

Computer Program Execution

A. Introduction

Objectives

At the end of this lab you should be able to:

- ✦ Use the CPU simulator to create basic CPU instructions
- ✦ Use the simulator to execute basic CPU instructions
- ✦ Use CPU instructions to move data to registers, compare values in registers, push data to the stack, pop data from the stack, jump to address locations and add values held in registers.
- ✦ Explain the function of the special CPU registers PC (Program Counter) and SR (Status Register) and status flags OV, N and Z.
- ✦ Produce code for simple conditional statements and loops.
- ✦ Use direct addressing mode of accessing data in memory
- ✦ Use indirect addressing mode of accessing data in memory
- ✦ Write a subroutine and call it
- ✦ Pass parameters to a subroutine

B. Processor (CPU) Simulators

The computer architecture tutorials are supported by simulators, which are created to help underpin theoretical concepts normally covered during the lectures. The simulators provide visual and animated representation of mechanisms involved and enable the students to observe the hidden inner workings of systems, which would be difficult or impossible to do otherwise. The added advantage of using simulators is that they allow the students to experiment and explore different technological aspects of systems without having to install and configure the real systems.

C. Basic Theory

The programming model of computer architecture defines those low-level architectural components, which include the following

- ✦ CPU instruction set
- ✦ CPU registers
- ✦ Different ways of addressing instructions and data in instructions, i.e. addressing modes such as direct and indirect addressing.

It also defines interactions between the above components. It is this low-level programming model which makes programmed computations possible.

D. Simulator Details

This section includes basic information on the simulator enabling the students to use the simulator. The tutor(s) will be available to help in case of difficulty in using the simulator. The main window is composed of several views that represent different functional parts of the simulated Central Processing Unit. These are shown in Figure 1 below and are composed of

- ✦ CPU Instructions memory
- ✦ Special CPU registers
- ✦ CPU (general purpose) registers
- ✦ Program stack
- ✦ Program creation and program running features

