Supplement for Assignment #7 (sections 4.8 - 4.10 of the textbook)

Summary of the MARIE Assembly Language

Type of Instructions	**Mnemonic**	**Hex Opcode**	**Description**
Arithmetic	ADD X	3	Add the contents of address X to AC
	SUBT X	4	Subtract the contents of address X from the AC
	ADDI X	B	Add Indirect: Use the value at X as the actual address of the data operand to add to AC
	CLEAR	A	Put all zeros in the AC
Data Transfer	LOAD X	1	Load the contents of address X into AC
	STORE X	2	Store the contents of AC at address X
I/O	INPUT	5	Input a value from the keyboard into AC
	OUTPUT	6	Output the value in AC to the display
Branch	JUMP X	9	Unconditional branch to X by loading the value of X into PC
	SKIPCOND C	8	Skip the next instruction based on the condition, C: C = 000_{16}: skip if AC is negative ($b_{11}b_{10} = 00_2$) C = 400_{16}: skip if the AC = 0 ($b_{11}b_{10} = 01_2$) C = 800_{16}: skip if the AC is positive ($b_{11}b_{10} = 10_2$)
Subroutine call and return	JNS X	0	Jump-and-Store: Store the PC at address X and jump to X+1
	JUMPI X	C	Use the value **at** X as the address to jump to
	HALT	7	Terminate the program

MARIE Machine-language Instruction Format

15 … 12	11 10 … 0
Opcode	Address (or Condition)

A simple MARIE program can be written to perform the high-level language statements:

RESULT = X + Y - Z
print RESULT

Address	Label	Assembly Language	Machine Language
0		LOAD X	1006_{16}
1		ADD Y	3007_{16}
2		SUBT Z	4008_{16}
3		STORE RESULT	2009_{16}
4		OUTPUT	6000_{16}
5		HALT	7000_{16}
6	X,	DEC 10	$000A_{16}$
7	Y,	DEC 20	0014_{16}
8	Z,	DEC 5	0005_{16}
9	RESULT,	DEC 0	0000_{16}

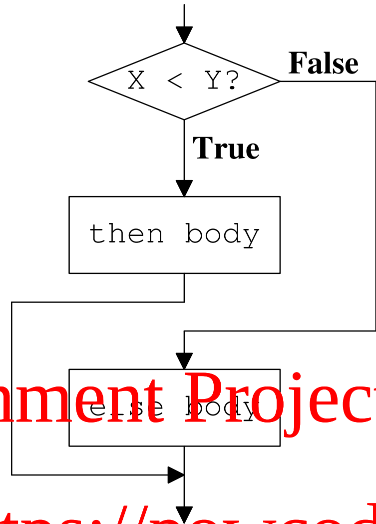
The lines at address 6 to 9 are *assembler directives* (directions to the assembler) to initialize the memory location associated with X (address 6) to DECimal 10, the memory location associated with Y (address 7) to 20, etc. Lines at address 0 to 5 are the actual machine-language MARIE program. If the PC = 0 (program counter), the program execution would start at address 0 which contains 1006_{16}. This instruction would be fetched into the CPUs IR (instruction register), bits 15-12 contain the operations code of 1_{16} would be decoded to determine that it is a LOAD instruction. Execution of the LOAD causes the specified memory address's (006_{16} in bits 11-0) content to be loaded into the accumulator (AC) register (i.e., the value 10_{10} would be loaded into the AC). During the fetch-decode-execute cycle, the PC would get incremented to the next instruction. The program instructions are executed sequentially until the HALT instruction which stops the program.

The branch instructions, JUMP and SKIPCOND, potentially cause the PC to "jump" (i.e., alter the *flow of control* in the program). These instructions are useful for implementing high-level language selection (IF, IF-THEN-ELSE, SWITCH, etc.) and looping statements (FOR, WHILE, REPEAT, etc.). For example, consider the following IF-THEN-ELSE statement and corresponding flow-chart:

HLL statement

```
if X < Y then
    ...
else
    ...
end if
```

Flow chart



Assembly Language

```
          LOAD X
          SUBT Y
          SKIPCOND 000
          JUMP ELSE
THEN,
          JUMP END_IF
ELSE,
END_IF,
```

