Part 5

Control Logic

Intel x86 Jump Instructions

Fly over code

Operations: Program Flow Control

- Unlike high-level languages, processors don't have fancy expressions or blocks
- Programs are controlled by jumping over blocks of code based on status flags

Operations: Program Flow Control

- The processor moves the program counter *(where your program is running in memory)* to a new address and execution continues

Types of Jumps: Unconditional

- Unconditional jumps simple transfers the running program to a new address
- Basically, it just "gotos" to a new line
- These are used extensively to recreate the blocks we use in 3GLs (like Java)

Instruction: Jump

```
JMP  address
```

Usually a label – an constant that holds an address

Infinite Loop

```
.data
message:
    .ascii "I'm getting dizzy!\n\0"

.text
.global _start

_start:
     mov   $message, %rax
Loop:
     call  PrintCString
     jmp   Loop
```


Infinite Loop

```
_start:
     mov  $message, %rax
Loop:
     call PrintCString
     jmp  Loop
```


Types of Jumps: Conditional

- Conditional jumps (aka *branching*) will only jump if a certain condition is met
- What happens
  - processor jumps if and only if a specific status flag is set
  - otherwise, it simply continues with the next instruction

Instruction: Compare

- Performs a comparison operation between two arguments
- The result of the comparison is used for conditional jumps
- Necessary to construct all conditional statements – if, while, …

Instruction: Compare

- Behind the scenes…
  - first argument is subtracted from the second
  - both values are interpreted as signed integers and both are sign-extended to the same size
  - subtraction result is discarded

Instruction: Compare

- Why subtract the operands?
- The result can tell you which is larger
- For example: A and B are both positive…
  - A – B → positive number → A was larger
  - A – B → negative number → B was larger
  - A – B → zero → both numbers are equal

Instruction: Compare

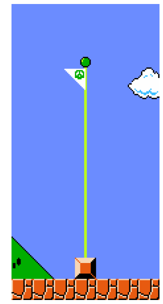
Immediate, Register, Memory

```
CMP arg-1 , arg-2
```

Register, Memory

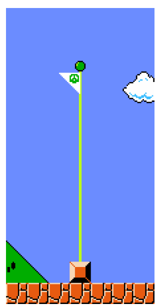
Flags

- A *flag* is a Boolean value that indicates the result of an action
- These are set by various actions such as calculations, comparisons, etc…



Flags

- Flags are typically stored as individual bits in the *Status Register*
- You can't change the register directly, but numerous instructions use it for control and logic



Zero Flag (ZF)

- True if the last computation resulted in zero (all bits are 0)
- For compare, the zero flag indicates the two operands are equal
- Used by quite a few conditional jump statements

Sign Flag (SF)

- True of the *most significant bit* of the result is 1
- This would indicate a negative 2's complement number
- Meaningless if the operands are interpreted as unsigned

Carry Flag (CF)

- True if a 1 is "borrowed" when subtraction is performed
- …or a 1 is "carried" from addition
- For unsigned numbers, it indicates:
  - exceeded the size of the register on addition
  - or an underflow (too small value) on subtraction

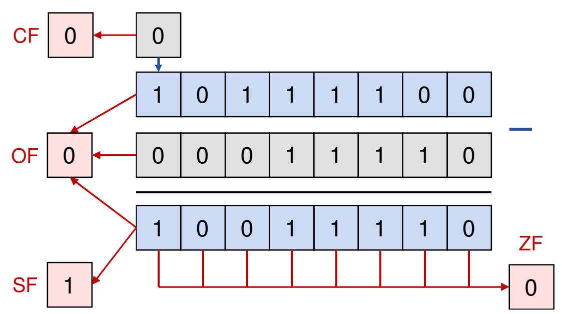
Overflow Flag (OF)

- Also known as "signed carry flag"
- True if the sign bit changed *when it shouldn't*
- For example:
  - (negative – positive number) should be negative
  - a positive result will set the flag
- For signed numbers, it indicates:
  - exceeded the size of the register on addition
  - or an underflow (too small value) on subtraction

x86 Flags Used by Compare

Name	Description	When True
CF	Carry Flag	If an extra bit was "carried" or "borrowed" during math.
ZF	Zero Flag	All the bits in the result are zero.
SF	Sign Flag	If the most significant bit is 1.
OF	Overflow Flag	If the sign-bit changed when it shouldn't have.

-68 vs. 30 (if interpreted as signed)
188 vs. 30 (if interpreted as unsigned)



Jump Instructions

- x86 contains a large number of conditional jump statements
- Each takes advantage of status flags (such as the ones set with compare)
- x86 assembly has several names for the same instruction – which adds readability

Jump on Equality

Jump	Description	When True
JE	Equal	ZF = 1
JNE	Not equal	ZF = 0

Conditional Jump Example

```
_start:
        cmp   $13, %rax
        je    Equal
        ...
Equal:
        ...
```

rax = 13?