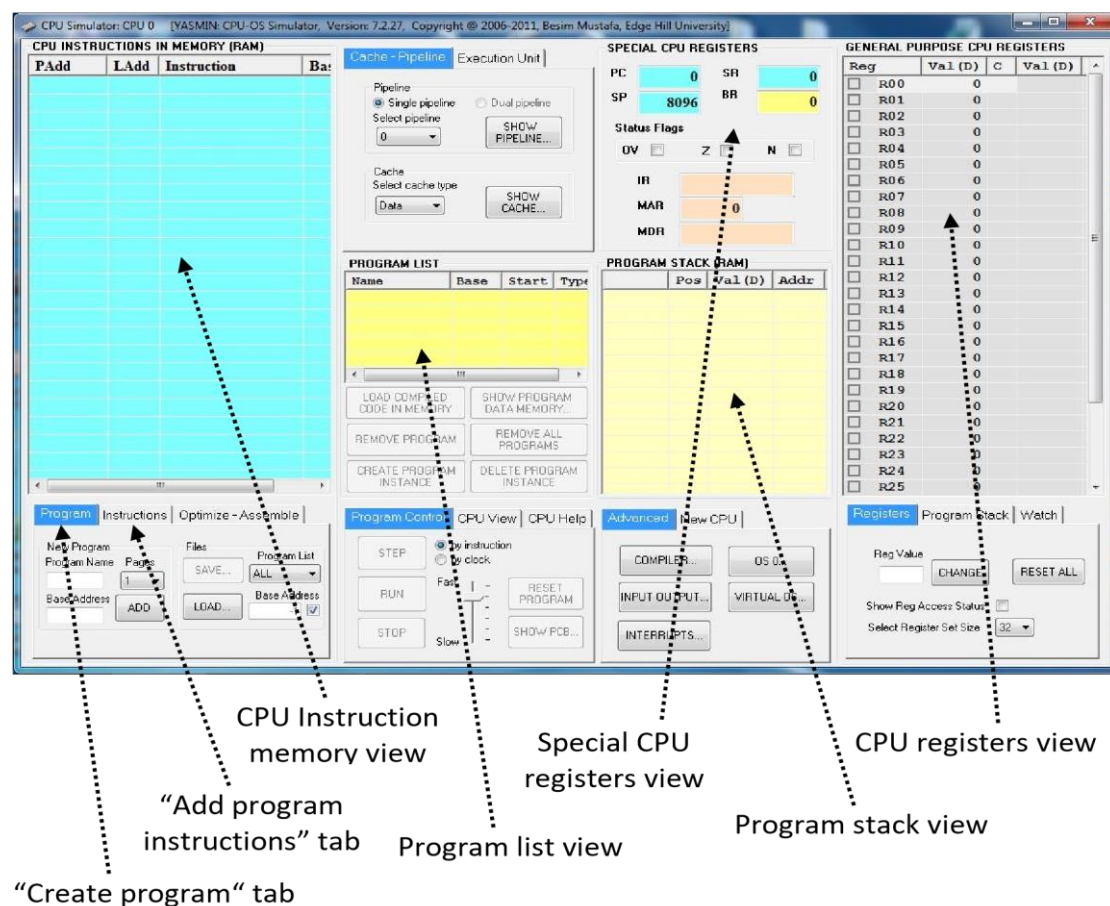


Image 1 – CPU Simulator window

Figure 1. CPU-OS Simulator Window

The parts of the simulator relevant to this lab are described below. **Please read this information carefully and try to identify the different parts on the real CPU Simulator window BEFORE attempting the following exercises. Use this information in conjunction with the exercises that follow.**

1. CPU instruction memory view

[illegible]

Figure 2. Instruction memory view

This view contains the program instructions. The instructions are displayed as sequences of low-level instruction mnemonics (in assembler-level format) and not as binary code. This is done for clarity and makes code more readable by humans.

Each instruction is associated with two addresses: the physical address (**PAdd**) and the logical address (**LAdd**). This view also displays the base address (**Base**) against each instruction. The sequence of instructions belonging to the same program will have the same base address.

2. Special CPU registers view

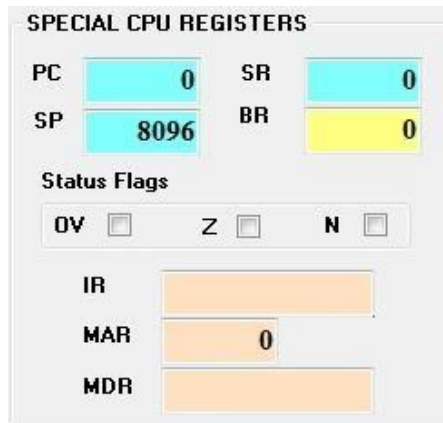


Figure 3. Special CPU registers view
the memory address currently being accessed.

This view shows the set of CPU registers, which have pre-defined specialist functions:

PC: Program Counter contains the address of the next instruction to be executed.

IR: Instruction Register contains the instruction currently being executed.

SR: Status Register contains information pertaining to the result of the last executed instruction.

SP: Stack Pointer register points to the value maintained at the top of the program stack (see below).

BR: Base Register contains current base address.

MAR : Memory Address Register contains

Status bits: **OV:** Overflow; **Z:** Zero; **N:** Negative

3. CPU registers view

GENERAL PURPOSE CPU REGISTERS				
Reg	Val (D)	C	Val (D)	
<input type="checkbox"/> R00	0			
<input type="checkbox"/> R01	0			
<input type="checkbox"/> R02	0			
<input type="checkbox"/> R03	0			
<input type="checkbox"/> R04	0			
<input type="checkbox"/> R05	0			
<input type="checkbox"/> R06	0			
<input type="checkbox"/> R07	0			
<input type="checkbox"/> R08	0			
<input type="checkbox"/> R09	0			
<input type="checkbox"/> R10	0			
<input type="checkbox"/> R11	0			
<input type="checkbox"/> R12	0			
<input type="checkbox"/> R13	0			
<input type="checkbox"/> R14	0			
<input type="checkbox"/> R15	0			
<input type="checkbox"/> R16	0			
<input type="checkbox"/> R17	0			
<input type="checkbox"/> R18	0			
<input type="checkbox"/> R19	0			
<input type="checkbox"/> R20	0			
<input type="checkbox"/> R21	0			
<input type="checkbox"/> R22	0			
<input type="checkbox"/> R23	0			
<input type="checkbox"/> R24	0			
<input type="checkbox"/> R25	0			

Registers

Program Stack

Watch

Reg Value

CHANGE

RESET ALL

Figure 4. CPU Registers view

The register set view shows the contents of all the general-purpose registers, which are used to maintain temporary values as the program's instructions are executed. **Registers are very fast memories that hold temporary values while the CPU executes instructions.**

This architecture supports from 8 to 64 registers. These registers are often used to hold values of a program's variables as defined in high-level languages.

