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# 4.1 – Flow Control

**CSU11021 – Introduction to Computing I**

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# Program Flow Control



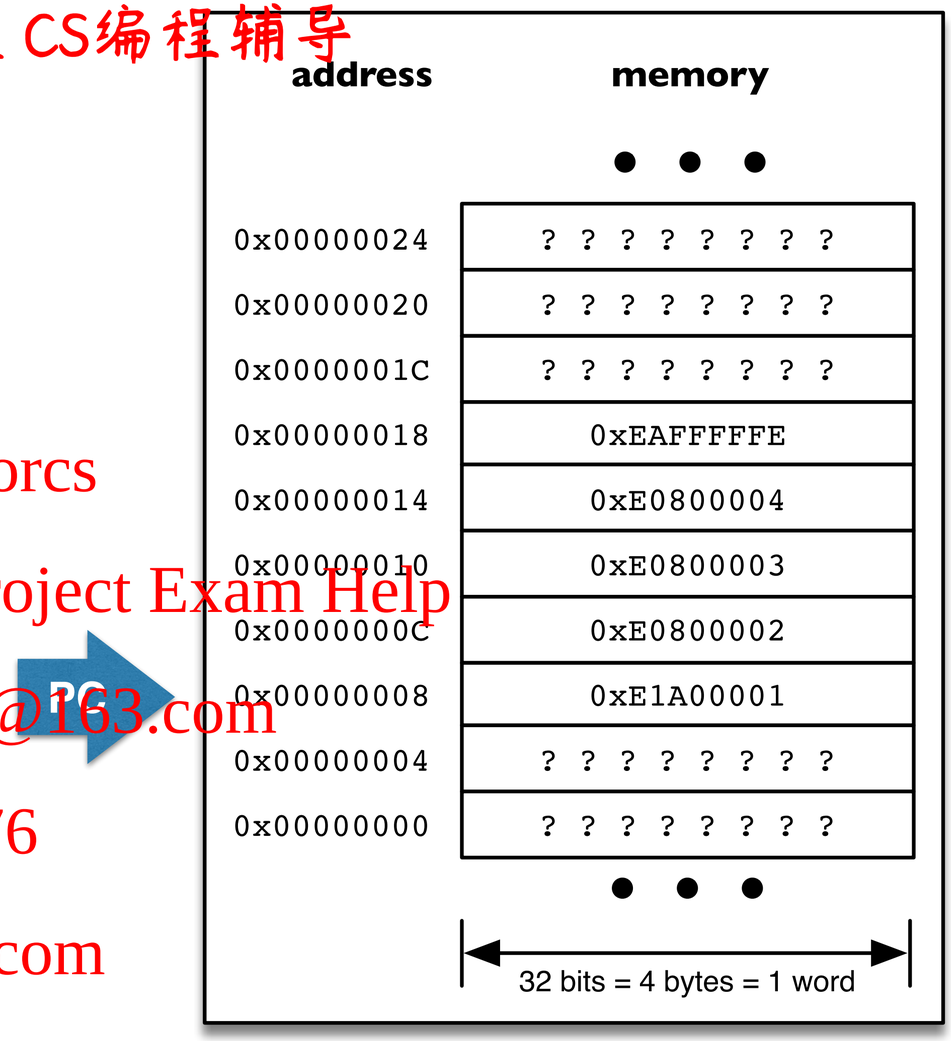


Default flow of execution of a program is **sequential**

After executing one instruction, the next instruction in memory is executed sequentially by incrementing the Program Counter (PC)

To write useful programs, **sequence** needs to be combined with **selection** and **iteration**





# Example – $x^y$



Design and write an assembly language program to compute $x^4$ using repeated multiplication



```
MOV     R0, #1          sult = 1
MUL     R0, R1, R0      sult = result × value (value ^ 1)
MUL     R0, R1, R0      sult = result × value (value ^ 2)
MUL     R0, R1, R0        @ result = result × value (value ^ 3)
MUL     R0, R1, R0        @ result = result × value (value ^ 4)
```



