Computer Architecture (Practical Class)
Assembly: Controlling Execution Flow

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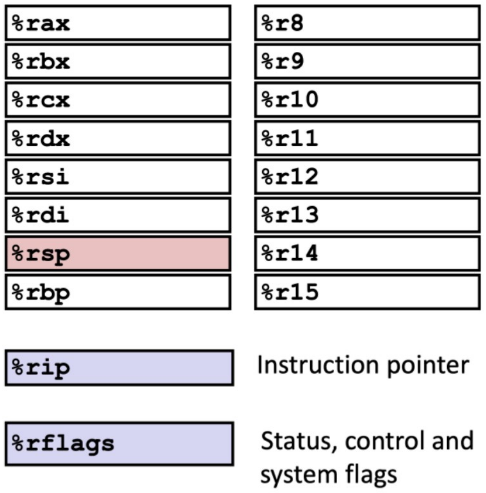
Data-dependent control flow

- So far, we have only considered the behavior of straight-line code, where instructions follow one another in sequence
- Some constructs in C, such as conditionals, loops, and switches, require conditional execution
  - Where the sequence of operations that get performed depends on the outcomes of tests applied to the data
- The CPU has a *FLAGS* register, where a set of single-bit condition codes describe the attributes of the most recent arithmetic or logical operation
- The execution order of a set of instructions can be altered with a *jump* instruction, indicating that control should pass to some other part of the program, possibly contingent on the result of some test on conditin codes

The RFLAGS Register

- 64-bit register used as a collection of bits representing Boolean values to store the results of operations and the state of the processor
- Each bit is a Boolean flag (1 - active/true, 0 - inactive/false)
- As instructions execute, they may change some of these flags

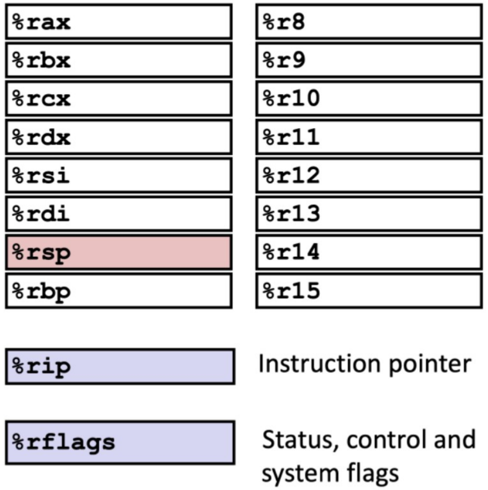


The RFLAGS Register - Important flags for control flow

- CF - carry flag
  - Set on most significant bit carry or borrow; cleared otherwise
- ZF - zero flag
  - Set if result is zero; cleared otherwise
- SF - sign flag
  - Set equal to the most significant bit of result (0 if positive, 1 if negative)
- OF - overflow flag
  - Set if result is too large (a positive number) or too small (a negative number) to fit in destination operand; cleared otherwise

The RIP Register

- The program counter (called *%rip* in x86-64) indicates the address in memory of the next instruction to be executed
- After the instruction's execution, %rip is automatically increased to the address of the next instruction
- A jump instruction can cause the execution to switch to a completely different position in the program
  - Unconditionally - the instruction pointer is set to a new value
  - Conditionally - the instruction pointer is set to a new value if a condition is true



`jmp` *address*

- The `jmp` instruction changes the RIP register to `address`, a location within the program to jump to, usually denoted by a label

Unconditional Jump Example

```
.global jmptest
jmptest:
    ...
    movq %rax, %rcx
    addq %rdx, %rcx
    jmp end

    # this line is never executed!
    movq $1, %rax

end:
    movq $10, %rax

    ...
    ret
```

- Conditional jumps are taken or not depending on the state of the RFLAGS register at the time the branch is executed
- Each conditional jump instruction examines specific flag bits to determine whether the condition is proper for the jump to occur. Some examples:
    - `JE` – Jump if equal (ZF=1)
    - `JL` – Jump if less (SF<>OF)
    - `JG` – Jump if greater (ZF=0 e SF=OF)
- Similarly to the `jmp` instruction, they only take one argument indicating the address within the program to jump to

Important note

- Before a conditional jump, **condition codes in RFLAGS must be set appropriately by some operation...**