Not all architectures have this many registers. Some have more (e.g. 128 register) and some others have less (e.g. 8 registers). In all cases, these registers serve similar purposes.

This view displays each register's name (**Reg**), its current value (**Val**) and some additional values, which are reserved for program debugging. It can also be used to reset the individual register values manually which is often useful for advanced debugging. **To**

manually change a register's content, first select the register then enter the new value in the text box, **Reg Value, and click on the **CHANGE** button in the **Registers** tab.**

4. Program stack view

[illegible]

Figure 5. Program stack view

The program stack is another area which maintains temporary values as the instructions are executed. The stack is a LIFO (last-in-first-out) data structure. It is also used for efficient interrupt handling and sub-routine calls. **Each program has its own individual stack.**

The CPU instructions PSH (push) and POP are used to store values on top of stack and pop values from top of stack respectively.

5. Program list view

PROGRAM LIST

Name	Base	Start	Type

◀ [Progress Bar] ▶

LOAD COMPILED CODE IN MEMORY

SHOW PROGRAM DATA MEMORY...

REMOVE PROGRAM

REMOVE ALL PROGRAMS

CREATE PROGRAM INSTANCE

DELETE PROGRAM INSTANCE

Figure 6. Program List View

Use the **REMOVE PROGRAM** button to remove the selected program from the list; use the **REMOVE ALL PROGRAMS** button to remove all the programs from the list. Note that when a program is removed, its instructions are also removed from the **Instruction Memory View**.

6. Program creation

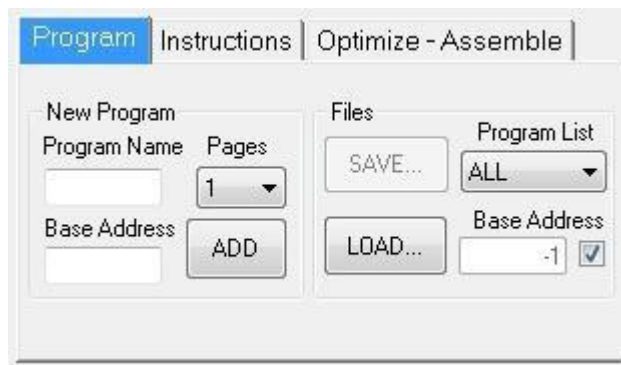


Figure 7. Create program tab

To create a new program enter its name in the **Program Name** box and its base address in the **Base Address** box then click on the **ADD** button. The new program's name will appear in the Program List view

(see Figure 6).

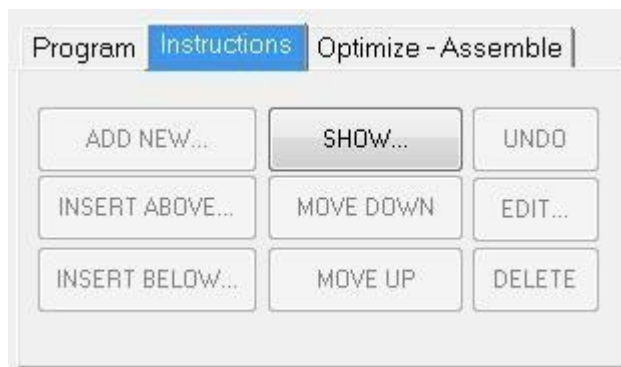


Figure 8. Add program instructions tab

Use **ADD NEW...** button to add a new instruction; use **EDIT...** button to edit the selected instruction; use **MOVE DOWN/MOVE UP** buttons to move the selected instruction down or up; use **INSERT ABOVE.../INSERT**

BELOW... buttons to insert a new instruction above or below the selected instruction respectively.