Practical but inefficient and tedious for small values of $y$



Impractical and very inefficient and tedious for larger values



Inflexible – would like to be able to compute $x^y$, not just $x^4$



```
        MOV     R0, #1          @ result = 1
do y times:
        MUL     R0, R0, R1      @ result = result × value
        repeat
```

# Example – $x^y$



```
x = 3;
y = 4;
result = 1;
while (y != 0) {
  result = result * x;
  y = y - 1;
}
```



```
    MOV     R0, #1          @ result = 1
    While:
      CMP   R2, #0
      BEQ   EndWh           @ while (y != 0) {
      MUL   R0, R0, R1      @  result = result × x
      SUB   R2, R2, #1      @  y = y - 1
      B     While           @ }
    EndWh:
```

# CMP Instruction





**CMP** (CoMPare) instruction performs a subtraction **without storing the result of the subtraction**

Subtraction allows us to determine equality (=) or inequality (< ≤ ≥ >)

Don't care about the value of the result
(i.e. don't care **by how much** *x* is greater than *y*, only whether it is or not.)



Properties of the result are remembered by the processor



```
CMP    R2, #0          @ Subtract 0 from r2, remembering the properties
                       @  of the result but not the value of the result
BEQ    EndWh           @ If the result was zero, then branch to EndWh
...    ...             @  otherwise (if result was not zero) then keep
                       @   going (with sequential instruction path)
EndWh:
```

# Pseudo-code



```
  MOV     R0, #1          @ result = 1
While:
  CMP     R2, #0
  BEQ     EndWh           @ while (x != 0) {
  MUL     R0, R0, R1      @   result = result × x
  SUB     R2, R2, #1      @   x = x - 1
  B       While           @ }
EndWh:
```





Pseudo-code is a useful tool for developing and documenting assembly language programs



- No formally defined syntax – informally structured comments
- Use any syntax that you are familiar with
  (and that others can read and understand!!)
- Particularly helpful for developing and documenting the structure of assembly language programs
- Not always a “clean” translation between pseudo-code and assembly language

# Example – Absolute Value



Design and write an assembly language program to compute the absolute value of an integer stored in register R1. The result should be stored in R0.



```
result = value
if (result < 0)
{
  result = 0 - result
}
```



```
    MOV    R0, R1          @ result = value
    CMP    R0, #0          @ if (result < 0)
    BGE    EndIfNeg        @ {
    RSB    R0, R0, #0      @   result = 0 - result
EndIfNeg:                  @ }
```

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# 4.2 – Branch Instructions

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# Branch instructions



By default, the processor increments the Program Counter (PC) to "point" to the next sequential instruction in



causing the **sequential** path to be followed

Using a **branch** instruction, we can modify the value in the PC to "point" to an instruction of our choosing

