

Program Control Flow

CIS*2030
Lab Number 4

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Overview

Ultimately, what makes computers useful is their ability to choose between different courses of action. Without the ability to make decisions, computers would be limited to executing simple programs consisting only of straight-line code. In this lab, we will explore some of the instructions in the 68000's ISA that control program flow. These instructions are used to control the order in which other instructions are executed, which, in turn, is the key to implementing higher level decision making constructs, like if-statements, switch-statements, while-loops, do-while loops, etc.

Objectives

Upon completion of this lab you will:

- Understand how computers make decisions,
- Understand the difference between conditional and unconditional branch instructions,
- Understand how compare instructions affect the various flags in the CCR,
- Understand which types of compare and branch instructions to use when working with signed or unsigned data, and,
- Understand how to construct high-level decision-making constructs from a control-flow graph.

Preparation

Prior to starting the lab, you should review your course notes, and perform the following reading assignments from your textbook (if you have not already done so):

- Sections 0.1, 0.2, and 0.3 (number systems, un/signed numbers, ASCII)

Introduction

As explained in class, computers are really designed to execute straight-line code. The program counter (PC) holds the address of the *next* instruction to be executed. The instruction cycle then fetches the instruction pointed to by the PC, decodes the instruction, increments the PC by the size of the instruction (so that the PC now points to the next instruction in memory), and finally executes the fetched instruction. The instruction cycle then repeats, and in this way instructions are executed in sequence; that is, one after another.

The key to executing instructions out of order (i.e., not sequentially) is to change the address in the PC, so that the PC no longer points to the *next instruction in memory*, but to the location of some other (target) instruction. Instructions that have the ability to alter the address in the PC are referred to as *branch* or *jump* instructions, and can be either *conditional* or *unconditional*. Conditional branch instructions first perform a test to see if a particular condition is true. If the condition is true, the branch is taken (i.e., the PC is updated with the target address of the branch). Otherwise, the branch is not taken (i.e., the PC is not updated, and so the next instruction to execute is the next one in sequence immediately following the branch). In the case of an unconditional branch instruction, or a jump instruction, the contents of the PC are always changed, and so the branch always happens.

In practice, both branch and jump instructions must contain a target address, which is the new address that is to be placed into the PC if the branch happens. In some situations, like loops, the target address may be close to the location of the current instruction. In cases like this, it is not necessary to store the full 32-bit address as part of the instruction. Rather, a smaller 16-bit, or even 8-bit, offset can be stored in the instruction that represents the difference in bytes from the current instruction to the target instruction. This offset can be treated as a signed value, allowing for both forward (positive) and backward (negative) branches. This is known as *PC-relative* addressing, and is used by branch all instructions, regardless of whether or not they are conditional or unconditional. In cases where the target is farther away than can be reached with an 8-bit or 16-bit offset, the entire 32-bit address can be stored as part of the instruction. This is known as *absolute* addressing, and is used by jump instructions.

As illustrated in Fig. 1, at the assembly-language level, decision-making is a two-step process. The first step involves storing the results of operations on program data in the flags in the condition-code register (CCR). The second step involves using a conditional branch instruction to test these flags to see if a particular condition is met. If the condition is met, the branch happens. Otherwise, the branch is not taken, and the instruction following the branch instruction is the next to be fetched and executed. This simple decision-making mechanism allows one course of action to be associated with the branch being true, and another with the branch being false.

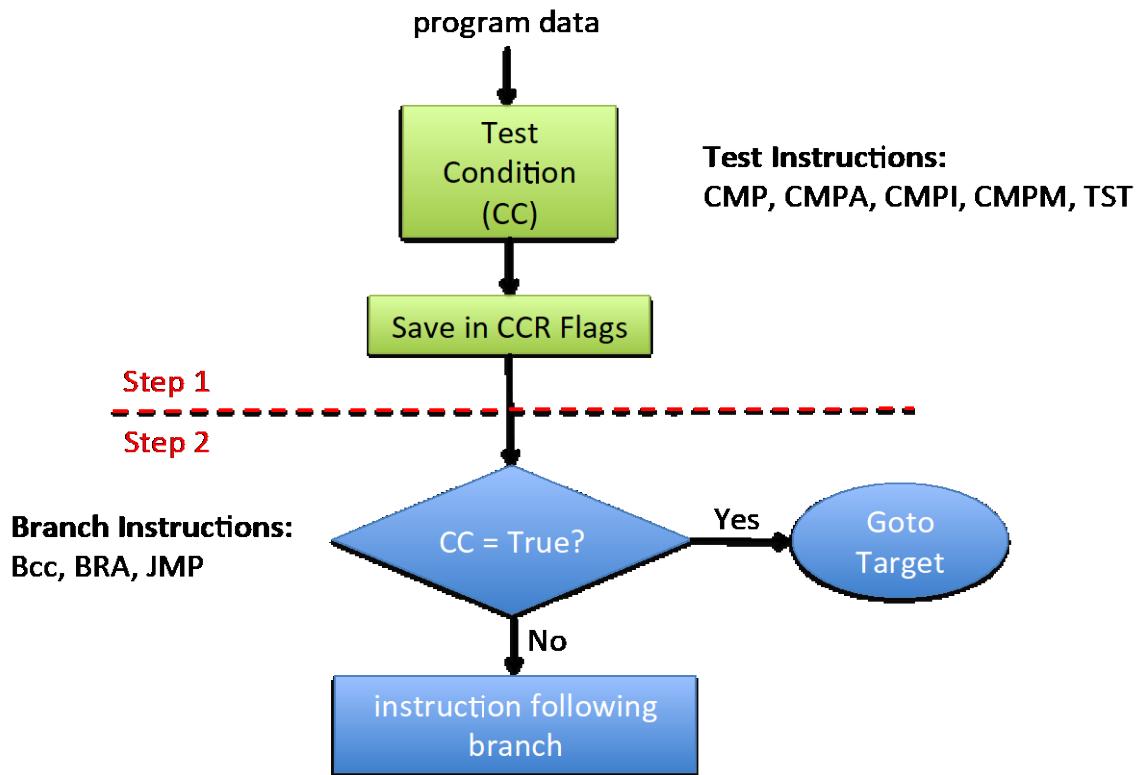


Figure 1: Decision making at the assembler level.

Part 1: Compare and Test Instructions

In practice, *any* instruction that updates the state of the flags in the CCR can be used in the first step described in Fig. 1. However, specific compare and test instructions are available for the purpose of testing individual data items or pairs of data items. These include: CMP, CMPA, CMPI, CMPM, and TST. Compare instructions are used to compare the relative magnitude of two values, and only affect the flags in the CCR. The comparison is accomplished by subtracting the contents of source operand from the destination operand without affecting either operand. The result of the subtraction is then used to set or clear the flags in the CCR, which can then be examined using different conditional branch instructions. Multiple compare instructions (with different address modes) are available for use in different situations. For example, CMPA is used when comparing pointers, CMPI is used to make a comparison with an immediate (constant) value, CMPM is used to compare two memory-resident values, and the CMP is used to compare data with the contents of a data register. The TST instruction operates similarly to the compare instructions, but has a single operand that is compared with zero. TST instructions are useful in situations where it is necessary to determine whether a value is zero/non-zero or positive/negative.

Before proceeding, review the various **compare instructions** on pages 83, 293-296 of your **textbook**, and the **TST instruction** on pages 85 and 362.

Questions

- What is the state of the zero (Z) flag in the CCR after execution of the following instruction:

CMP.W D0, D1

Assume that both D0 and D1 contain the hexadecimal value 0x00003215. Show your work by doing the calculation by hand. [2 points]

$$\begin{array}{r} 0x00003215 = 0011\ 0010\ 0001\ 0101 \\ - \quad 0011\ 0010\ 0001\ 0101 \\ \hline 0\ 000\ 0000\ 0000\ 0000\ 0000 \end{array}$$

Since CMP subtracts the source from destination, and the same hex value is being used, we expect the zero (Z) flag to be 1 as the answer is 0

- What is the state of the zero (Z), Negative (N), Overflow (V) and Carry (C) flags in the CCR after execution of the following instruction:

CMPI.B #5, (A0)

Assume that A0 contains the address 0x00009000 and memory location 0x00009000 contains the hexadecimal value 0x04. Show your work by doing the calculation by hand. [4 points]

CMPI subtracts the immediate data from the destination. In this case it would be $4 - 5 = -1$, based on this, our zero (Z) flag would be 0, Negative (N) would be 1, Overflow (V) would be 0, and Carry (C) would be 1

3. What is the state of the zero (Z), Negative (N), Overflow (V) and Carry (C) flags in the CCR after execution of the following instruction:

TST.L D0

Assume that D0 contains the hexadecimal value 0xFFFFFFFF. Show your work by doing the calculation by hand. [4 points]

TST compares the operand with 0 and this case, uses a long word size indicator. 0xFFFFFFFF is -1 in decimal so the calculation would be $-1 - 0 = -1$. Based on this, our Negative (N) flag would be 1, Zero(Z) flag would be 0, and Overflow(V) and Carry(C) are always 0

You should use Easy68K to verify that the answers that your answers for questions 1-3 are correct.