7. Program data memory view

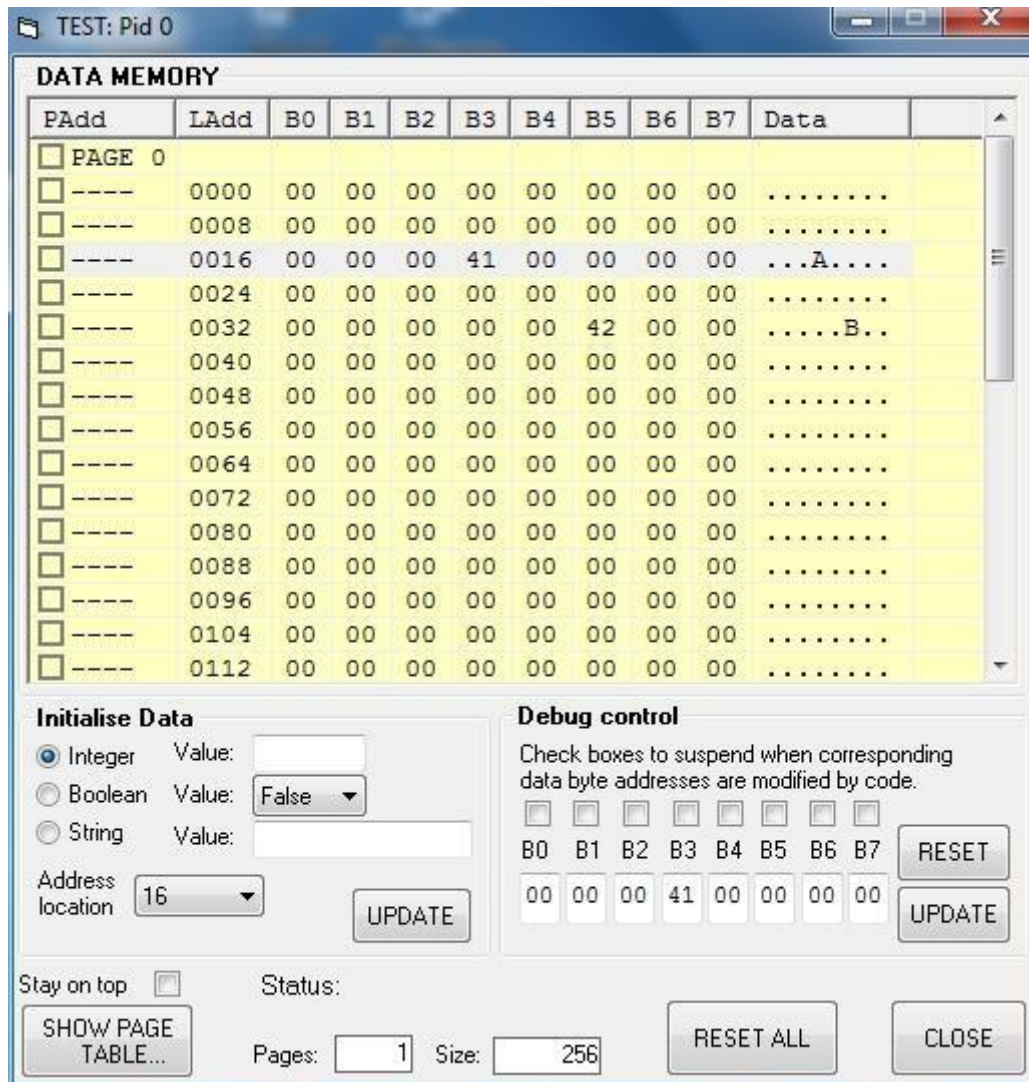


Figure 9. Program data memory view

The CPU instructions that access that part of the memory containing data can write or read the data in addressed locations. This data can be seen in the memory pages window shown in Figure 9 above.

You can display this window by clicking the **SHOW PROGRAM DATA MEMORY...** button in the main CPU window. The **Ladd** (logical address) column shows the starting address of each line in the display. Each line of the display represents 8 bytes of data. Columns **B0** through to **B7** represent bytes 0 to 7 on each line. The **Data** column shows the displayable characters corresponding to the 8 bytes. Those bytes that correspond to non-displayable characters are shown as dots. The data bytes are displayed in hex format only. For example, in Figure 9, there are non-zero data bytes in address locations 19 and 37. These data bytes correspond to displayable characters capital A and B.