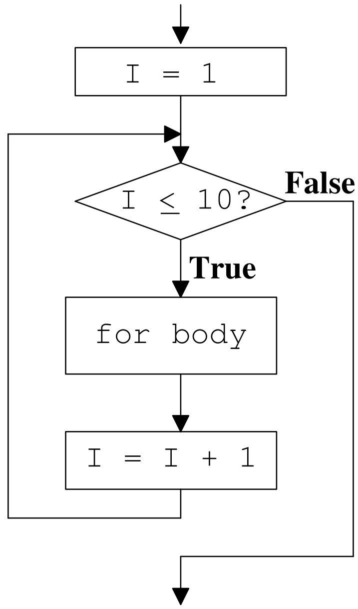

If X < Y is True, then the value of (X-Y) in the AC is negative. The "SKIPCOND 000" cause the JUMP ELSE instruction to be jumped over if the AC is negative. Since the then-part code follows the JUMP ELSE instruction, it is only executed if X < Y. After the then-part code is executed, the JUMP END_IF causes the else-body to be skipped. If X < Y is False, then the value of (X - Y) in the AC will not be negative the SKIPCOND 000 instruction will not jump over the JUMP ELSE instruction.

For a loop example, consider the following FOR-loop and corresponding flow-chart:

HLL statement

```
for I = 1 to 10 do
    ...
end for
```

Flow chart



Assembly Language

```
FOR_INIT, LOAD ONE
          STORE I
FOR_COND, LOAD I
          SUBT TEN
          SKIPCOND 800
          JUMP FOR_BODY
          JUMP END_FOR
 FOR_BODY,
          LOAD I
          ADD ONE
          STORE I
          JUMP FOR_COND
 END_FOR,
```

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If I ≤10 is False, then (I - 10) is positive, so the SKIPCOND 800 skips to JUMP END_FOR. Thus, dropping out of the FOR loop. Otherwise, the JUMP FOR_BODY is not skipped. After the for-body executes and the loop-control variable I is incremented, the JUMP FOR_COND loops back to recheck the loop control variable.

The simplicity of the MARIE instruction set make writing assembly-language programs difficult. So, we'll only write small toy programs in MARIE, and later learn to write realistic assembly-language programs in the slightly more complex MIPS instruction set. However, the simplicity of the MARIE architecture is a huge benefit as we turn our attention to the hardware of implementing the CPU datapath and control unit.

MARIE Registers and Buses:

The revised Figure 4.9 (below) has moved the Memory from the CPU chip and hence the internal CPU Datapath. Thus, memory can only be accessed via the MAR (Memory-Address Register) and the MBR (Memory-Buffer Register) which is much more realistic. This has some impact on the microoperations that access memory. For example, fetching the instruction pointed at by the PC into the IR would require the following microoperations:

MAR ← PC

MBR ← M[MAR] (read from memory into the MBR instead of directly into the IR as descibed on page 199)

IR ← MBR

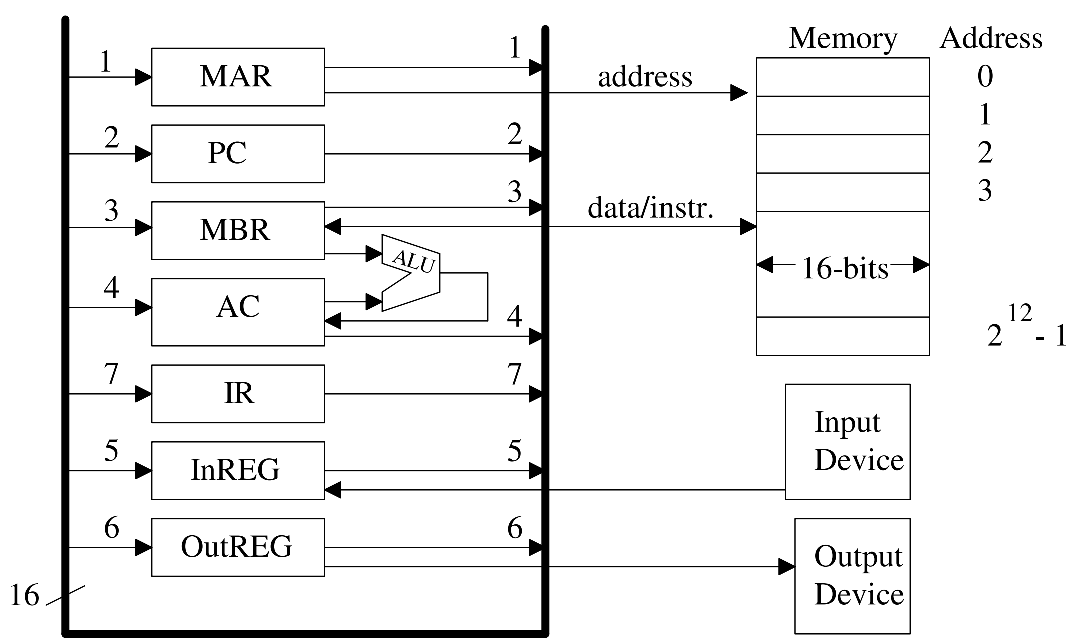
However, the authors seem to understand this since their microoperations to execute the Load X (on page 196) use the MBR correctly:

MAR ← X (X is the address part of the IR, so this should technically be MAR ← IR_{11-0})

MBR ← M[MAR] (read from memory into the MBR instead of directly into the AC)

AC ← MBR

Revised Figure 4.9 Datapath in MARIE



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The text discusses the microoperations of the fetch-decode-execute machine cycle in the execution of the "Simple Program" below that calculates RESULT = X + Y.