Part 2: Branch Instruction Encodings

As discussed in class, the 68000 supports fourteen different conditional branch instructions, and one unconditional branch instruction, called BRA. The conditional branch instructions have the format “Bcc Label”, where *cc* is one of 14 conditional tests (**see Table 3-14 of your textbook**) and *Label* is the memory address of the instruction to branch to should the condition being tested (cc) evaluates to true. The unconditional branch instruction has the format “BRA Label”, where, once again, *Label* is the location to branch to.

With regards to branch instruction encodings, both conditional and unconditional branch instructions employ a form of “PC-relative addressing,” where either an 8-bit signed offset or a 16-bit signed offset is added to the current address in the PC to form the address represented by the branch Label. An 8-bit signed value allows for a branch +126 bytes forward in memory or -128 bytes backward in memory, while a 16-bit signed value extends the previous range to +32766 to - 32768. As illustrated in Fig. 2., branch instructions that use an 8-bit offset encode the offset in the instruction’s operation word, while branch instructions that use a 16-bit offset encode the offset in a single extension word following the operation word.

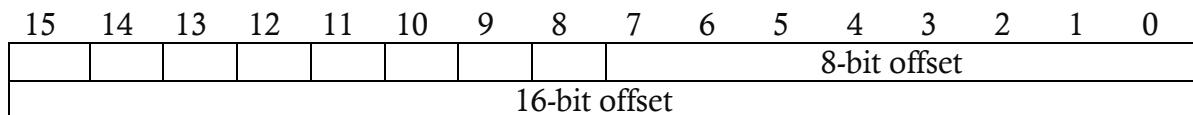


Figure 2: Branch instruction format.

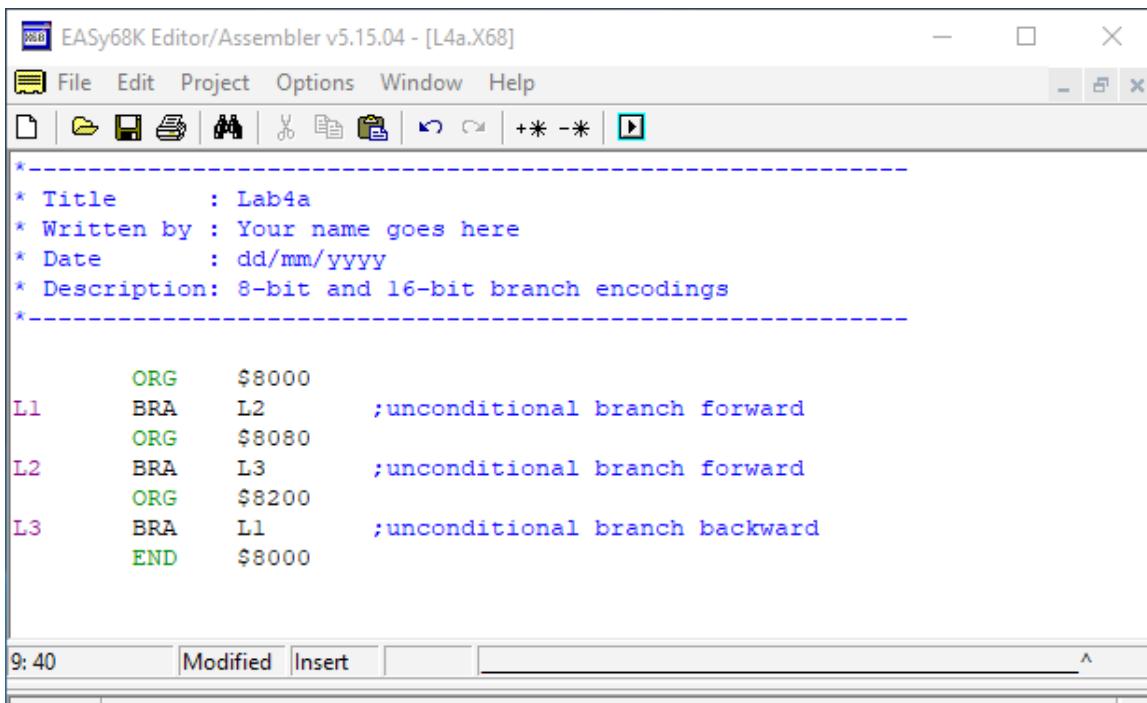
Before proceeding, **read Sec. 2.4.14 of your textbook to review how PC-relative addressing works**, and how the assembler computes the 8-bit (or 16-bit) offset to be added to the PC to form the effective address of the branch location.

Step 1

Download the sample program called **Lab4a.X68** from the course website.

Step 2

Start Easy68K. Once running, load the file Lab4a.X68 using the **File->Open File** menu choice. You should see something similar to below. (Remember to properly comment your code.)



```

EASy68K Editor/Assembler v5.15.04 - [L4a.X68]
File Edit Project Options Window Help
□ | ⌂ | ⌂ | ⌂ | ⌂ | ⌂ | ⌂ | ⌂ | ⌂ | +* -* | □
*-----
* Title      : Lab4a
* Written by : Your name goes here
* Date       : dd/mm/YYYY
* Description: 8-bit and 16-bit branch encodings
*-----


        ORG      $8000
L1      BRA      L2      ;unconditional branch forward
        ORG      $8080
L2      BRA      L3      ;unconditional branch forward
        ORG      $8200
L3      BRA      L1      ;unconditional branch backward
        END      $8000

9:40 Modified Insert

```

Step 3

What memory address is associated with each of the three labels L1, L2 and L3? Print the (32-bit hexadecimal) memory address in the table below. [3 points]

Label	Address (32-bit)
L1	00008000
L2	00008080
L3	00008200

Step 4

Calculate the offset of the BRA L2 instruction by hand, showing your work. Will the offset be stored as an 8-bit or 16-bit signed value? Explain. [3 points]

$$\begin{aligned} \text{Displacement} &= \text{target address} - \text{PC} \\ &= 0x8080 - 0x8002 \\ &= 0x7E \\ &= 126 \end{aligned}$$

The offset of BRA L2 is 007E and is stored as a 16-bit signed value as during the program execution, it has not encountered L2 yet so default to long branch

Step 5

Calculate the offset of the BRA L3 instruction by hand, showing your work. Will the offset be stored as an 8-bit or 16-bit signed value? Explain. [3 points]

$$\begin{aligned} \text{Displacement} &= \text{target address} - \text{pc} \\ &= 0x8200 - 0x8082 \\ &= 0x17E \\ &= 382 \end{aligned}$$

The offset of BRA L3 is 017E and is stored as a 16-bit signed value because it has yet to encounter the label L3 and also the value is over the range for 8-bits

Step 6

Calculate the offset of the `BRA L1` instruction by hand, showing your work. Will the offset be stored as an 8-bit or 16-bit signed value? Explain. [3 points]

$\text{Displacement} = \text{target address} - \text{PC}$ $= 0x8000 - 0x8202$ $= 0xFDFE$ The offset is FDFE and is stored as 16-bit signed as the value is too big to use 8-bit signed	<p>A handwritten binary subtraction diagram. It shows two rows of binary digits: 1000 0000 0000 0000 and 1000 0010 0000 0010. A minus sign is placed between them. Below the first row, there is a plus sign followed by 0111 1101 1111 1101. To the right of the second row, there is a plus sign followed by 0111 1101 1111 1110. A horizontal line with a minus sign above it separates the first two rows from the last two. Another horizontal line with a plus sign above it separates the second row from the third row. To the right of the third row, there is a plus sign followed by 1111 1101 1111 1110. This results in the final answer 0xFDFE.</p>
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Two important benefits arising from the use of PC-relative addressing are (1) the resulting code is able run no matter where it is located in memory, and (2) encoding the offset in the operation word, or at most one extension word, is efficient. However, one limitation associated with PC-relative addressing is the maximum branching address is only 32K bytes on either side of the current instruction. In cases where it is necessary to branch farther away, a JMP instruction can be used. The JMP instruction is functionally equivalent to the BRA instruction, but places a full 32-bit address into the PC. Thus, a JMP instruction can be used to reach *any* location in the processor's address space.