To manually change the values of any bytes, first select the line(s) containing the bytes. Then use the information in the **Initialize Data** frame to modify the values of the bytes in the selected line(s) as **Integer**, **Boolean** or **String** formats. You need to click the **UPDATE** button to make the change.

E. Lab Exercises - Investigate and Explore

The lab exercises are a series of activities, which are carried out by the students under basic guidelines. **So, how is this tutorial conducted?** The students are expected to follow the instructions given in order to identify and locate the required information, to act upon it and make notes of their observations. In order to be able to do these activities you should consult the information in **Section D** above and also frequently refer to the **Appendix** for information on various CPU instructions you will be asked to create and use.

Remember, you need to carefully read and understand the instructions before you attempt each activity.

Enter the instructions you create in order to answer the questions in the blank boxes. Refer to Appendix at the end of this document to find the details on the desired instructions. You are expected to execute the instructions you created on the simulator in order to verify your answers.

START HERE: Creating a program and adding instructions to it

Now, let us start. First you need to place some instructions in the **Instruction Memory View** (see Figure 2), representing the RAM in the real machine, before executing any instructions. To do this, follow the steps below:

In the **Program** tab (see Figure 7), first enter a **Program Name**, and then enter a **Base Address** (this can be any number, but for this exercise use 100). Click on the **ADD** button. A new program name will be entered in the **Program List** view (see Figure 6). By the way, you can use the **SAVE...** button to save instructions in a file. You can also use the **LOAD...** button to load instructions from a file.

You are now ready to enter instructions into the CPU Simulator. You do this by clicking on the **ADD NEW...** button in the **Instructions** tab (see Figure 8). This will display the **Instructions: CPU0** window. You use this window to select and enter the CPU instructions. Further information on this can be found on this module's site. **Appendix** lists the instructions you will need in this exercise.

Now, have a go at the following activities (enter your answers in the text boxes provided).

A word of caution: Regularly save your code in a file in case the simulator crashes in which case you can restart the simulator and re-load your file.

Part A: (Refer to the appendix for help with CPU instructions)

1. Create an instruction, which moves number 5 to register R00.

The screenshot shows the CPU INSTRUCTIONS IN MEMORY (RAM) table with the following data:

PAdd	LAdd	Instruction
0100	0000	MOV #5, R00

The SPECIAL CPU REGISTERS view shows PC: 0, SP: 8096, BR: 100, and SR Status Flag: 0. The GENERAL PURPOSE CPU REGISTERS view shows R00: 5, R01: 0, R02: 0, R03: 0.

2. Execute the above instruction (You do this by double-clicking on the instruction). Observe the result in the **CPU Registers** view (Figure 4).
3. Create an instruction, which moves number 7 to register R01.

The screenshot shows the CPU INSTRUCTIONS IN MEMORY (RAM) table with the following data:

PAdd	LAdd	Instruction
0100	0000	MOV #5, R00
0106	0006	MOV #7, R01

The SPECIAL CPU REGISTERS view shows PC: 6, SP: 8096, BR: 100, and SR Status Flag: 0. The GENERAL PURPOSE CPU REGISTERS view shows R00: 5, R01: 7, R02: 0, R03: 0.

4. Execute it (You do this by double-clicking on the instruction)
5. Observe the contents of R00 and R01 in the **CPU Registers** view (Figure 4).
6. Create an instruction, which adds the contents of R00 and R01.

The screenshot shows the CPU INSTRUCTIONS IN MEMORY (RAM) table with the following data:

PAdd	LAdd	Instruction
0100	0000	MOV #5, R00
0106	0006	MOV #7, R01
0112	0012	ADD R00, R01

The SPECIAL CPU REGISTERS view shows PC: 12, SP: 8096, BR: 100, and SR Status Flag: 0. The GENERAL PURPOSE CPU REGISTERS view shows R00: 5, R01: 12, R02: 0, R03: 0.

7. Execute it.
8. Note down which register the result is put in.

R01

9. Create an instruction, which pushes the value in the above register to the top of the program stack, and then execute it. Observe the value in **Program Stack** (Figure 5).