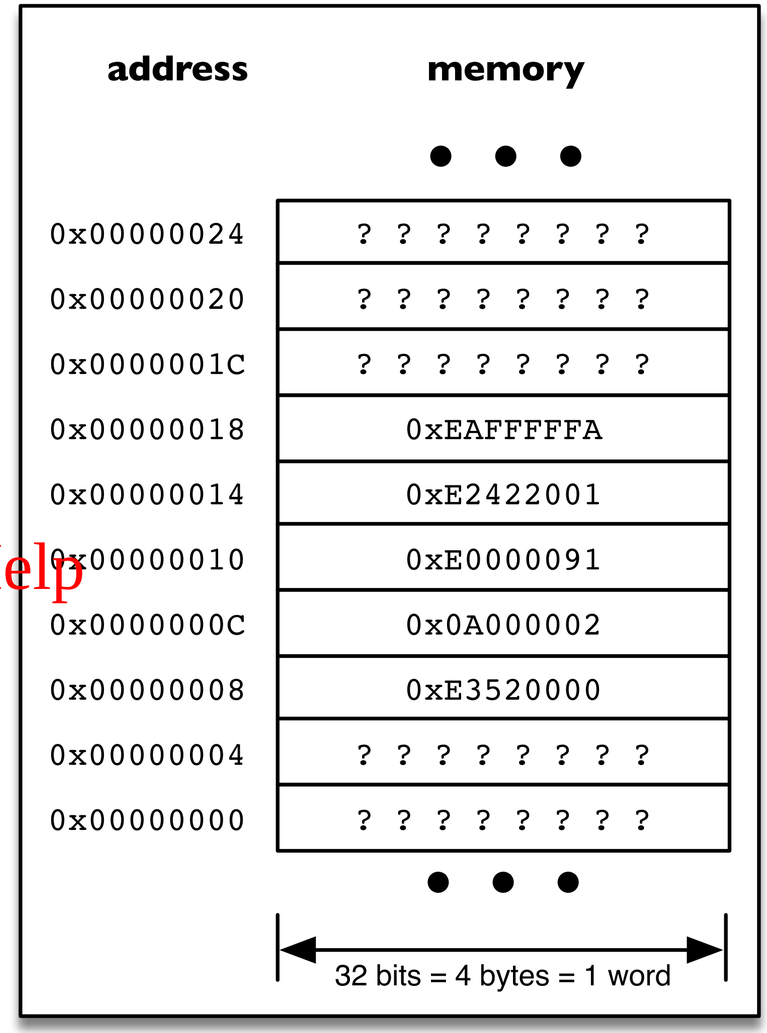


breaking the pattern of **sequential** execution

branch instructions can be

**unconditional** – always update the PC (i.e. always branch)

**conditional** – update the PC only if some condition is met, based on the preceding CoMParison (`CMP`)



# B – Unconditional Branch Instruction (and Labels)

```
        B       MyLabel

        ...     ...
        ...     ...
        ...     ...

MyLabel:
        <some instruction>
        ...     ...
```

```
@ Branch unconditionally to label MyLabel
@
@ instructions

@ more instructions
@ ...
```



## Labels …

- when you define them, must end with a colon:
- must be unique (within a .s file) – only the first definition is used
- must begin with a letter, . (dot) or_ (underscore) but not a numeral
- can contain UPPER and lower case letters, numerals, or _ (underscores)
- are case sensitive (so mylabel is not MyLabel)

# Bxx – Conditional Branch Instruction





Unconditional branch instructions are necessary but they still result in an instruction execution that is pre-determined when we write the program

To write useful programs, the choice of instruction execution path must be deferred until the program is running ("runtime")



- i.e. the decision to take a branch or continue following the sequential path must be deferred until "runtime"



Conditional branch instructions will take a branch only **if some condition is met when the branch instruction is executed**



- otherwise the processor continues to follow the sequential path

# Example – Max



Design and write an assembly language program that evaluates the function max(a, b), where a and b are integers stored in R1 and R2 respectively. The result s stored in R0.



```
if (a ≥ b) {
    max = a
} else {
    max = b
}
```



```
  CMP     R1, R2          @ if (a >= b)
  BLT     ElseMaxB        @ {
  MOV     R0, R1          @   max = a
  B       EndMax          @ }
ElseMaxB:                 @ else {
  MOV     R0, R2          @   max = b
EndMax:                   @ }
```

| Description | Symbol | Java | Instruction | Mnemonic |
|---|---|---|---|---|
| | | | Equality | |
| equal | = | == | BEQ | EQual |
| not equal | ≠ | | BNE | Not Equal |
| | | | (unsigned values) | |
| less than | < | < | BLO | LOwer |
| less than or equal | ≤ | <= | BLS | Lower or Same |
| greater than or equal | ≥ | >= | BHS | Higher or Same |
| greater than | > | > | BHI | HIgher |
| | | | Inequality (signed values) | |
| less than | < | < | BLT | Less Than |
| less than or equal | ≤ | <= | BLE | Less than or Equal |
| greater than or equal | ≥ | >= | BGE | Greater than or Equal |
| greater than | > | > | BGT | Greater Than |