Before proceeding, **read Sec. 3.2.7 and page 310 of your textbook** to review how the JMP instruction works. Notice the different address modes that can be used with a JMP instruction.

Part 3: Conditional Branch Instructions that examine a single bit in the CCR

As discussed in class, the different conditional branch instructions are organized into three distinct groups. One group contains those that enable the programmer to make decisions based on an examination of a single bit in the CCR. These branch instructions are summarized in below:

Instruction	Effect
<code>BCC Label</code>	if (C=0) PC \leftarrow Label
<code>BCS Label</code>	if (C=1) PC \leftarrow Label
<code>BVC Label</code>	if (V=0) PC \leftarrow Label
<code>BVS Label</code>	if (V=1) PC \leftarrow Label
<code>BPL Label</code>	if (N=0) PC \leftarrow Label
<code>BMI Label</code>	if (N=1) PC \leftarrow Label
<code>BNE Label</code>	if (Z=0) PC \leftarrow Label
<code>BEQ Label</code>	if (Z=1) PC \leftarrow Label

In the previous table, PC \leftarrow Label refers to PC-relative addressing, and **Label** refers to the following:

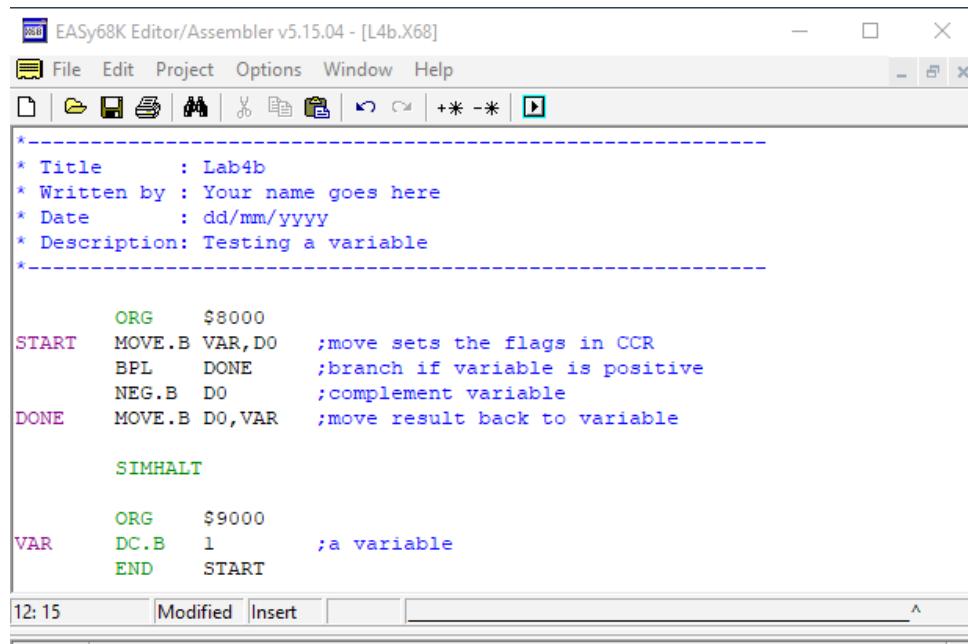
- An explicit numeric address or a symbolic name (i.e., label in the assembly-language program) for a numeric address in the original source code.
- Either an 8-bit or 16-bit offset encoded into the actual machine instruction, depending on the relative location of the target to the branch instruction.

Step 1

Download the sample program called **Lab4b.X68** from the course website.

Step 2

Start Easy68K. Once running, load the file Lab4b.X68 using the **File->Open File** menu choice. You should see something similar to below. (Remember to properly comment your code.)



The screenshot shows the EASy68K Editor/Assembler interface. The window title is "EASy68K Editor/Assembler v5.15.04 - [L4b.X68]". The menu bar includes File, Edit, Project, Options, Window, and Help. The toolbar has icons for Open, Save, Print, Find, Replace, and others. The main code editor area contains the following assembly code:

```
*-----  
* Title      : Lab4b  
* Written by : Your name goes here  
* Date       : dd/mm/yyyy  
* Description: Testing a variable  
*-----  
  
        ORG      $8000  
START    MOVE.B  VAR,D0      ;move sets the flags in CCR  
        BPL     DONE        ;branch if variable is positive  
        NEG.B  D0          ;complement variable  
DONE     MOVE.B  D0,VAR     ;move result back to variable  
  
        SIMHALT  
  
        ORG      $9000  
VAR      DC.B   1           ;a variable  
END      START
```

Note: You can read about the NEG instruction on **pages 84 and 330 of your textbook**.

Step 3

Read through the previous source code. In a single sentence, explain the high-level purpose of the program. Don't explain what each instruction does! **[2 points]**

This code takes in a number from D0 and checks if it is positive, if it is, then returns it but if not, makes it positive using NEG then returns that.

Step 4

What 8-bit (hexadecimal) value do you expect for **VAR** after executing this code? [1 point]

Variable	Expected Value
VAR	01

Step 5

Assemble the program, and then fill out the “Before Run” section of the following table. [1 point]

Variable	Before Run	After Run
VAR	01	01

Now, run the program, and then complete the “After Run” section of the previous table. Compare the expected value for with the actual value you obtained after running the program.

Step 6

Use the trace facility to answer the following question. What is the value in the CCR immediately before and after the `MOVE.B VAR,D0` instruction executes? [4 points]

Instruction	Before				After			
	N	Z	V	C	N	Z	V	C
MOVE.B VAR,D0	0	0	0	0	0	0	0	0

Why are the individual flags in the CCR set or cleared the way that they are after the `MOVE.B VAR, D0` instruction executes? Be precise. [4 points]

Since there is no calculation occurring and it is merely copying the value at VAR into D0. N=0 because the value does not become negative. Z=0 as the value does not become 0. V=0 as no overflow occurs. C=0 as there was no carry.

Step 7

Use the trace facility to answer the following question. What is the 32-bit (hexadecimal) value in the PC immediately before and after the `BPL DONE` instruction executes? [1 point]

Instruction	PC Before	PC After
<code>BPL DONE</code>	0000 8006	0000 800C

Clearly the previous branch is taken, and control is passed to the instruction at location `DONE`. Explain why the branch was taken. You should make reference to the appropriate flag(s) in the CCR in your answer. [2 points]

The branch was taken because BPL checks whether or not the negative (N) is 0. In this case the CCR has N=0 as no negative number has occurred which tells BPL to branch if positive.

Step 8

Modify the branch condition in the source code presented in step 1 by replacing the test for a positive number with a test for a *negative* number. Save the new program in a file called **Lab4c.X68**.

Step 9

What 8-bit (hexadecimal) value do you expect for **VAR** after executing this code? [1 point]

Variable	Expected Value
VAR	0

Step 10

Assemble the program, and then fill out the “Before Run” section of the following table. [1 point]

Variable	Before Run	After Run
VAR	FF	0

Now, run the program, and then complete the “After Run” section of the previous table. Compare the expected value for with the actual value you obtained after running the program.

Step 11

Use the trace facility to answer the following question. What is the 32-bit (hexadecimal) value in the PC immediately before and after the **BMI DONE** instruction executes? [1 point]

Instruction	PC Before	PC After
BMI DONE	0000 8006	0000 800A

Clearly the previous branch is not taken, and the next instruction to execute following the branch is `NEG.B D0`. Explain why the branch was not taken. You should make reference to the appropriate flag(s) in the CCR in your answer. [2 points]

Since `BMI` checks if the negative (N) flag is 1, in this case the CCR has N=0 and so `BMI` will not branch as the value is greater than 0.