The screenshot shows the CPU INSTRUCTIONS IN MEMORY (RAM) table with the following data:

PAdd	LAdd	Instruction	Base
0100	0000	MOV #5, R00	0100
0106	0006	MOV #7, R01	0100
0112	0012	ADD R00, R01	0100
0117	0017	PSH R01	0100

The PROGRAM STACK (RAM) view shows the following data:

Pos	Val (D)	Addr
TOS->	0	12 0017

10. Create an instruction to push number 2 on top of the program stack and execute it. Observe the value in **Program Stack** (Figure 5).

The screenshot shows the CPU INSTRUCTIONS IN MEMORY (RAM) table with the following data:

PAdd	LAdd	Instruction	Base	T
0100	0000	MOV #5, R00	0100	0
0106	0006	MOV #7, R01	0100	0
0112	0012	ADD R00, R01	0100	1
0117	0017	PSH R01	0100	0
0120	0020	PSH #2	0100	0

The PROGRAM STACK (RAM) view shows the following data:

Pos	Val (D)	Addr
TOS->	1	2 0020
BOS->	0	12 0017

11. Create an instruction to unconditionally jump to the first instruction.

PAdd	LAdd	Instruction	Base	T
<input checked="" type="checkbox"/> 0100	0000	MOV #5, R00	0100	0
<input checked="" type="checkbox"/> 0106	0006	MOV #7, R01	0100	0
<input checked="" type="checkbox"/> 0112	0012	ADD R00, R01	0100	1
<input checked="" type="checkbox"/> 0117	0017	PSH R01	0100	0
<input checked="" type="checkbox"/> 0120	0020	PSH #2	0100	0
<input checked="" type="checkbox"/> 0124	0024	JMP 0000	0100	2

12. Execute it.

13. Observe the value in the **PC** register. This is the address of the next instruction to be executed. Make a note of the instruction it is pointing to?

0

14. Create an instruction to pop the value on top of the **Program Stack** into register R02.

PAdd	LAdd	Instruction	Base	T
<input checked="" type="checkbox"/> 0100	0000	MOV #5, R00	0100	0
<input checked="" type="checkbox"/> 0106	0006	MOV #7, R01	0100	0
<input checked="" type="checkbox"/> 0112	0012	ADD R00, R01	0100	1
<input checked="" type="checkbox"/> 0117	0017	PSH R01	0100	0
<input checked="" type="checkbox"/> 0120	0020	PSH #2	0100	0
<input checked="" type="checkbox"/> 0124	0024	JMP 0000	0100	2
<input checked="" type="checkbox"/> 0128	0028	POP R02	0100	0

Reg	Val (D)	C	Val (T)
PC	25		
SP	8095		
SR Status Flag			
OV	<input type="checkbox"/>	Z	<input type="checkbox"/>
IR	POP R02		
MAR	128		
MDR	POP R02		

Reg	Val (D)	C	Val (T)
R00	5		
R01	12		
R02	2		
R03	0		
R04	0		
R05	0		
R06	0		
R07	0		
R08	0		
R09	0		
R10	0		
R11	0		
R12	0		
R13	0		
R14	0		

15. Execute it.

16. Create an instruction to pop the value on top of the **Program Stack** into register R03.

PAdd	LAdd	Instruction	Base	T
<input checked="" type="checkbox"/> 0000	0000	MOV #5, R00	0000	0
<input checked="" type="checkbox"/> 0006	0006	MOV #7, R01	0000	0
<input checked="" type="checkbox"/> 0012	0012	ADD R00, R01	0000	1
<input checked="" type="checkbox"/> 0017	0017	PSH R01	0000	0
<input checked="" type="checkbox"/> 0020	0020	PSH #2	0000	0
<input checked="" type="checkbox"/> 0024	0024	JMP 0	0000	2
<input checked="" type="checkbox"/> 0028	0028	POP R02	0000	0
<input checked="" type="checkbox"/> 0031	0031	POP R03	0000	0

Reg	Val (D)	C	Val (T)
PC	31		
SP	8096		
SR Status Flag			
OV	<input type="checkbox"/>	Z	<input type="checkbox"/>
IR	POP R03		
MAR	31		