Address	Label	Assembly Language	Machine Language
100		LOAD X	1104_{16}
101		ADD Y	3105_{16}
102		STORE RESULT	2106_{16}
103		HALT	7000_{16}
104	X,	DEC 35	0023_{16}
105	Y,	DEC -23	$FFE9_{16}$
106	RESULT,	DEC 0	0000_{16}

Revised Figure 4.14 (a) LOAD X (1104_{16} in ML)

Step	Step #	RTN	PC	IR	MAR	MBR	AC
	(initial values)		100				
Fetch	T_0	MAR ← PC	100		100		
	T_1	MBR ← M[MAR]	100		100	1104	
	T_2	IR ← MBR	100	1104	100	1104	
	T_3	PC ← PC + 1	101	1104	100	1104	
Decode IR[15-12]	T_4	MAR ← IR[11-0]	101	1104	104	1104	
Get operand	T_5	MBR ← M[MAR]	101	1104	104	0023	
Execute	T_6	AC ← MBR	101	1104	104	0023	0023

Revised Figure 4.14 (b) ADD Y (3105_{16} in ML)

Step	Step #	RTN	PC	IR	MAR	MBR	AC
	(initial values AFTER LOAD X)		101	1104	104	0023	0023
Fetch	T_0	MAR ← PC	101	1104	101	0023	0023
	T_1	MBR ← M[MAR]	101	1104	101	3105	0023
	T_2	IR ← MBR	101	3105	101	3105	0023
	T_3	PC ← PC + 1	102	3105	101	3105	0023
Decode IR[15-12]	T_4	MAR ← IR[11-0]	102	3105	105	3105	0023
Get operand	T_5	MBR ← M[MAR]	102	3105	105	FFE9	0023
Execute	T_6	AC ← AC + MBR	102	3105	105	FFE9	000C

Revised Figure 4.14 (c) STORE RESULT (2106_{16} in ML)
(YOU COMPLETE THIS AS PART OF LECTURE)

Step	Step #	RTN	PC	IR	MAR	MBR	AC
	(initial values AFTER ADD Y)		102	3105	105	FFE9	000C
Fetch	T_0						
	T_1						
	T_2						
	T_3						
Decode IR[15-12]	T_4						
Execute*	T_5						

* "Get Operand" step is not necessary for STORE instructions

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Advanced MARIE Assembly Language Example: Print null terminated string to output

HLL:
```
index = 0
while str[index] != 0 do
    output str[index]
    index = index + 1
end while
```

Address	Label	Assembly Language	Machine Language
0		CLEAR	$A000_{16}$
1		STORE INDEX	2011_{16}
2	WHILE,	LOAD STR_BASE	1013_{16}
3		ADD INDEX	3011_{16}
4		STORE ADDR	2012_{16}
5		CLEAR	$A000_{16}$
6		ADDI ADDR	$B012_{16}$
7		SKIPCOND 400	8400_{16}
8		JUMP DO	$900A_{16}$
9		JUMP END_WHILE	$900A_{16}$
A	DO,	OUTPUT	6000_{16}
B		LOAD INDEX	$100D_{16}$
C		ADD ONE	$300B_{16}$
D		STORE INDEX	2011_{16}
E		JUMP WHILE	9002_{16}
F	END_WHILE,	HALT	7000_{16}
10	ONE,	DEC 1	0001_{16}
11	INDEX,	DEC 0	0000_{16}
12	ADDR,	HEX 0	0000_{16}
13	STR_BASE,	HEX 14	0014_{16}
14	STR,	DEC 72 / H	0048_{16}
15		DEC 69 / E	0045_{16}
16		DEC 76 / L	$004C_{16}$
17		DEC 76 / L	$004C_{16}$
18		DEC 79 / O	$004F_{16}$
19		DEC 13 /carriage return	$000D_{16}$
1A		DEC 87 / W	0057_{16}
1B		DEC 79 / O	$004F_{16}$
1C		DEC 82 / R	0052_{16}
1D		DEC 76 / L	$004C_{16}$
1		DEC 68 / D	0044_{16}
1F	NULL,	DEC 0 / NULL CHAR	0000_{16}