Part 4: Signed and Unsigned Conditional Branch Instructions

The remaining conditional branch instructions are organized into two groups: those that allow for a comparison of two signed numbers, and those that allow two unsigned values to be compared. These branch instructions are summarized in below:

Type	Instruction	Effect
Signed Branches	<code>BGE Label</code>	if (A>=B) PC \leftarrow Label
	<code>BGT Label</code>	if (A>B) PC \leftarrow Label
	<code>BLE Label</code>	if (A<=B) PC \leftarrow Label
	<code>BLT Label</code>	if (A<B) PC \leftarrow Label
Unsigned Branches	<code>BHS Label</code>	if (A>=B) PC \leftarrow Label
	<code>BHI Label</code>	if (A>B) PC \leftarrow Label
	<code>BLS Label</code>	if (A<=B) PC \leftarrow Label
	<code>BLO Label</code>	if (A<B) PC \leftarrow Label

In the previous table, it is assumed that the flags in the CCR have first been set as a result of subtracting value B from value A (e.g., by using one of the compare instructions introduced in Part 1).

`PC \leftarrow Label` refers to PC-relative addressing, and `Label` refers to the following:

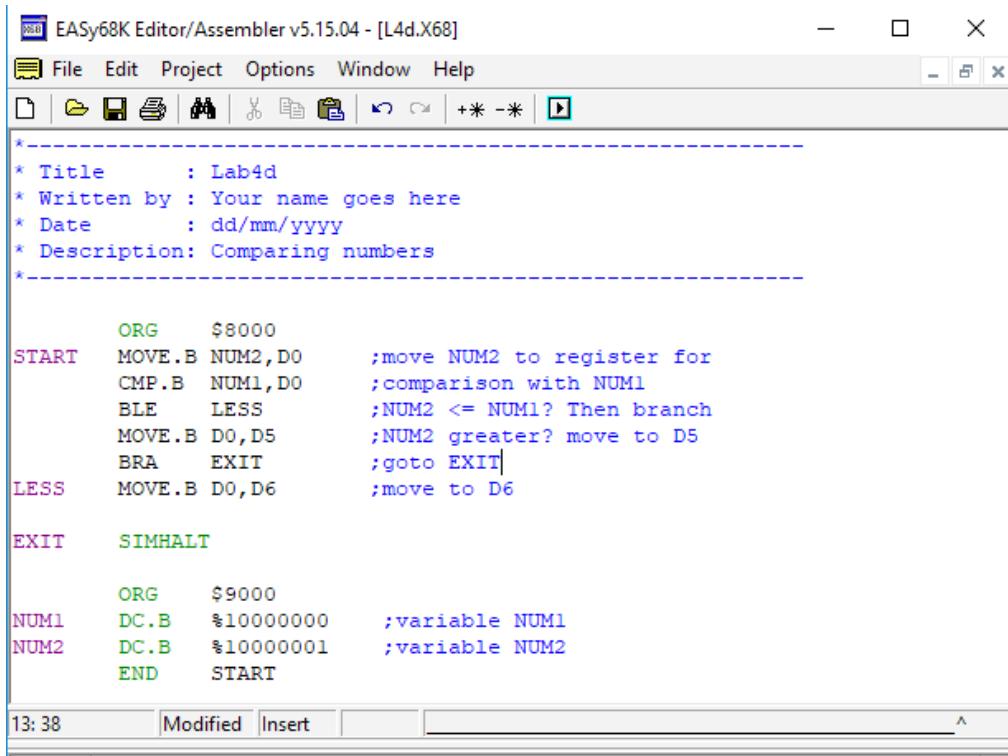
- An explicit numeric address or a symbolic name (i.e., label in the assembly-language program) for a numeric address in the original source code.
- Either an 8-bit or 16-bit offset encoded into the actual machine instruction, depending on the relative location of the target to the branch instruction.

Step 1

Download the sample program called **Lab4d.X68** from the course website.

Step 2

Start Easy68K. Once running, load the file Lab4d.X68 using the **File->Open File** menu choice. You should see something similar to below. (Remember to properly comment your code.)



The screenshot shows the EASy68K Editor/Assembler interface. The title bar reads "EASy68K Editor/Assembler v5.15.04 - [L4d.X68]". The menu bar includes File, Edit, Project, Options, Window, and Help. The toolbar contains icons for file operations like Open, Save, and Run. The main window displays assembly code:

```
*-----  
* Title      : Lab4d  
* Written by : Your name goes here  
* Date       : dd/mm/yyyy  
* Description: Comparing numbers  
*-----  
  
ORG    $8000  
START  MOVE.B NUM2,D0      ;move NUM2 to register for  
       CMP.B  NUM1,D0      ;comparison with NUM1  
       BLE   LESS           ;NUM2 <= NUM1? Then branch  
       MOVE.B D0,D5          ;NUM2 greater? move to D5  
       BRA   EXIT            ;goto EXIT|  
LESS   MOVE.B D0,D6          ;move to D6  
  
EXIT   SIMHALT  
  
ORG    $9000  
NUM1   DC.B  %10000000      ;variable NUM1  
NUM2   DC.B  %10000001      ;variable NUM2  
END    START
```

The status bar at the bottom shows "13:38 Modified Insert".

Step 3

Read through the previous source code. In 2-3 sentences, explain the high-level purpose of the program. Don't explain what each instruction does! Get to the core of the apple! [2 points]

This program checks if NUM2 is greater than NUM1, if so, then moves the value at D0(NUM2) to D5. If NUM2 is less than or equal to NUM1, then moves value at D0(NUM2) to D6. The program compares two numbers and depending on if the number is $>$ or \leq , then moves it to a certain data register.

Step 4

Are the variables NUM1 and NUM2 signed or unsigned? How do you know? Hint: Examine the conditional branch instruction. [2 points]

Since the conditional branch BLE is used, the variables NUM1 and NUM2 are signed. You can also trace through the program and see that the negative (N) is set to 1 which also tells us that the values had to be signed.

Step 5

What 32-bit (hexadecimal) values do you expect registers D5 and D6 to have after executing this code? [1 point]

Registers	Expected Value
D5	0000 0081
D6	0000 0000

Step 6

Assemble the program, and then fill out the “Before Run” section of the following table. [2 points]

Registers	Before Run	After Run
D5	0000 0000	0000 0081
D6	0000 0000	0000 0000

Now, run the program, and then complete the “After Run” section of the previous table. Compare the expected value for with the actual value you obtained after running the program.

Step 7

Use the trace facility to answer the following question. What is the value in the CCR immediately before and after the `CMP.B NUM1, D0` instruction executes? [4 points]

Instruction	Before				After			
	N	Z	V	C	N	Z	V	C
<code>CMP.B NUM1, D0</code>	1	0	0	0	0	0	0	0

Why are the individual flags in the CCR set or cleared the way that they are after the `CMP.B NUM1, D0` instruction executes? Be precise. [4 points]

This instruction will calculate destination - source and update CCR. In this case, it will be NUM2 - NUM1 which is $81 - 80 = 1$. Based on this, negative(N) is 0, zero(Z) is 0, overflow(V) is 0, and carry(C) is 0.

Step 8

Use the trace facility to answer the following question. What is the 32-bit (hexadecimal) value in the PC immediately before and after the `BLE LESS` instruction executes? [1 point]

Instruction	PC Before	PC After
<code>BLE LESS</code>	0000800C	00008010

Clearly the previous branch is not taken, and control is passed to the instruction immediately following the `BLE LESS` instruction. Explain why the branch was not taken. You should make reference to the appropriate flag(s) in the CCR in your answer. [2 points]

BLE branches if in the CCR, Z=1 or N ≠ V. In the CMP instruction, it does destination-source which is D0 (NUM2) - NUM1 = 81 - 80 = 1. In this case, Negative(N) is 0, Zero(Z) is 0, Overflow(V) is 0, and Carry(C) is 0. ∴ all flags are cleared.

Step 9

Modify the branch condition in the source code presented in step 1, so that the program works correctly under the assumption that the variables `NUM1` and `NUM2` are unsigned values. Save the new program in a file called **Lab4e.X68**.

Step 10

What 32-bit (hexadecimal) values do you expect registers `D5` and `D6` to have after executing this code? [1 point]

Registers	Expected Value
D5	0000 0081
D6	0000 0000

Step 11

Assemble the program, and then fill out the “Before Run” section of the following table. [2 points]

Registers	Before Run	After Run
D5	00000000	00000081
D6	00000000	00000000

Now, run the program, and then complete the “After Run” section of the previous table. Compare the expected value for with the actual value you obtained after running the program.