Reg	Val (D)	C	Val (T)
R00	5		
R01	12		
R02	2		
R03	12		
R04	0		
R05	0		
R06	0		
R07	0		
R08	0		
R09	0		
R10	0		
R11	0		
R12	0		
R13	0		
R14	0		

17. Execute it.

18. Execute the last instruction once again. What happened? Explain.

Stack underflow because the stack is empty

19. Create a compare instruction, which compares values in registers R04 and R05.

PAdd	LAdd	Instruction	Base	T
<input checked="" type="checkbox"/> 0000	0000	MOV #5, R00	0000	0
<input checked="" type="checkbox"/> 0006	0006	MOV #7, R01	0000	0
<input checked="" type="checkbox"/> 0012	0012	ADD R00, R01	0000	1
<input checked="" type="checkbox"/> 0017	0017	PSH R01	0000	0
<input checked="" type="checkbox"/> 0020	0020	PSH #2	0000	0
<input checked="" type="checkbox"/> 0024	0024	JMP 0	0000	2
<input checked="" type="checkbox"/> 0028	0028	POP R02	0000	0
<input checked="" type="checkbox"/> 0031	0031	POP R03	0000	0
<input checked="" type="checkbox"/> 0034	0034	CMP R04, R05	0000	3

Reg	Val (D)	C	Val (T)
PC	34		
SP	8096		
SR Status Flag			
OV	<input type="checkbox"/>	Z	<input type="checkbox"/>
IR	CMP R04, R05		
MAR	34		
MDR	CMP R04, R05		

Reg	Val (D)	C	Val (T)
R00	5		
R01	12		
R02	2		
R03	12		
R04	0		
R05	0		
R06	0		
R07	0		
R08	0		
R09	0		
R10	0		
R11	0		
R12	0		
R13	0		
R14	0		

20. Manually insert two equal values in registers R04 and R05 (Figure 4).

21. Execute the above compare instruction.

22. Which of the status flags **OV/Z/N** is set (i.e. box is checked)?

Z

23. Manually insert a value in first register greater than that in second register.

24. Execute the compare instruction again.

25. Which of the status flags **OV/Z/N** is set?

N

26. Manually insert a value in first register smaller than that in second register.

27. Execute the compare instruction once again.

28. Which of the status flags **OV/Z/N** is set?

Box is not checked

29. Create an instruction, which will jump to the first instruction if the values in registers R04 and R05 are equal.

<input type="checkbox"/>	0034	0034	CMP R04, R05	0000
<input checked="" type="checkbox"/>	0039	0039	JEQ 0	0000

30. Test the above instruction by manually putting equal values in registers R04 and R05, then first executing the compare instruction followed by executing the jump instruction (**Remember: You execute an instruction by double-clicking on it**). If it worked the first instruction should be highlighted.

31. Now that you have some understanding of basic CPU instructions and are able to program the simulator here is a bit of challenge for you: preparing a little program loop. Program loops are extremely useful and are very frequently used by computer programs. Here's what you have to do:

1. Create an instruction that moves number 0 into register R01
2. Create an instruction that adds number 1 to register R01
3. Create an instruction that compares number 10 and register R01
4. Create an instruction that jumps back to instruction 2 above if R01 is not equal to number 10.
5. Create a HLT instruction.

Make a note of the instructions 1 to 5 you created above in the box below:

CPU INSTRUCTIONS IN MEMORY (RAM)				
PAdd	LAdd	Instruction		Base
<input type="checkbox"/> → 0100	0000	MOV #0, R01		0100
<input type="checkbox"/> 0106	0006	ADD #1, R01		0100
<input type="checkbox"/> 0112	0012	CMP #10, R01		0100
<input type="checkbox"/> 0118	0018	JNE 0006		0100
<input type="checkbox"/> 0122	0022	HLT		0100

6. Starting from instruction 1 manually execute instructions 1 to 4 one after the other. What happened when you executed instruction 4?

