

# CSCI 2021: x86-64 Control Flow

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# 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

## P2 Grades Posted

## Lab07 / HW07

- ▶ Assembly Coding and debugging
- ▶ Chance to configure assembly environment
- ▶ All techniques used in Project 3

## Project 3

1. Battery ASM Functions
2. Binary Bomb via GDB

Overview Video Posted  
Testing bugs fixed via  
`make sanity-restore`

# Announcements

## Unified Office Hours Tue 25-Oct @ Toaster, Walter Library

- ▶ 8am-6pm
- ▶ All in-person TA office hours there
- ▶ Basement of Walter Library, behind Wise Owl Cafe

## Unified Office Hours Tue 01-Nov @ Keller 3-180

- ▶ 8am-6pm
- ▶ All in-person TA office hours there
- ▶ Just outside Atrium on ground level

# Control Flow in Assembly and the Instruction Pointer

## Instruction Pointer Register

- ▶ **%rip: special register** (not general purpose) referred to as the **Instruction Pointer** or Program Counter
- ▶ **%rip** contains main memory address of next assembly instruction to execute
- ▶ After executing an instruction, **%rip** automatically updates to the subsequent instruction  
OR in a Jump instruction, **%rip** changes non-sequentially
- ▶ **Do not** add/subtract with **%rip** via `addq/subq`: **%rip** automatically updates after each instruction

## Jump Instructions

- ▶ **Labels** in assembly indicate jump targets like `.LOOP`:
- ▶ **Unconditional Jump**: always jump to a new location by changing **%rip** non-sequentially
- ▶ **Comparison / Test**: Instruction, sets EFLAGS bits indicating relation between registers/values (greater, less than, equal)
- ▶ **Conditional Jump**: Jumps to a new location if certain bits of EFLAGS are set by changing **%rip** non-sequentially; otherwise continues sequential execution

## 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: each bit is True/False for a specific condition
- ▶ 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-2
    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
```

# Logical And / Or in Assembly

Logical boolean operators like `a && b` and `x || y` translate sequences of compare/test instructions followed by conditional jumps

```
// andcond.c
int andcond(int edi){
    int ecx;
    if(edi >= 2 && edi <= 10){
        ecx = 10;
    }
    else{
        ecx = 5;
    }
    return ecx;
}
```

C Boolean expressions may “short circuit”: never execute code associated with later parts of the condition if early part resolves conditional

```
### andcond_asm.s
.text
.global andcond
andcond:
    cmpl $2,%edi      # compare: edi-2
    jl .ELSE          #
    cmpl $10, %edi    # compare: edi-10
    jg .ELSE          #

    ## if(edi >= 2 && edi <= 10){
    movl $10,%ecx     # greater/equal
    ## }

    jmp .AFTER

.ELSE:
    ## else{
    movl $5,%ecx      # less than
    ## }

.AFTER:
    movl %ecx,%eax
    ret
```

## cmov Family: Conditional Moves

- ▶ Instruction family which copies data conditioned on FLAGS<sup>1</sup>
- ▶ 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 flags set on **all 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 }
```

---

<sup>1</sup>Other architectures like ARM have conditional versions of many instructions like `addlt r1, r2, r3`; RISC V ditches the FLAGS register in favor of jumps based on comparisons like `BLT x0, x1, LOOP`