Step 12

Use the trace facility to answer the following question. What is the 32-bit (hexadecimal) value in the PC immediately before and after the `BLS LESS` instruction executes? [1 point]

Instruction	PC Before	PC After
BLS LESS	0000800C	00008010

Clearly the previous branch is not taken, and control is passed to the instruction immediately following the `BLS LESS` instruction. Explain why the branch was not taken. You should make reference to the appropriate flag(s) in the CCR in your answer. [2 points]

For BLS, the flags in the CCR should have C=1 and Z=1. The instruction CMP.B NUM1,D0 will do destination-source which is D0(NUM2) - NUM1 = 81 - 80 = 1. This shows that the negative(N) flag is 0, zero(Z) is 0, Overflow(V) is 0, and Carry(C) is also 0.

Part 5: A Conditional Program

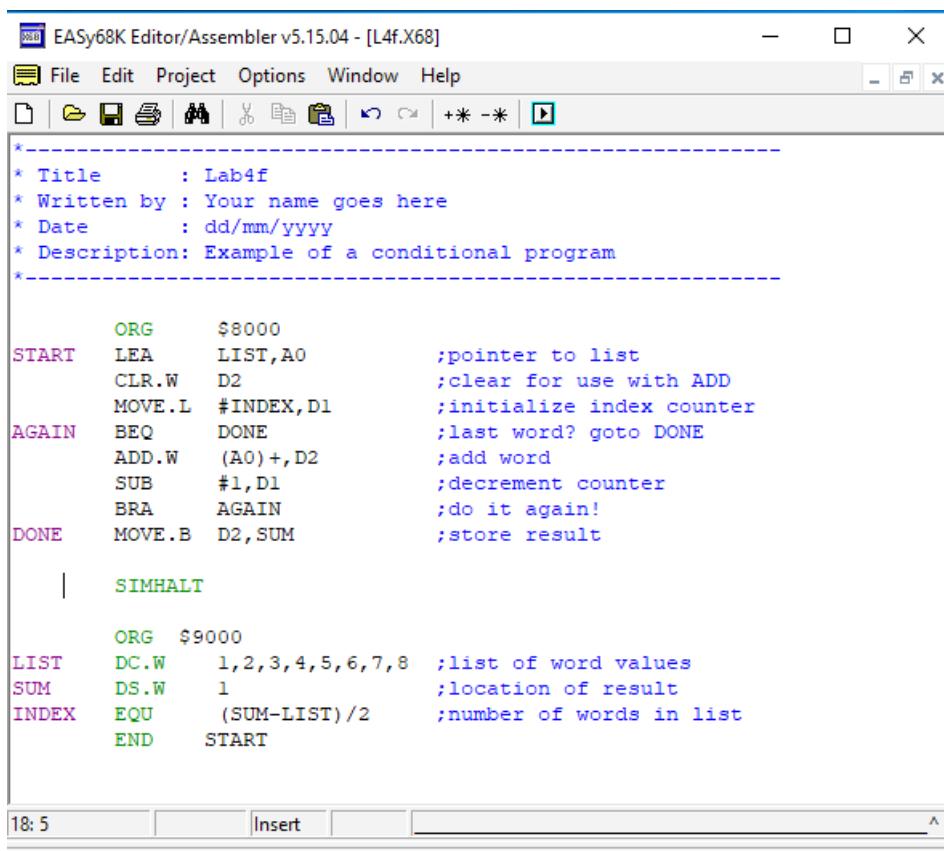
Conditional instructions enable programs to solve problems by choosing between different courses of action during the execution of the program code. Before proceeding, we will look at an example of a slightly more complex program than we have encountered in the previous examples.

Step 1

Download the sample program called **Lab4f.X68** from the course website.

Step 2

Start Easy68K. Once running, load the file Lab4f.X68 using the **File->Open File** menu choice. You should see something similar to below. (Remember to properly comment your code.)



The screenshot shows the EASy68K Editor/Assembler interface. The window title is "EASy68K Editor/Assembler v5.15.04 - [L4f.X68]". The menu bar includes File, Edit, Project, Options, Window, and Help. The toolbar has icons for Open, Save, Print, and Run. The assembly code is displayed in the main pane:

```
*-----  
* Title      : Lab4f  
* Written by : Your name goes here  
* Date       : dd/mm/yyyy  
* Description: Example of a conditional program  
*-----  
  
        ORG      $8000  
START   LEA      LIST,A0          ;pointer to list  
        CLR.W    D2              ;clear for use with ADD  
        MOVE.L   #INDEX,D1          ;initialize index counter  
AGAIN   BEQ      DONE             ;last word? goto DONE  
        ADD.W    (A0)+,D2          ;add word  
        SUB     #1,D1             ;decrement counter  
        BRA     AGAIN             ;do it again!  
DONE    MOVE.B   D2,SUM          ;store result  
  
        | SIMHALT  
  
        ORG      $9000  
LIST    DC.W    1,2,3,4,5,6,7,8 ;list of word values  
SUM     DS.W    1              ;location of result  
INDEX   EQU     (SUM-LIST)/2    ;number of words in list  
END    START  
  
18: 5
```

Questions

4. What is the purpose of the program? Be brief? **[2 points]**

This program goes through a list of word values and adds each value in the list and adds that into D2. It then moves the value at D2 to the end of the list. All of this while index ≠ 0 where the counter is the # of words left in the list.

5. What is the 32-bit hexadecimal final value in address register A0 once the program terminates? **[1 point]**

0000 9010

6. What is the final 16-bit value in memory location 0x00009010 once the program terminates? **[1 point]**

0x24FF

7. How many times is the conditional branch BEQ DONE found to be true and, therefore, taken? **[1 point]**

It is found to be true only once and this is when the index counter (D1) = 0

8. How many times is the unconditional branch `BRA AGAIN` instruction executed? [1 point]

It is executed for every word in the list which would be
8 times

Step 3

Modify the previous program so that it now works with a list of 32-bit long words rather than a list of 16-bit words. Save the new program in a file called **Lab4g.X68**. Make sure to simulate the program to ensure that it works correctly.

Part 6: If-else Construct

In the remainder of the lab, we continue our discussion of instructions that can be used to affect program flow by considering how these instructions are used to implement fundamental decision-making and looping constructs in high-level languages. Before proceeding, make sure that you review your lecture notes, especially those notes that describe how to construct control-flow graphs for different high-level constructs.

As discussed in class and illustrated in Fig. 3, the *if-else* statement can be represented using a control-flow graph (CFG) with four blocks. The condition block contains the condition to be checked, code block 1 contains the code to execute if the condition is true, code block 2 contains the code to execute if the condition is false (i.e., the *else*), and the exit block is where control is passed to once the *if-else* statement completes executing. In principle, the four blocks can be in any, arbitrary order in memory. However, in Fig. 2, the assumption is that the condition block appears first in memory, followed by the two code blocks, and, finally, the exit block.

Recall that all of the conditional branch instructions only branch on a *true* condition. However, in the case of the *if-else* statement, it is clear that we do not want to branch (but simply fall through into code block 1) if the condition associated with the *if* is true. Similarly, if the condition associated with the *if* is false, we want to branch over code block 1 in memory and go to code block 2. In practice, this behaviour requires branching on the *reverse* condition. For example, if the condition in the high-level code is “`==`”, the reverse condition is “`!=`”. Or, if the condition is “`<`”, the reverse condition is “`>=`”.

