsi / esi / si (arg 2)
  3. rdx / edx / dx (arg 3)
  4. rcx / ecx / cx (arg 4)
  5. r8 / r8d / r8w (arg 5)
  6. r9 / r9d / r9w (arg 6)
- ▶ Additional arguments are pushed onto the stack
- ▶ Return Value in rax / eax / ...

### Caller/Callee Save

**Caller save** registers: alter freely

```
rax rcx rdx rdi rsi  
r8  r9  r10 r11
```

**Callee save** registers: must restore these on return

```
rbx rbp r12 r13 r14  
r15
```

Careful messing with stack pointer

```
rsp # stack pointer
```

# Pushing and Popping the Stack

- ▶ If local variables are needed on the stack, can use `push` / `pop` for these
- ▶ `pushX %reg`: grow `rsp` (lower value), move value to top of main memory stack,
  - ▶ `pushq %rax`: grows `rsp` by 8, puts contents of `rax` at top
  - ▶ `pushl $25`: grows `rsp` by 4, puts constant 5 at top of stack
- ▶ `popX %reg`: move value from top of main memory stack to `reg`, shrink `rsp` (higher value)
  - ▶ `popl %eax`: move (`%rsp`) to `eax`, shrink `rsp` by 4

main:

```
pushq    %rbp                # save register, aligns stack
                                # like subq $8,%rsp; movq %rbp,(%rsp)
call     sum_range            # call function
movl     %eax, %ebp           # save answer
...
call     sum_range            # call function, ebp not affected
...
popq     %rbp                # restore rbp, shrinks stack
                                # like movq (%rsp),%rbp; addq $8,%rsp
ret
```

## Exercise: Local Variables which need an Address

### Compare code in files

- ▶ `swap_pointers.c` : familiar C code for swap via pointers
- ▶ `swap_pointers_asm.s` : hand-coded assembly version

### Determine the following

1. Where are local C variables `x,y` stored in assembly version?
2. Where does the assembly version “grow” the stack?
3. How are the values in `main()` passed as arguments to `swap_ptr()`?
4. Where does the assembly version “shrink” the stack?

## Exercise: Local Variables which need an Address

```
1 #include <stdio.h>
2
3 void swap_ptr(int *a, int *b){
4     int tmp = *a;
5     *a = *b;
6     *b = tmp;
7     return;
8 }
9
10 int main(int argc, char *argv[]){
11     int x = 19;
12     int y = 31;
13     swap_ptr(&x, &y);
14     printf("%d %d\n",x,y);
15     return 0;
16 }
```

```
1 .text
2 .global swap_ptr
3 swap_ptr:
4     movl    (%rdi), %eax
5     movl    (%rsi), %edx
6     movl    %edx, (%rdi)
7     movl    %eax, (%rsi)
8     ret
9
10 .global main
11 main:
12     subq    $8, %rsp
13     movl    $19, (%rsp)
14     movl    $31, 4(%rsp)
15     movq    %rsp, %rdi
16     leaq    4(%rsp), %rsi
17     call    swap_ptr
18
19     leaq    .FORMAT(%rip), %rdi
20     movl    (%rsp), %esi
21     movl    4(%rsp), %edx
22     movl    $0, %eax
23     call    printf@PLT
24
25     addq    $8, %rsp
26     movl    $0, %eax
27     ret
28
29 .data
30 .FORMAT:
31     .asciz "%d %d\n"
```



# Answers: Local Variables which need an Address

1. Where are local C variables x,y stored in assembly version?
2. Where does the assembly version “grow” the stack?
3. How are the values in main() passed as arguments to swap\_ptr()?

// C CODE

```
int x = 19, y = 31;
```

```
swap_ptr(&x, &y) // need main mem addresses for x,y
```

### ASSEMBLY CODE

main:

# main() function

```
subq    $8, %rsp    # grow stack by 8 bytes
```

```
movl    $19, (%rsp) # move 19 to local variable x
```

```
movl    $31, 4(%rsp) # move 31 to local variable y
```

```
movq    %rsp, %rdi   # address of x into rdi, 1st arg to swap_ptr()
```

```
leaq    4(%rsp), %rsi # address of y into rsi, 2nd arg to swap_ptr()
```

```
call    swap_ptr     # call swap function
```