`cmp` *operand1*, *operand2*

- The compare instruction is the most common way to evaluate two values for a conditional jump
- Compares the second operand with the first operand by executing a subtraction (operand2 – operand1)
- Does not change the operands, but changes the condition codes in the `RFLAGS` register
- Examples:
  - if operand2 == operand1 then ZF (zero flag) = 1
  - if operand2 > operand1 then SF (sign flag) = 0
  - if operand2 < operand1 then SF (sign flag) = 1
- The `CMP` instruction can be applied to 8 (b), 16 (w), 32 (l), or 64(q) bits

jX	Condition	Description
`jmp`	`1`	Unconditional
`je`	`ZF`	Equal / Zero
`jne`	`~ZF`	Not Equal / Not Zero
`js`	`SF`	Negative
`jns`	`~SF`	Nonnegative
`jg`	`~(SF^OF)&~ZF`	Greater (signed)
`jge`	`~(SF^OF)`	Greater or Equal (signed)
`jl`	`(SF^OF)`	Less (signed)
`jle`	`(SF^OF)|ZF`	Less or Equal (signed)
`ja`	`~CF&~ZF`	Above (unsigned)
`jb`	`CF`	Below (unsigned)

Controlling Execution Flow

```
    ...
    # compares %rcx with %rsi through %rsi - %rcx
    cmpq %rcx, %rsi
    jg jmp_rsi_is_greater
    je jmp_rsi_is_equal
    jl jmp_rsi_is_less
jmp_rsi_is_greater:
    movq $1, %rax
    jmp end
jmp_rsi_is_equal:
    movq $0, %rax
    jmp end
jmp_rsi_is_less:
    movq $-1, %rax
end:
    ret
```

Exercise

Are you able to reduce the number of jumps without changing the program behaviour?

Consider the following C code

```c
long x;
long y;

long test_xy(){
  if(x > y)
    return 1;
  else
    return 0;
}
```

Can be written in Assembly as

```
test_xy:
    movq x(%rip), %rdi
    cmpq y(%rip), %rdi
    jle false
    movq $1, %rax
    jmp end
false:
    movq $0, %rax
end:
    ret
```

Consider the following Assembly code

```
test_xyz:
  movq   x(%rip), %rdi
  movq   y(%rip), %rsi
  movq   z(%rip), %rdx
  movq   %rdi, %rax
  addq   %rsi, %rax
  subq   %rdx, %rax
  cmpq   $-3, %rdi
  jge    .L2
  cmpq   %rdx, %rsi
  jge    .L3
  movq   %rdi, %rax
  imulq  %rsi, %rax
  jmp    .L4
.L3:
  movq   %rsi, %rax
  imulq  %rdx, %rax
  jmp    .L4
.L2:
  cmpq   $2, %rdi
  jle    .L4
  movq   %rdi, %rax
  imulq  %rdx, %rax
.L4:
  ret
```

Fill in the missing expressions in C code

```
long x;
long y;
long z;

long test_xyz()
{
  long val = _______;
  if (_______){
     if(_______)
       val = ______;
     else
       val = ______;
  }else if(_______)
    val = _______;

  return val;
}
```

Consider the following Assembly code

```
test_xyz:
  movq   x(%rip), %rdi
  movq   y(%rip), %rsi
  movq   z(%rip), %rdx
  movq   %rdi, %rax
  addq   %rsi, %rax
  subq   %rdx, %rax
  cmpq   $-3, %rdi
  jge    .L2
  cmpq   %rdx, %rsi
  jge    .L3
  movq   %rdi, %rax
  imulq  %rsi, %rax
  jmp    .L4
.L3:
  movq   %rsi, %rax
  imulq  %rdx, %rax
  jmp    .L4
.L2:
  cmpq   $2, %rdi
  jle    .L4
  movq   %rdi, %rax
  imulq  %rdx, %rax
.L4:
  ret
```

Fill in the missing expressions in C code

```
long x;
long y;
long z;

long test_xyz()
{
  long val = x + y - z;
  if (x < -3){
     if(y < z)
       val = x * y;
     else
       val = y * z;
  }else if(x > 2)
    val = x * z;

  return val;
}
```

`JC` – Jump if carry (CF=1)

- The *carry* flag is used in **unsigned** integer arithmetic when it generates a carry or borrow for the most significant bit
- The jump is taken if the *carry* flag is active (1)

Test Carry Example

```
.global addtest_carry

addtest_carry:
    ...
    addq %rax, %rcx

    # jump if carry
    jc carry_detected
    movq $0, %rax
    jmp end

carry_detected:
    movq $1, %rax

end:
    ret
```

JO – Jump if overflow (OF=1)

- The *overflow* flag is used in **signed** integer arithmetic when a positive value is too large, or a negative value is too small, to be properly represented in the register
- The jump is taken if the *overflow* flag is active (1)