# Flow Control Cheat Sheet

## ARM Conditional Branch Instructions

| Description | Symbol | Java | Instruction | Mnemonic |
|---|---|---|---|---|
| **Equality** | | | | |
| equal | = | == | BEQ | **EQ**ual |
| not equal | ≠ | != | BNE | **N**ot **E**qual |
| **Inequality (unsigned values)** | | | | |
| less than | < | < | BLO (or BCC) | **LO**we |
| less than or equal | ≤ | <= | BLS | **L**ower |
| greater than or equal | ≥ | >= | BHS (or BCS) | **H**igher |
| greater than | > | > | BHI | **HI**gher |
| **Inequality (signed values)** | | | | |
| less than | < | < | BLT | **L**ess T |
| less than or equal | ≤ | <= | BLE | **L**ess t |
| greater than or equal | ≥ | >= | BGE | **G**reate |
| greater than | > | > | BGT | **G**reate |
| **Flags** | | | | |
| Negative Set | | | BMI | **MI**nus |
| Negative Clear | | | BPL | **PL**us |
| Carry Set | | | BCS (or BHS) | **C**arry **S**et |
| Carry Clear | | | BCC (or BLO) | **C**arry **C**lear |
| Overflow Set | | | BVS | o**V**erflow **S**et |
| Overflow Clear | | | BVC | o**V**erflow **C**lear |
| Zero Set | | | BEQ | **EQ**ual |
| Zero Clear | | | BNE | **N**ot **E**qual |

Equality and Inequality Mnemonics are based on a previous execution of a compare (`CMP`) instruction of the form `CMP Rx, Ry`. For example, `BLE label` will branch to `label` if *Rx* is less than or equal to *Ry*.

## Pseudo Code Examples

| Pseudo Code | | ARM Assembly Language |
|---|---|---|
| `if (x <= y)`<br>`{`<br>`  x = x + 1;`<br>`}` | *assume x and y are signed values* | `  CMP  Rx, Ry`<br>`  BGT  label`<br>`  ADD  Rx, Rx, #1`<br>`label` |
| `if (x < y)`<br>`{`<br>`  z = x;`<br>`}`<br>`else {`<br>`  z = y;`<br>`}` | *assume x and y are unsigned values* | `  CMP  Rx, Ry`<br>`  BHS  label1`<br>`  MOV  Rz, Rx`<br>`  B  label2`<br>`label1`<br>`  MOV  Rz, Ry`<br>`label2` |
| `while (x > 2)`<br>`{`<br>`  y = x * y;`<br>`  x = x - 1;`<br>`}` | *assume x and y are unsigned values* | `label1  CMP  Rx, #2`<br>`  BLS  label2`<br>`  MUL  Ry, Rx, Ry`<br>`  SUB  Rx, Rx, #1`<br>`  B  label1`<br>`label2` |



ARM Flow Control "Cheat Sheet"
available on Blackboard

# Example – Factorial



Design and write an assembly language program to compute $n!$, where $n$ is a non-negative integer stored in register R1. Store your result in R0.



$$\prod_{k=1}^{n} k \quad \forall n \in \mathbb{N}$$



```
result = 1
tmp = n
while (tmp > 1)
{
 result = result × tmp
 tmp = tmp - 1
}
```

# Example – Factorial





```
  MOV    R0, #1        @ re
  MOV    R2, R1        @ tmp = n
WhileMul:
  CMP    R2, #1        @ while (tmp > 1)
  BLS    EndWhMul      @ {
  MUL    R0, R0, R2    @   result = result * tmp
  SUB    R2, R2, #1    @   tmp = tmp - 1
  B      WhileMul      @ }
EndWhMul:
```

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# 4.3 – Flow control templates

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# Selection – General Form

## Template for if-then construct



```
if ( <condition> )
{
  <body>
}
<rest of program>
```

```
        CMP     variables or constants in <condition>
        Bxx     EndIfLabel on opposite <condition>
        <body>
EndIfLabel:
        <rest of program>
```



## Template for if-then-else construct



```
if ( <condition> )
{
    <if body>
}
else {
    <else body>
}
<rest of program>
```

```
        CMP     variables or constants in <condition>
        Bxx     ElseLabel on opposite <condition>
        <if body>
        B       EndIfLabel unconditionally
ElseLabel:
        <else body>
EndIfLabel:
        <rest of program>
```