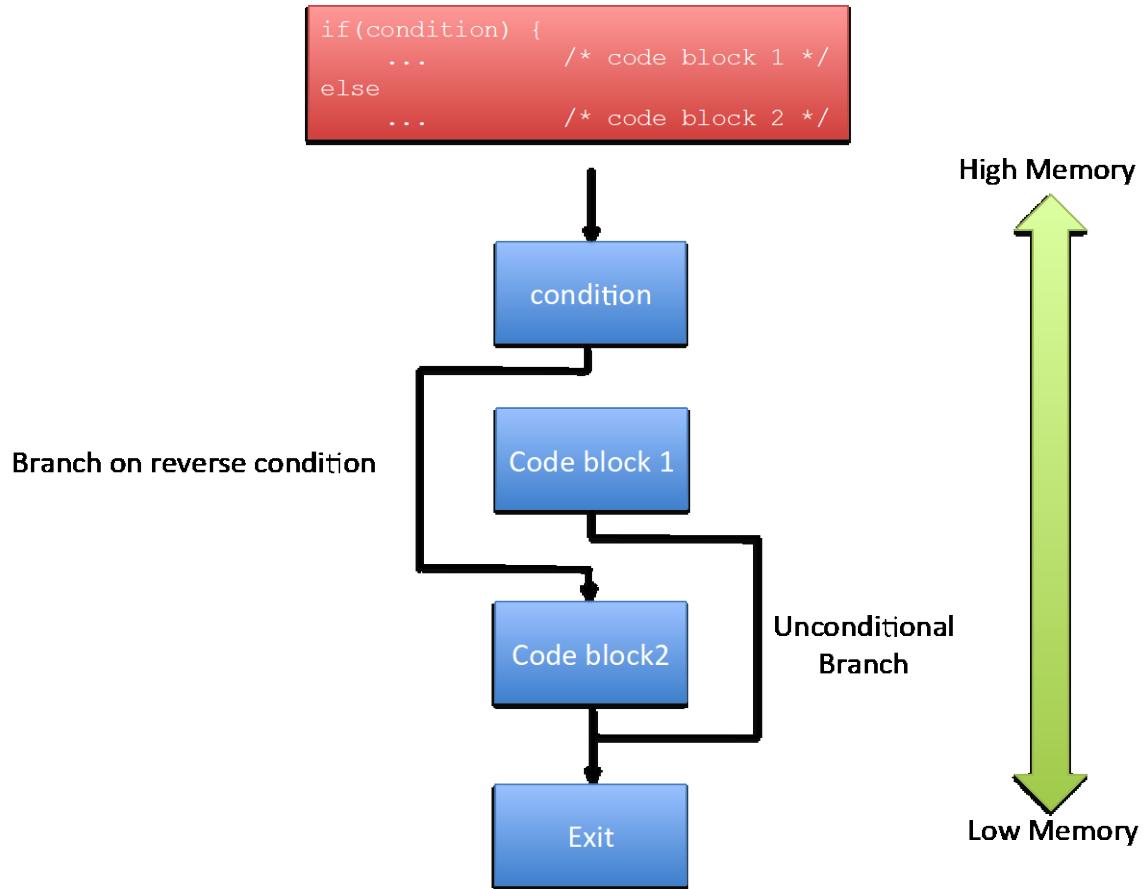


Figure 3: Control-Flow Graph for *if-else* statement.

Step 1

Create an assembly-language program called **Lab4h.X68**. The program should meet the following specifications:

- Reserve space in memory for three 8-bit variables with the names A, B, and C. The initial values of A, B, and C should be the first, second and third digit of your student identification number, respectively.
- The program will implement the following snippet of high-level code.
- The local variable `temp` can be implemented using any of the registers D0 through D8.

```

if (A == B)  {

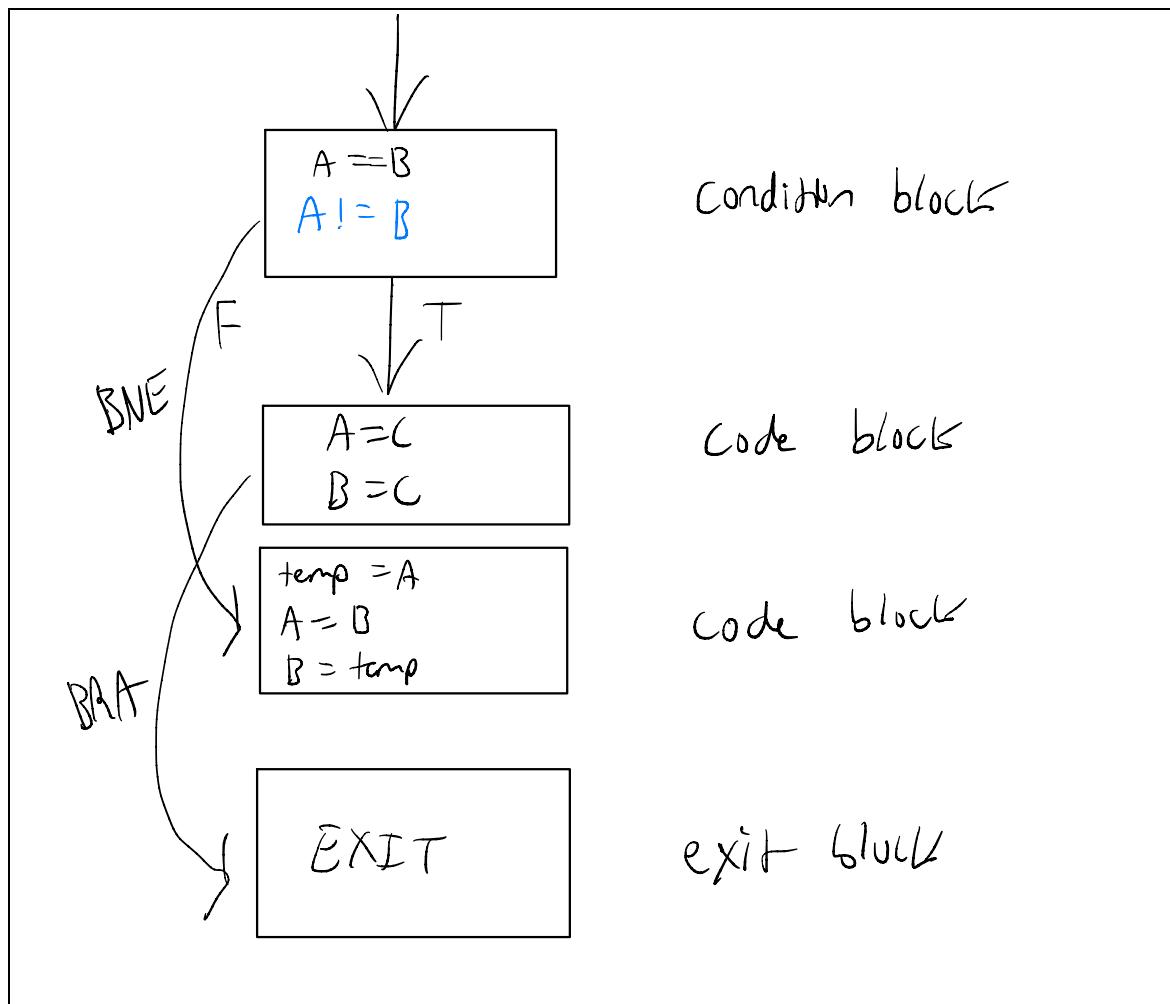
    A = C;
    B = C;
}

else {

    temp = A;
    A = B;
    B = temp;
}

```

Before you start to code, draw a complete CFG (below) for the if-else statement **following the same procedure in class**. Make sure to show the contents of each block. Also, label the various arcs with the specific name of the 68000-branch instruction that will be used to implement the transition indicated by the arc. **[10 points]**



Step 2

What 32-bit (hexadecimal) values do you expect `A` and `B` to have after executing this code?
[1 point]

Variables	Expected Value
<code>A</code>	0000 0002
<code>B</code>	0000 0002

Step 3

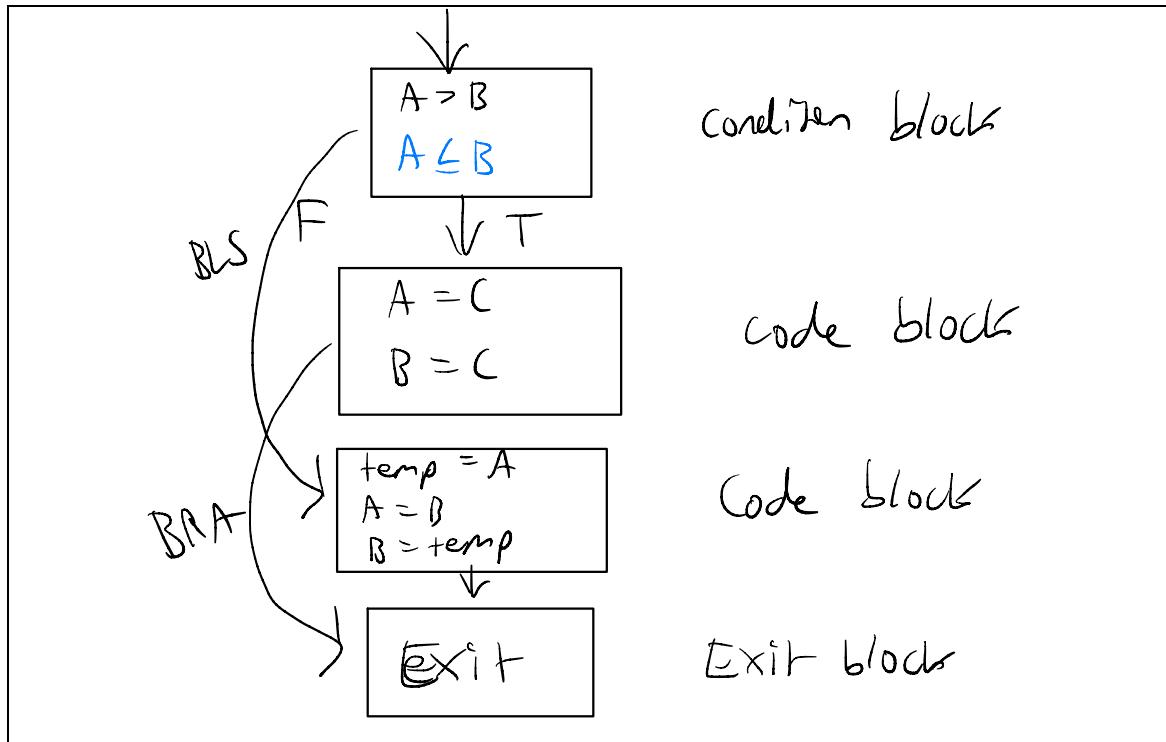
Assemble the program, and then fill out the “Before Run” section of the following table. [2 points]