Signed Jump Instructions

Jump	Description	When True
JG	Jump Greater than	SF = OF, ZF = 0
JGE	Jump Greater than or Equal	SF = OF
JL	Jump Less than	SF ≠ OF, ZF = 0
JLE	Jump Less than or Equal	SF ≠ OF

Unsigned Jumps

Jump	Description	When True
JA	Jump Above	CF = 0, ZF = 0
JAE	Jump Above or Equal	CF = 0
JB	Jump Below	CF = 1, ZF = 0
JBE	Jump Below or Equal	CF = 1

Conditional Jump Example

```
_start:
    mov  $42, %rax
    cmp  $13, %rax
    jge  Bigger
    ...
Bigger:
    add  $5, %rax
```

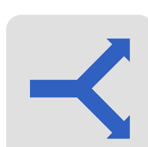
rax >= 13?
(yes, its backwards!)

If Statements on the x86

How to we conditionally execute code?

If Statements in assembly

- High-level programming language have easy to use If-Statements
- However, processors handle all branching logic using jumps
- You basically jump over true and else blocks



If Statements in assembly

- Converting from an If Statement to assembly is easy
- Let's look at If Statements…
  - the block only executes if the expression is true
  - so, if the expression is false your program will skip over the block
  - this is a jump…

If Statement jumps over code

```
rax = 18;
if (rax >= 21)
{
   //true part
}
rbx = 12;
```

False

Converting an If Statement

- Compare the two values
- If the result is *false* …
  - then jump over the true block
  - you will need label to jump to
- To jump on false, reverse your logic
  - `a < b` → `not (a >= b)`
  - `a >= b` → `not (a < b)`

Please Note…

- Following examples use *very* generic label names
- In your program, each label you create must be unique
- So, please don't think that each label (as it is typed) is "the" label you need to use

Converting an If Statement

```
if (rax >= 21)
{
   //true block
}
//end
```

Greater-Than or Equal
So, jump on Less-Than

Jump over true part

```
    cmp  $21, %rax
    jl   End

    #true block

End:
```

Branch when false. JL (Jump Less Than) is the opposite of JGE

Jump over true part

```
    cmp  $21, %rax
    jl   End

    #true block

End:
```

Jumps over true part

Else Clause

- The Else Clause is a tad more complex
- You need to have a true block and a false block
- Like before…
  - you must jump over instructions
  - just remember: *the program will continue with the next instruction unless you jump!*

Else Clause

```
if (rax >= 21)
{
   //true block
}
else
{
   //false block
}
//end
```


Jump over true part

```
      cmp   $21, %rax
      jl    Else

      #true block
      jmp   End
   Else:
      #false block
   End:
```

Jump to false block

False block flows down to End

Jump over true part

```
      cmp   $21, %rax
      jl    Else

      #true block
      jmp   End
   Else:
      #false block
   End:
```

If we run the true block, we have to jump over the false block

Alternative Approach

- In the examples before, I put the False Block first and used inverted logic for the jump
- You can construct If Statements without inverting the conditional jump, but the format is layout is different

If Statement – No Else

```
      cmp   $21, %rax
      jge   Then
      jmp   End
   Then:
      #true block
   End:
```

Jumps to true block

If Statement – No Else

```
cmp   $21, %rax
jge   Then
jmp   End
Then:
      #true block
End:
```

Jump to end if false (it didn't jump with JGE)

If Statement with Else

```
      cmp   $21, %rax
      jge   Then

      #false block
      jmp   End
Then:
      #true block
End:
```

Notice that this is identical to the last slide – the false block is just empty

While Loops

Doing the same thing again and again … and again

While Statement

- Processors do not have While Statements – just like If Statements
- Looping is performed much like an implementing an If Statement
- A While Statement is, in fact, the same thing as an If Statement

If Statement vs. While Statement

If Statement	While Statement
Uses a conditional expression	Uses a conditional expression
Executes a block of statements	Executes a block of statements
Executes only once	Executes multiple times

Converting a While Statement

- To create a While Statement
  - start with an If Statement and…
  - add an unconditional jump at the end of the block that jumps to the beginning
- You will "branch out" of an infinite loop
- Structurally, this is almost identical to what you did before
- However, you do need another label :(

Converting an While Statement

```
while (rax < 21)
{
    //true block
}
//end
```

Less-Than.
So, jump on
Greater-Than or Equal

Converting an While Statement

```
While:
    cmp  $21, %rax
    jge  End

    #true block
    jmp  While
End:
```

Branch when false. JL (Jump Less Than) is the opposite of >=

Converting an While Statement

```
While:
    cmp  $21, %rax
    jge  End

    #true block
    jmp  While
End:
```

Loop after block executes

Converting an While Statement

```
While:
    cmp  $21, %rax
    jge  End

    #true block
    jmp  While
End:
```

Escape infinite loop

Alternative Approach

- Before, we created an If Statement by inverting the branch logic (jump on false)
- You can, alternatively, also implement a While Statement without inverting the logic
- Either approach is valid – use what you think is best

Alternative Approach

```
while (rax < 21)
{
    //true block
}
//end
```

Alternative Approach

```
While:
    cmp  $21, %rax
    jl   Do
    jmp  End
Do:
    #true block
    jmp  While
End:
```