# Iteration – General Form



## Template for while construct

```
<initialize>

while ( <condition> )
{

    <body>

}
<rest of program>
```

```
        <initialize>

WhileLabel:
        CMP     variables or constants in <condition>
        Bxx     EndWhLabel on opposite <condition>
        <body>
        B       WhileLabel
EndWhLabel:
        <rest of program>
```

## Template for a for construct

```
for ( <initialize>, <condition>, <update> ) {

    <body>

}
<rest of program>
```

```
        <initialize>
ForLabel:
        CMP     variables or constants in <condition>
        Bxx     EndForLabel on opposite <condition>
        <body>
        <update>
        B       ForLabel
EndForLabel:
        <rest of program>
```

# Iteration – General Form



Template for do-while co

```
<initialize>

do {
    <body>
} while ( <condition> )

<rest of program>
```

```
        <initialize>
DoLabel:
        <body>
        CMP     variables or constants in <condition>
        Bxx     DoLabel on <condition>
        <rest of program>
```

# Example – Fibonacci Numbers





Fibonacci numbers are defined as follows:

$$F_n = F_{n-2} + F_{n-1}$$

with $F_0 = 0$ and $F_1 = 1$

```
fn2 = 0
fn1 = 1
fn = 1
curr = 2
while (curr < n)
{
    fn2 = fn1
    fn1 = fn
    curr = curr + 1
    fn = fn1 + fn2
}
```



Design and write an assembly language program to compute a Fibonacci number, $F_n$, where $n$ is stored in register R1.

# Example – Fibonacci Numbers





```
  @ Calculate Fibonacci num[illegible]here n is stored in R1
  @ Store the result in R0

  MOV    R4, #0          @ fn2 = 0
  MOV    R5, #1          @ fn1 = 1
  MOV    R0, #1          @ fn = 1
  MOV    R6, #2          @ curr = 2
WhileFib:
  CMP    R6, R1          @ while (curr < n)
  BHS    EndWhFib        @ {
  MOV    R4, R5          @   fn2 = fn1
  MOV    R5, R0          @   fn1 = fn
  ADD    R6, R6, #1      @   curr = curr + 1
  ADD    R0, R5, R4      @   fn = fn1 + fn2
  B      WhileFib        @ }
EndWhFib:
```

# Compound Conditions – AND





```
if (x ≥ 40 AND x < 50)
{
    y = y + 1
}
```

Test each condition and if any one fails, branch to end of if-then construct (or if they all succeed, execute the body)



```
        ...     ...
        CMP     r1, #40         @ if (x ≥ 40
        BLO     EndIf           @   AND
        CMP     r1, #50         @   x < 50)
        BHS     EndIf           @ {
        ADD     r2, r2, #1      @   y = y + 1
EndIf:                          @ }
        ...     ...
```

# Compound Conditions – OR



```
if (x < 40 OR x ≥ 50)
{
    z = z + 1
}
```



Test each condition and if they all fail, branch to end of if-then construct (or if any test succeeds, execute the body without testing further conditions)



```
        ...     ...
        CMP     R1, #40         @ if (x < 40
        BLO     Then            @   |
        CMP     R1, #50         @   x ≥ 50)
        BLO     EndIf           @ {
Then:   ADD     R2, R2, #1      @   y = y + 1
EndIf:                          @ }
        ...     ...
```

# Example – Upper Case



Design and write an assembly language program that will convert the ASCII character stored in R0 to UPPER CASE, if the character is a lower case letter (a-z)

You can convert lower case to UPPER CASE by subtracting 0x20 from the ASCII code

```
if (char ≥ 'a' AND char ≤ 'z')
{
    char = char – 0x20
}
```

# Example – Upper Case





```
  CMP    R0, #'a'          @ if (char >= 'a'
  BLO    EndIfLc           @
  CMP    R0, #'z'          @          'z')
  BHI    EndIfLc           @ {
  SUB    R0, R0, #0x20     @   char = char - 0x20
EndIfLc:                   @ }
```



Algorithm ignores characters not in the range [‘a’, ‘z’]

Note use of #’a’, #’z’ for convenience instead of #0x61 and #0x7A

- Assembler converts ASCII symbol to character code