Variables	Before Run	After Run
<code>A</code>	0000 0001	0000 0002
<code>B</code>	0000 0001	0000 0002

Now, run the program, and then complete the “After Run” section of the previous table. Compare the expected values with the actual values you obtained after running the program.
[10 points]

Step 4

In the high-level code given in step 1, replace the equality (==) test by greater than (>), and implement a program called **Lab4i.X68** that implements the modified high-level code. (You should assume that variables `A`, `B`, and `C` are unsigned.) Begin your implementation by re-drawing the CFG for the if-else construct below, remembering to identify the appropriate branch instructions associated with the arcs. [10 points]



Step 5

What 32-bit (hexadecimal) value do you expect B to have after executing this code? [1 point]

Variable	Expected Value
B	00000001

Step 6

Assemble the program, and then fill out the “Before Run” section of the following table. [2 points]

Variables	Before Run	After Run
A	00000001	00000001
B	00000001	00000001

Now, run the program, and then complete the “After Run” section of the previous table. Compare the expected values with the actual values you obtained after running the program. **[10 points]**

Part 7: Short-Circuit Evaluation

As discussed in class, many high-level languages, like C, employ short-circuit evaluation to improve the speed and robustness of code. Short-circuit evaluation applies to Boolean expressions used in conditions, and results in the termination of the evaluation as soon as the result is known.

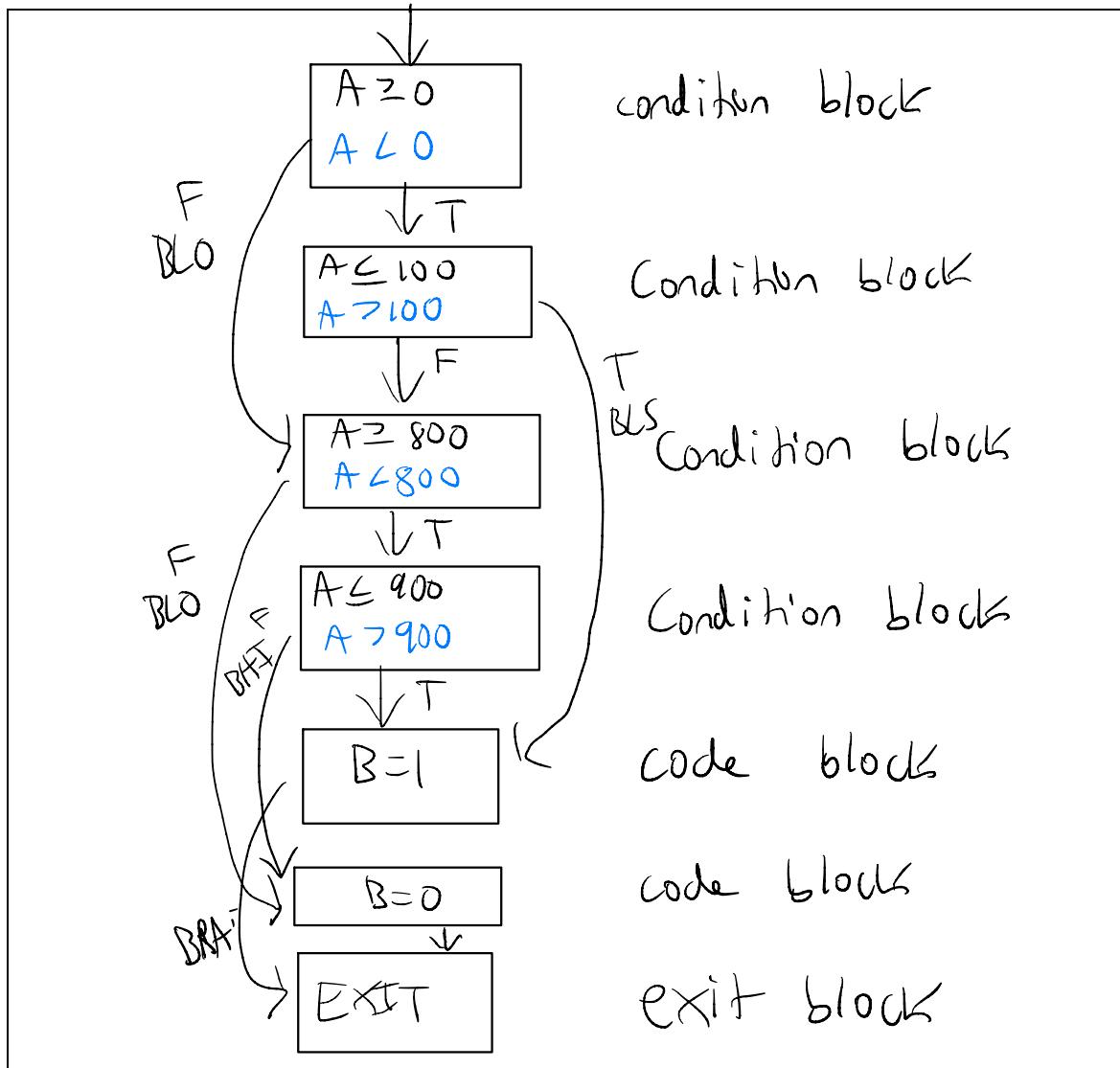
Step 1

Create an assembly-language program called **Lab4j.X68**. The program should meet the following specifications:

- Reserve space in memory for two 16-bit (unsigned) variables with the names A and B, respectively. The initial value of A should be the first, second and third digit of your student identification number concatenated together to form a 3-digit decimal number. Variable B is uninitialized.
- The program will implement the following snippet of high-level code.

```
if((A >= 0 && A <=100) || (A >= 800 && A <= 900)) {  
    B = 1;  
}  
else {  
    B = 0;  
}
```

Before you start to code, draw a complete CFG (below) for the if-else statement **following the same procedure in class**. Use short-circuit evaluation in your implementation. Make sure to show the contents of each block. Also, label the various arcs with the specific name of the 68000-branch instructions that will be used to implement the transition indicated by the arc. **[20 points]**



Step 2

What 32-bit (hexadecimal) values do you expect registers A and B to have after executing this code? [1 point]

Variable	Expected Value
B	0000 0000

Step 3

Assemble the program, and then fill out the “Before Run” section of the following table. [2 points]

Variables	Before Run	After Run
A	0070	0070
B	FFFF	0000

Now, run the program, and then complete the “After Run” section of the previous table. Compare the expected values with the actual values you obtained after running the program. [20 points]

Part 8: While-Statement and For-Statement

As explained in class and shown below, in C, the *for*-statement and *while*-statement are equivalent looping constructs.

```
i = start;  
for(i=start; i<end; i++) {  
    /* perform loop body */  
    ...  
}  
while(i<end) {  
    ...  
    i++;  
}
```

The only difference between the two loop constructs is that the *for*-statement gathers together all of the constituent components of the *while*-statement into one convenient location for the programmer. However, during compilation, the *for*-statement is turned back into a *while*-statement. This means that both high-level looping constructs result in the same assembly-language code being generated by the compiler.