Test Overflow Example

```
.global addtest_overflow

addtest_overflow:
    ...
    movb $-127, %cl
    addb $-10, %cl

    # jump if overflow
    jo overflow_detected
    movq $0, %rax
    jmp end

overflow_detected:
    movq $1, %rax

end:
    ret
```

Arithmetic Operations: Detect *Carry* and *Overflow* (3/3)

- In C, we do not have access to these flags and overflows are not signaled as errors
- We can check if an overflow has occurred on $x + y$ by seeing, if and only if, $sum < x$ (or equivalently, $sum < y$) for unsigned addition
- For signed addition, the computation of *sum* has had positive overflow if and only if $x >= 0$ and $y >= 0$ but $sum < 0$. The computation has had negative underflow if and only if $x < 0$ and $y < 0$ but $sum \geq 0$

Test Overflow/Underflow in C

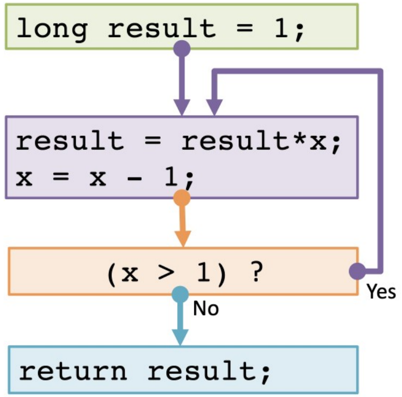
```c
/* return 1 if arguments x and y can be added
   without causing overflow/underflow          */
int add_ok(int x, int y) {
   int sum = x+y;
   int neg_over = x < 0 && y < 0 && sum >= 0;
   int pos_over = x >= 0 && y >= 0 && sum < 0;

   return !neg_over && !pos_over;
 }
```

Loops

- C provides several looping constructs - namely, *do-while*, *while*, and *for*
- No corresponding instructions exist in machine code
- Instead, combinations of conditional tests and jumps are used to implement the effect of loops
- Gcc and other compilers generate loop code based on several loop patterns
- We will study the translation of loops as a progression, starting with the *do-while* basic pattern

Consider the following C code

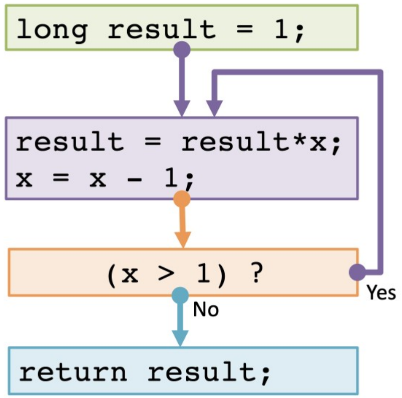
```
long x;

long fact_do_while()
{
  long result = 1;

  do{
    result = result * x;
    x = x - 1;
  } while(x > 1);

  return result;
}
```



The *do-while* Loop

Corresponding Assembly code

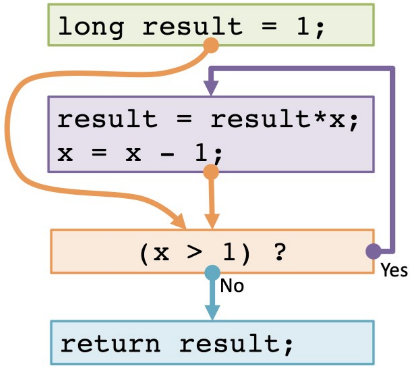
```
fact_do_while:
    movq   x(%rip), %rdi
    movq   $1, %rax

my_loop:
    imulq  %rdi, %rax
    decq   %rdi

    cmpq   $1, %rdi
    jg     my_loop

ret
```



This pattern is frequently used by GCC in x86-64 code. Why?

Consider the following C code

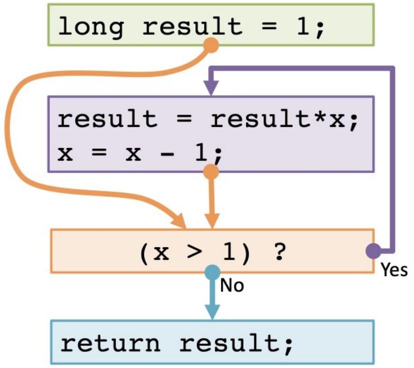
```
long x;

long fact_while()
{
  long result = 1;

  while( x > 1 ){
    result = result * x;
    x = x - 1;
  }

  return result;
}
```



It differs from *do-while* in that the test expression is evaluated and the loop is potentially terminated before the first execution of the body statement