# 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 to shrink stack

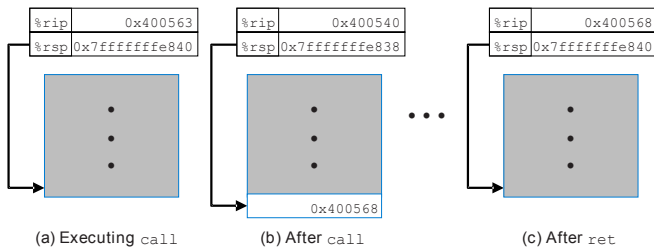


Figure: Bryant/O'Hallaron Fig 3.26 demonstrates call/return in assembly

## 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
- ▶ Segmentation Faults often occur if `%rsp` is NOT the return address: attempt to fetch/execute instructions out of bounds
- ▶ Stack is often used to store local variables, stack pointer `%rsp` is manipulated via `pushX` / `subq` instructions to grow the stack.
- ▶ Before returning MUST shrink stack and restore `%rsp` to its original value via `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 -g 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: ??? (return_seven_buggy_asm.s:18)
==2664132== Address 0x42 is not stack'd, malloc'd or (recently) free'd
```

*Valgrind reports like this often 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
  - ▶ Functions called with 16-byte alignment
  - ▶ `call` pushes 8-byte Return Address on the stack
  - ▶ At minimum, must grow stack by 8 bytes to `call` again
- ▶ `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

RetVal	rax / eax / ax / al
Arg 1	rdi / edi / di / dil
Arg 2	rsi / esi / si / sil
Arg 3	rdx / edx / dx / dl
Arg 4	rcx / ecx / cx / cl
Arg 5	r8 / r8d / r8w / r8b
Arg 6	r9 / r9d / r9w / r9b
Arg 7	Push into the stack
Arg 8	Push into the stack
...	...

C function prototype indicates number, order, type of args so it is known which registers args will be in

```
int myfunc(char *cp,  
            int a, long b);
```

## Caller/Callee Save

**Caller save** registers: alter freely

rax rcx rdx rdi rsi  
r8 r9 r10 r11 # 9 regs

**Callee save** registers: must restore these before returning

rbx rbp r12 r13 r14  
r15 # 6 regs

**Stack Pointer:** special considerations discussed in detail

rsp # 1 reg

# Caller and Callee Save Register Mechanics

```
main:          # main: the calleR
...
movq $21, %rdi  # calleR save arg 1
movq $31, %rsi  # calleR save arg 2
movq $41, %r10  # calleR save
movq $7, %rbx   # calleE save
movq $11, %r12  # calleE save

call foo # foo: the calleE

## | ? | %rdi | calleR save arg 1 |
## | ? | %rsi | calleR save arg 2 |
## | ? | %r10 | calleR save      |
## | 7 | %rbx | calleE save      |
## | 11 | %r12 | calleE save      |

cmpq $21, %rdi  # unpredictable
cmpq $7, %rbx   # predictably equal

# main MUST restore %rbx and %r12 to
# original values as function above
# main() expects them to be unchanged
```

## CalleR Save Regs

May all change across  
function call boundaries.

Not a problem for **Leaf  
Functions** which do not call  
any other funcs

## CalleE Save Regs

Have the same values in them  
after a function call

Using them requires saving  
their original values in the  
stack and restoring them



# Pushing and Popping the Stack

- ▶ If local variables or callee save regs are needed on the stack, can use push / pop for these
- ▶ Push and Pop Instructions are compound: manipulate %rsp and move data in single instruction

pushX data	<b>Grow Stack, store data at top</b>
pushq %rax	Like: subq \$8,%rsp; movq %rax, (%rsp)
pushl \$24	Like: subq \$4,%rsp; movq \$25, (%rsp)
popX data	<b>Shrink Stack, restore data from it</b>
popl %edi	Like: movl (%rsp),%edi; addq \$4,%rsp;
popq %rax	Like: movq (%rsp),%rax; addq \$8,%rsp;

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 // swap_pointers.c
2 #include <stdio.h>
3
4 void swap_ptr(int *a, int *b){
5     int tmp = *a;
6     *a = *b;
7     *b = tmp;
8     return;
9 }
10
11 int main(int argc, char *argv[]){
12     int x = 19;
13     int y = 31;
14     swap_ptr(&x, &y);
15     printf("%d %d\n", x, y);
16     return 0;
17 }
```

```
1 # swap_pointers_asm.s
2 .text
3 .global swap_ptr
4 swap_ptr:
5     movl    (%rdi), %eax
6     movl    (%rsi), %edx
7     movl    %edx, (%rdi)
8     movl    %eax, (%rsi)
9     ret
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 .data
29 .FORMAT:
30     .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  $\text{rsp} + \text{offsets}$

```
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, &size);
10    ...
11 }
```

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

```
1 ## EQUIVALENT ASSEMBLY
2 main:
3     subq    $24, %rsp        # space for buf/size and stack alignment
4     movl    $-1, (%rsp)      # retAddr:8, locals: 16, padding: 8, tot: 32
5     ....                    # initialize buf and size: main line 6
6     leaq    4(%rsp), %rdi     # address of buf arg1
7     leaq    0(%rsp), %rsi     # address of size arg2
8     call    set_buf          # call function, aligned to 16-byte boundary
9     movl    %eax, %r8         # get return value
10    ...
11    addq    $24, %rsp         # shrink stack 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 = bar(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
# Push all arguments into the stack
```

```
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
```