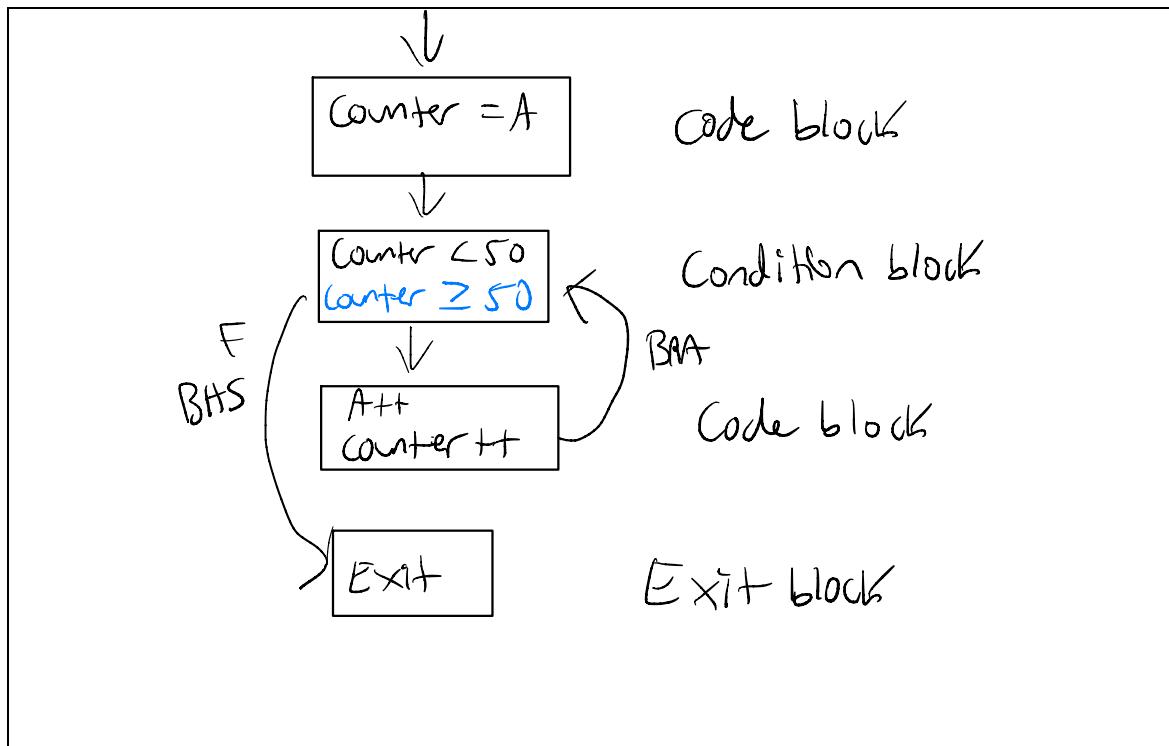
Step 1

Create an assembly-language program called **Lab4k.X68**. The program should meet the following specifications:

- Reserve space in memory for a 16-bit variable with the name A. The initial value of A should be the first digit your student identification number.
- The program will implement the following snippet of high-level code.

```
for(i=A; i<50; i++) {
    A = A + 1;
}
```

Before you start to code, draw a complete CFG (below) for the for-statement **following the same procedure in class**. Make sure to show the contents of each block. Also, label the various arcs with the specific name of the 68000-branch instruction that will be used to implement the transition indicated by the arc. **[10 points]**



Step 2

What 32-bit (hexadecimal) values do you expect A and B to have after executing this code? **[1 point]**

Variable	Expected Value
A	00000032

Step 3

Assemble the program, and then fill out the “Before Run” section of the following table. [2 points]

Variable	Before Run	After Run
A	00000000	00000002

Now, run the program, and then complete the “After Run” section of the previous table. Compare the expected values with the actual values you obtained after running the program. [10 points]

Part 9: Loops and Arrays

Your final task is to write a program to count the number of even and odd digits that appear in your student identification number.

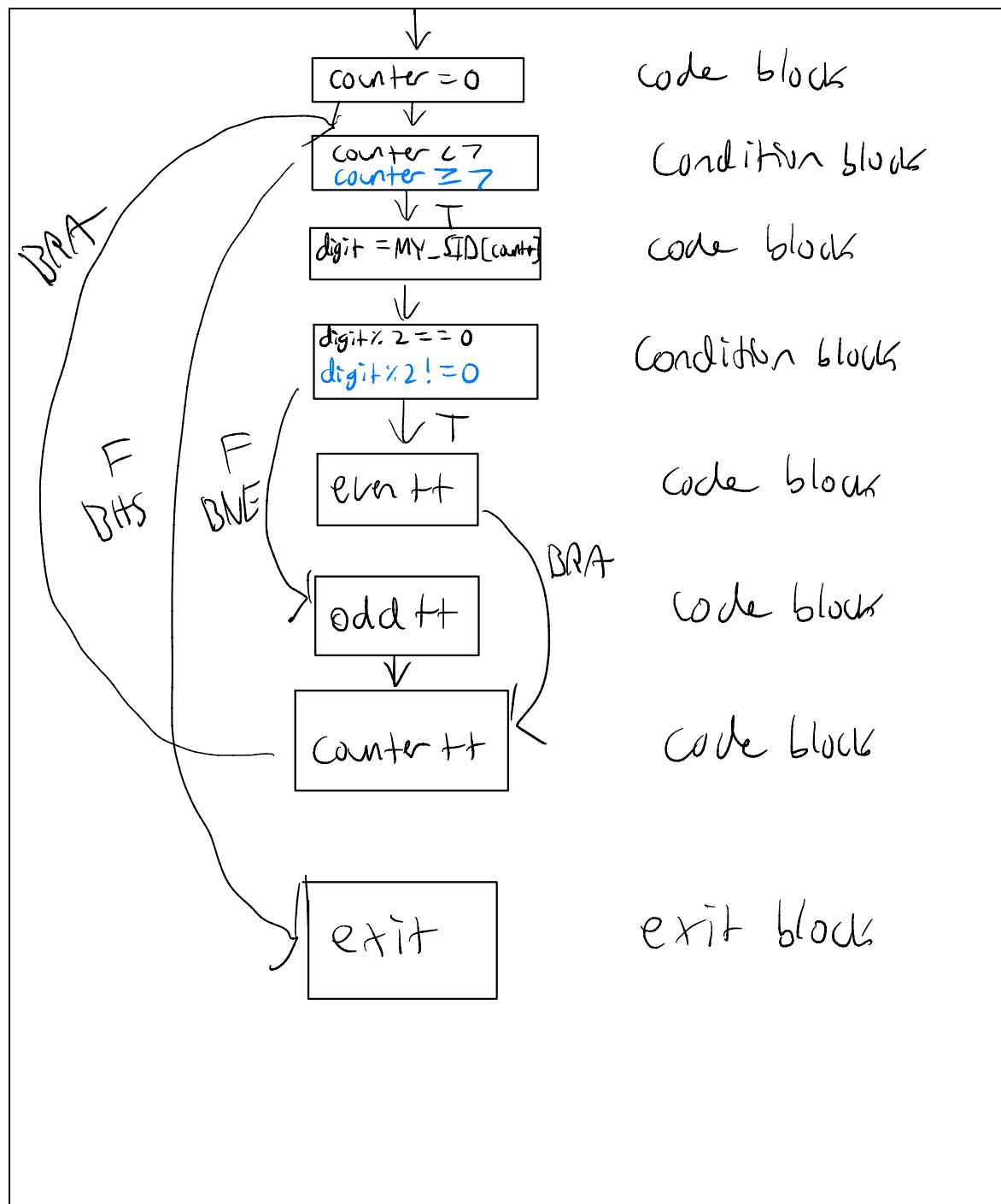
Step 1

Create an assembly-language program called **Lab41.X68**. The program should meet the following specifications:

- Reserve space in memory for an array of seven 16-bit words, and initialize the array so that the array contains the 7 digits that comprise your student identification number. You should call this array, MY_SID.
- The program will implement the following snippet of high-level code.
- even, odd and digit can be implemented using any register D0–D7.
- You should use the *indirect-addressing with index and offset* addressing mode to access individual elements of the array.

```
MY_SID[] = {1,2,3,4,5,6,7};      /* Your SID */
even=0;
odd=0;
for(i=0; i<7; i++) {
    digit = MY_SID[i];
    if(digit % 2 == 0)
        even++;
    else
        odd++;
}
```

Before you start to code, draw a complete CFG (below) for the for-statement **following the same procedure in class**. Make sure to show the contents of each block. Also, label the various arcs with the specific name of the 68000-branch instruction that will be used to implement the transition indicated by the arc. **[10 points]**



Verify the program runs correctly. **[20 points]**