4. Where does the assembly version “shrink” the stack?

```
addq    $8, %rsp    # shrink stack by 8 bytes
```

```
movl    $0, %eax     # set return value
```

```
ret
```

# Diagram of Stack Variables

- ▶ Compiler determines if local variables go on stack
- ▶ If so, calculates location as  $\text{rsp} + \text{offsets}$

<pre> 1 // C Code: locals.c 2 int set_buf(char *b, int *s); 3 int main(){ 4     // locals re-ordered on 5     // stack by compiler 6     int size = -1; 7     char buf[16]; 8     ... 9     int x = set_buf(buf, &amp;size); 10 ## .EQUIVALENT ASSEMBLY 11 main: 3     subq    \$24, %rsp 4     movl    \$-1, (%rsp) 5     .... 6     leaq    4(%rsp), %rdi 7     leaq    0(%rsp), %rsi 8     call    set_buf 9     movl    %eax, %r8 10    ... 11    addq    \$24, %rsp </pre>	<pre> # space for buf/size and stack alignment # old rip already in stack so: 20+4+8 = 32 # initialize buf and size: main line 6 # address of buf arg1 # address of size arg2 # call function, aligned to 16-byte boundary # get return value # shrink stack size </pre>
---	--

REG	VALUE	Name
rsp	#1024	top of stack during main
MEM		
...	...	...
#1031	h	buf[3]
#1030	s	buf[2]
#1029	u	buf[1]
#1028	p	buf[0]
#1024	-1	size

# Summary of Procedure Calls: `ABC()` calls `XYZ()`

<code>ABC()</code>	Caller	<code>callq XYZ</code>	# <code>ABC</code> to <code>XYZ</code>
<code>XYZ()</code>	Callee	<code>retq</code>	# <code>XYZ</code> to <code>ABC</code>

1. `ABC()` “saves” any Caller Save registers it needs by either copying them into Callee Save registers or pushing them into the stack
2. `ABC()` places up to 6 arguments in `%rsi`, `%rdi`, `%rdx`, ..., remaining arguments in stack
3. `ABC()` ensures that stack is “aligned”: `%rsp` contains an address that is evenly divisible by 16
4. `ABC()` issues the `callq ABC` instruction which (1) grows the stack by subtracting 8 from `%rsp` and copies a return address to that location and (2) changes `%rip` to the starting address of `func`
5. `XYZ()` now has control: `%rip` points to first instruction of `XYZ()`
6. `XYZ()` may issue `pushX val` instructions or `subq N,%rsp` instructions to grow the stack for local variables
7. `XYZ()` may freely change Caller Save registers BUT Callee Save registers it changes must be restored prior to returning.
8. `XYZ()` must shrink the stack to its original position via `popX %reg` or `addq N,%rsp` instructions before returning.
9. `XYZ()` sets `%rax` / `%eax` / `%ax` to its return value if any.
10. `XYZ()` finishes, issues the `retq` instruction which (1) sets the `%rip` to the 8-byte return address at the top of the stack (pointed to by `%rsp`) and (2) shrinks the stack by doing `addq $8,%rsp`
11. `ABC()` function now has control back with `%rip` pointing to instruction after `call XYZ`; may have a return value in `%rax` register
12. `ABC()` must assume all Caller Save registers have changed

# Historical Aside: Base Pointer rbp was Important

```
int bar(int, int, int);
int foo(void) {
    int x = callee(1, 2, 3);
    return x+5;
}
```

- ▶ 32-bit x86 / IA32 assembly used rbp as bottom of stack frame, rsp as top.
- ▶ Push all arguments onto the stack when calling changing both rsp and rbp
- ▶ x86-64: default rbp to general purpose register, not used for stack tracking

# Old x86 / IA32 calling sequence: set both %esp and %ebp for function call foo:

```
pushl %ebp           # modifying ebp, save it
## Set up for function call to bar()
movl %esp,%ebp       # new frame for next function
pushl 3              # push all arguments to
pushl 2              # function onto stack
pushl 1              # no regs used
call bar             # call function, return val in %eax
## Tear down for function call bar()
movl %ebp,%esp       # restore stack top: args popped
## Continue with function foo()
addl 5,%eax          # add onto answer
popl %ebp            # restore previous base pointer
ret
```