Corresponding Assembly code

```
fact_while:
    movq   x(%rip), %rdi
    movq   $1, %rax
    jmp    test_expression

my_loop:
    imulq  %rdi, %rax
    decq   %rdi

test_expression:
    cmpq   $1, %rdi
    jg     my_loop

ret
```



The unconditional jump before the loop causes the program to first perform the test before modifying the values of *x* or *result*

Consider the following C code

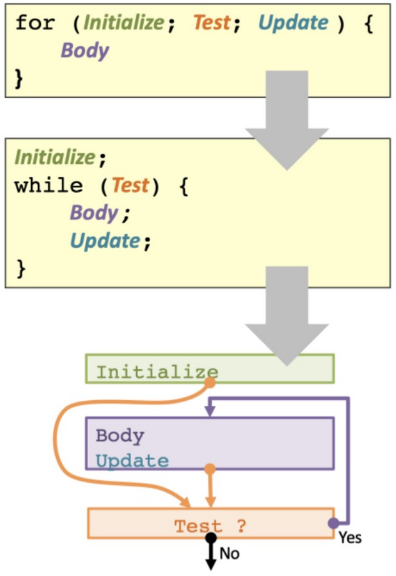
```
long x;

long fact_while()
{
  long result = 1;

  while( x > 1 ){
    result = result * x;
    x = x - 1;
  }

  return result;
}
```

Another possible pattern in Assembly code

```
fact_while:
    movq  x(%rip), %rdi
    movq  $1, %rax

my_loop:
    cmpq  $1, %rdi
    jle   end_my_loop

    imulq %rdi, %rax
    decq  %rdi
    jmp   my_loop

end_my_loop:
    ret
```

The loop itself has the same general structure as the previous pattern. One interesting feature, however, is that the loop test has been changed from $x > 1$ in the original C code to $x \leq 1$

- The C language standard defines a behavior of a *for loop* that can be easily translated to a *while loop*
- The code generated by gcc for a for loop then follows one of the two translation strategies for while loops that were discussed earlier



Consider the following C code

```c
long x;

long fact_for()
{
  long result = 1;
  long i;

  for(i = 2; i <= x; i++) {
    result = result * i;
  }

  return result;
}
```

Can be translated to a while loop

```c
long x;

long fact_for_while()
{
  long result = 1;
  long i;

  i = 2;
  while(i <= x){
    result = result * i;
    i++;
  }

  return result;
}
```

Consider the following C code

```c
long x;

long fact_for_while()
{
  long result = 1;
  long i;

  i = 2;
  while(i <= x){
    result = result * i;
    i++;
  }

  return result;
}
```

Corresponding Assembly code

```
fact_for_while:
    movq  x(%rip), %rdi
    movq  $1, %rax
    movq  $2, %rdx

my_loop:
    cmpq  %rdi, %rdx
    jg    end_my_loop

    imulq %rdx, %rax
    incq  %rdx
    jmp my_loop

end_my_loop:
    ret
```

The `loop`, `loope`, `loopz`, `loopne`, and `loopnz` instructions

- LOOP instructions can be used in place of certain conditional jump instructions and give the programmer a simpler way of writing loop sequences
- They provide iteration control and combine loop index management with conditional branching
- LOOP is a single instruction that functions the same as a DECQ RCX instruction followed by a JNZ instruction

Important notes:

- The `loop` instructions test the flags, but do not change them
- The target label is enconded as a signed 8-bit offset. This means that only jumps offsets of -128 to +127 are allowed with these instructions

How to use:

1. Prior to enter the set of instructions to iterate, load the `%rcx` register with the number of required iterations
2. Then, use the `loop` instruction at the end of that set
3. The loop instruction automatically decrements `%rcx` by one and jumps to the label if `%rcx` is different from 0

Important notes:

- What will happen if the `%rcx` register is zero or less before the first call to any `loop` instruction?
- What will happen if the `%rcx` register is changed inside the loop by any other instrucion or function call?

loop instruction example

```
    ...
    movq $100, %rcx      # number of iterations
my_loop:
    ...                  # loop body
    ...
    loop my_loop
    ...
```

- `loop` automatically decrements `%rcx` by one and jumps to the label if `%rcx` is different from 0
- `loope`/`loopz`: decrements `%rcx` by one and jumps to the label if `%rcx` is different from 0, *and the flag `ZF` is active*
- `loopne`/`loopnz`: decrements `%rcx` by one and jumps to the label if `%rcx` is different from 0, *and the flag `ZF` is **not** active*