Jumps to Do Block

Alternative Approach

```
While:
    cmp  $21, %rax
    jl   Do
    jmp  End
Do:
    #true block
    jmp  While
End:
```

bge was false, jump out of the loop

Alternative Approach

```
While:
    cmp  $21, %rax
    jl   Do
    jmp  End
Do:
    #true block
    jmp  While
End:
```

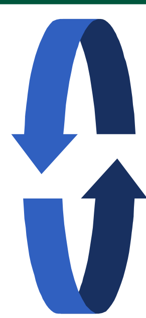
Repeat the loop

Do Loops

Test Last While Loops

Do Loops

- Programming languages also support test-last loop statements
- Many programming languages use the keyword "repeat" or "do"
- Easier than While Statements



Converting Do Loops

```
do
{
   //true block
}
while (rax < 10);
//end
```

We jump UP when TRUE

Converting Do Loops

```
Do:
    #true block

    cmp  $21, %rax
    jl   Do
```

Positive logic

Alternative Approach

- You can also implement Do Loops using negative logic
- But it requires a few an extra label and jump statement

Alternative Approach

```
Do:
    #true block

    cmp  $21, %rax
    jge  End
    jmp  Do
End:
```

Negative logic

Alternative Approach

```
Do:
    #true block

    cmp  $21, %rax
    jge  End
    jmp  Do
End:
```

Infinite loop

Switch Statements on the x86

Reason for the C, Java, and C# design

Switch Statements on the x86

- You might have noticed the strange behavior of Switch statements in C, Java, and C#
- Java and C# inherited their behavior from C

Switch Statements on the x86

- C, in turn, was designed for embedded systems
- Language creates very efficient assembly code
- The Switch Statement converts easily to efficient code

Switch Statement

- It is very efficient because…
  - it is restricted to integer constants
  - once a case is matched, no others are checked
  - they can fall through to match multiple values
- So, how?
  - start of the statement sets up just 1 register
  - compared to each "case" constant
  - jumps to a label created for each

Switch Statement Syntax

```
switch (integer)
{
  case value :
    Statements

  default:
    Statements
}
```

integer expression

You can have as many of these as needed

Executed if nothing matched

C/Java Code

```
switch (Party)
{
  case 1:
     Democrat();
  case 2:
     Republican();
  default:
     ThirdParty();
}
```


Assembly Code

```
    mov  Party, %rax
    cmp  $1, %rax
    je   case_1
    cmp  $2, %rax
    je   case_2
    jmp  default

case_1:
    call Democrat
case_2:
    call Republican
default:
    call ThirdParty
```


Assembly Code

```
    mov  Party, %rax
    cmp  $1, %rax
    je   case_1
    cmp  $2, %rax
    je   case_2
    jmp  default

case_1:
    call Democrat
case_2:
    call Republican
default:
    call ThirdParty
```

Jump header

Assembly Code: Jump Header

```
mov   Party, %rax
cmp   $1, %rax
je    case_1
cmp   $2, %rax
je    case_2
jmp   default
```

case 1:

case 2:

default:

Assembly Code

```
     mov  Party, %rax
     cmp  $1, %rax
     je   case_1
     cmp  $2, %rax
     je   case_2
     jmp  default
case_1:
     call Democrat
case_2:
     call Republican
default:
     call ThirdParty
```

Case Body

Assembly Code: The Case Body

```
case_1:
    call Democrat
case_2:
    call Republican
default:
    call ThirdParty
```

Each "falls through". They are just labels!

Fall-Through Labels

```
1
Democrat
Republican
Third Party
```


Break Statement

- Even in the last example, we still fall-through to the default
- The "Break" Statement is used exit a case
- Semantics
  - simply jumps to a label after the last case
  - so, break converts directly to a single jump

Java Code

```
switch (Party)
{
  case 1:
     Democrat();
     break;
  case 2:
     Republican();
     break;
  default:
     ThirdParty();
}
```

Let's jump to the end

Assembly Code: The Cases

```
case_1:
    call Democrat
    jmp  End
case_2:
    call Republican
    jmp  End
default:
    call ThirdParty
End:
```

Break jumps to the end

When Fallthrough Works

- The fallthrough behavior of C was designed for a reason
- It makes it easy to combine "cases" – make a Switch Statement match multiple values
- … and keeps the same efficient assembly code

Java Code: Primes from 1 to 10

```
switch (number)
{
  case 2:
  case 3:
  case 5:
  case 7:
     result = True;
     break;
  default:
     result = False;
}
```

Match Multiple

Primes: Jump Header

```
mov  Number, %rax

cmp  $2, %rax
je   case_2
cmp  $3, %rax
je   case_3
cmp  $5, %rax
je   case_5
cmp  $7, %rax
je   case_7

jmp  default
```

These are our primes

Assembly Code: The Cases

```
case_2:
case_3:
case_7:
case_9:
     mov  $1, Result
     jmp  End
default:
     mov  $0, Result
```

All these labels will be at the same address. You, of course, would write prettier code.