CMSC216: x86-64 Control Flow

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Logistics

Reading Bryant/O'Hallaron

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

Goals

- ► ~~RIP: Instruction Pointer~~
- ► Jumps and Control flow
- ► Comparison / Test Instructions
- ► Procedure calls
- ► Stack Manipulation

Assignments

- ► Lab07: Stack Manipulation for Procedure Calls
- ► HW07: GDB on Binaries, Stack Smashing
- ► P3: Due Mon 07-Apr Pre-break Draft version of P3 has had minor typos/bugs fixed and is now finalized

Announcements

Midterm Feedback Posted

- ▶ Linked at the bottom of the course schedule
- ▶ Responses for some free-form feedback is given
- ▶ Thanks to all that provided feedback

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

```
00000000000005fa <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
000000000000060f <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
000000000000061c <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:
...
0000000000001119 <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
000000000000112e <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>
000000000000113b <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 like addition / subtraction / etc.

Bit	Abbrev	Name	Description
0	**CF**	Carry flag	Set if last op caused Unsigned overflow
6	**ZF**	Zero flag	Set if last op yielded a 0 result
7	**SF**	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	**OF**	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.

Instruction	Jump Condition	FLAGS
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 xor OF) and !ZF
jge LAB	Greater-than-equal signed	!(SF xor OF)
jl LAB	Less-than signed	(SF xor OF)
jle LAB	Less-than-equal signed	(SF xor !OF) or !ZF
ja LAB	Above unsigned	!CF and !ZF
jae LAB	Above-equal unsigned	!CF
jb LAB	Below unsigned	CF and !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
```

Logical And / Or in Assembly

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

```c
// 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

```asm
### 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
```

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`
- ▶ Trace the execution
- ▶ Determine final value in `%eax`
- ▶ Will demo `jmp_tests_asm.s` in GDB to show how `EFLAGS` changes

Answers: The `test` Instruction

```asm
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
```

```c
// Rough C translation is
if(edi == 0){
  eax += 20;
}
if(esi){
  eax += 30;
}
if(rdx != NULL){
  eax += 40;
}
if(ecx < 0){
  eax += 50;
}
```

cmov Family: Conditional Moves

- Instruction family which copies data conditioned on FLAGS[1]
- 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 }
```

---

[1]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 18

    `ret` 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
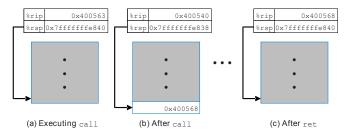
2. Pop the Return Address off to shrink stack

| %rip | 0x400563 |
| %rsp | 0x7fffffffe840 |

| %rip | 0x400540 |
| %rsp | 0x7fffffffe838 |

| %rip | 0x400568 |
| %rsp | 0x7fffffffe840 |

0x400568

(a) Executing `call`   (b) After `call`   · · ·   (c) After `ret`

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

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return_seven_asm.s 1/2: Control Transfer with `call`

```
### BEFORE CALL
return_seven:
    0x555555555139 <return_seven>    mov    $0x7,%eax
    0x55555555513e <return_seven+5>  retq

main: ...
    0x55555555513f <main>            sub    $0x8,%rsp
=> 0x555555555143 <main+4>           callq  0x555555555139 <return_seven>
    0x555555555148 <main+9>          lea    0x2ee1(%rip),%rdi
    0x55555555514f <main+16>         mov    %eax,%esi


(gdb) stepi
rsp = 0x7fffffffe450 -> call -> 0x7fffffffe448  # push on return address
rip = 0x555555555143 -> call -> 0x555555555139  # jump control to procedure


### AFTER CALL
return_seven:
=> 0x555555555139 <return_seven>     mov    $0x7,%eax
    0x55555555513e <return_seven+5>  retq

main: ...
    0x55555555513f <main>            sub    $0x8,%rsp
    0x555555555143 <main+4>          callq  0x555555555139 <return_seven>
    0x555555555148 <main+9>          lea    0x2ee1(%rip),%rdi
    0x55555555514f <main+16>         mov    %eax,%esi


(gdb) x/gx $rsp                            # stack grew 8 bytes with call
0x7fffffffe448: 0x0000555555555148  # return address in main on stack
```

return_seven_asm.s 2/2: Control Transfer with `ret`

```
### BEFORE RET
return_seven:
    0x555555555139 <return_seven>    mov    $0x7,%eax
=> 0x55555555513e <return_seven+5> retq

main: ...
    0x55555555513f <main>            sub    $0x8,%rsp
    0x555555555143 <main+4>          callq  0x555555555139 <return_seven>
    0x555555555148 <main+9>          lea    0x2ee1(%rip),%rdi
    0x55555555514f <main+16>         mov    %eax,%esi

(gdb) x/gx $rsp
0x7fffffffe448: 0x0000555555555148  # return address pointed to by %rsp

(gdb) stepi                                # EXECUTE RET INSTRUCTION
rsp = 0x7fffffffe448 -> ret -> 0x7fffffffe450   # pops return address off
rip = 0x55555555513e -> ret -> 0x555555555148   # sets %rip to return address

### AFTER RET
return_seven:
    0x555555555139 <return_seven>    mov    $0x7,%eax
    0x55555555513e <return_seven+5> retq

main: ...
    0x55555555513f <main>            sub    $0x8,%rsp
    0x555555555143 <main+4>          callq  0x555555555139 <return_seven>
=> 0x555555555148 <main+9>          lea    0x2ee1(%rip),%rdi
    0x55555555514f <main+16>         mov    %eax,%esi

(gdb) print $rsp      -->  $3 = 0x7fffffffe450
```

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 failure to restore the stack pointer as
happened here. If the stack grows, shrink it before returning.

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
```

- Skipping stack alignment works on some machines and breaks on others due to differing processor internals

  "I passed all the tests on GRACE but a bunch failed on Gradescope! What gives?"

  – Common lament of past students

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

```c
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

sumrange_asm.s

Full example of callee save regs like sumrange_c.c

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    Grow Stack, store data at top
pushq %rax    Like: subq $8,%rsp; movq %rax,(%rsp)
pushl $25     Like: subq $4,%rsp; movq $25, (%rsp)

popX data     Shrink Stack, restore data from it
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

```c
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 }
```

```asm
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 `rsp` + 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: 20, padding: 4, 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()

```
ABC()   Caller   callq XYZ   # ABC to XYZ
XYZ()   Callee   retq        # XYZ to ABC
```

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 staring 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

History: Base Pointer `rbp` was Previously Special Use

- ▶ 32-bit x86 / IA32 assembly used `rbp` and `rsp` to describe stack frames
- ▶ All function args pushed onto the stack when calling, changes both `rsp` and `rbp`
- ▶ x86-64: optimizes `rbp` to general purpose register, not used for stack purposes

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

```
# 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
```