Instruction 2 is highlighted

CPU INSTRUCTIONS IN MEMORY (RAM)				
PAdd	LAdd	Instruction		Base
<input type="checkbox"/> 0100	0000	MOV #0, R01		0100
<input checked="" type="checkbox"/> → 0106	0006	ADD #1, R01		0100
<input type="checkbox"/> 0112	0012	CMP #10, R01		0100
<input type="checkbox"/> 0118	0018	JNE 0006		0100
<input type="checkbox"/> 0122	0022	HLT		0100

7. Now first click on the **RESET PROGRAM** button (see **Program Control** tab in Figure 1) and then highlight instruction 1 above. Next click on the **RUN** button. Now observe the loop in action.

Part B: (Refer to the appendix for help with CPU instructions)

1. Produce the code for a conditional statement such that if the value in register R02 is **greater than** (>) the value in register R01 then register R03 is set to 8. Test it on the simulator.

CPU INSTRUCTIONS IN MEMORY (RAM)					
	PAdd	LAdd	Instruction	Base	T
<input type="checkbox"/>	0100	0000	CMP R02, R01	0100	3
<input type="checkbox"/>	0105	0005	JGT 5	0100	2
<input checked="" type="checkbox"/>	0109	0009	MOV #8, R03	0100	0

2. Produce the code for a loop that repeats **5 times** where the value of register R02 is incremented by 2 every time the loop repeats. Test it on the simulator.

CPU INSTRUCTIONS IN MEMORY (RAM)				
	PAdd	LAdd	Instruction	Base
<input type="checkbox"/>	0100	0000	MOV #5, R00	0100
<input type="checkbox"/>	0106	0006	ADD #2, R02	0100
<input type="checkbox"/>	0112	0012	SUB #1, R00	0100
<input type="checkbox"/>	0118	0018	CMP #0, R00	0100
<input type="checkbox"/>	0124	0024	JGT 6	0100
<input checked="" type="checkbox"/>	0128	0028	HLT	0100

3. The numbers 4, -3, 5 and -6 are manually pushed on top of stack in that order. Produce the code for a routine that **pops** two numbers from top of stack **multiplies** them and **pushes** the result back to top of stack. The routine repeats this until there is only one number left on top of stack. Test the code on the simulator.

CPU INSTRUCTIONS IN MEMORY (RAM)

	PAdd	LAdd	Instruction
<input type="checkbox"/>	0100	0000	MOV #3, R02
<input type="checkbox"/>	0106	0006	POP R00
<input type="checkbox"/>	0109	0009	POP R01
<input type="checkbox"/>	0112	0012	MUL R00, R01
<input type="checkbox"/>	0117	0017	PSH R01
<input type="checkbox"/>	0120	0020	SUB #1, R02
<input type="checkbox"/>	0126	0026	CMP #0, R02
<input type="checkbox"/>	0132	0032	JGT 6
<input checked="" type="checkbox"/>	0136	0036	HLT

Cache - Pipeline

☒ Single pipeline
☐ Dual pipeline

Select pipeline: 0

Cache: Select cache type: Data

SHOW PIPELINE...

SHOW CACHE...

PROGRAM LIST

Name	Base	Start
lab1	0100	0000

SPECIAL CPU REGISTERS

PC: 36 SR: 1
SP: 8098 BR: 100

SR Status Flag: OV ☐ Z ☒ N ☐
CPU Mode: User ☒ Kernel ☐

IR: HLT
MAR: 136
MDR: HLT

PROGRAM STACK (RAM)

	Pos	Val (D)	Ad
TOS->	0	360	00

GENERAL PURPOSE CPU REGISTERS

Reg	Val (D)	C	Val
<input type="checkbox"/> R00	90		
<input type="checkbox"/> R01	360		
<input checked="" type="checkbox"/> R02	0		
<input type="checkbox"/> R03	0		
<input type="checkbox"/> R04	0		
<input type="checkbox"/> R05	0		
<input type="checkbox"/> R06	0		
<input type="checkbox"/> R07	0		
<input type="checkbox"/> R08	0		
<input type="checkbox"/> R09	0		
<input type="checkbox"/> R10	0		
<input type="checkbox"/> R11	0		
<input type="checkbox"/> R12	0		
<input type="checkbox"/> R13	0		
<input type="checkbox"/> R14	0		
<input type="checkbox"/> R15	0		

Part C: Instructions for writing to and reading from memory (RAM):

1. Locate the instruction that **stores** a byte in program data memory and use it to store number 65 in memory address location 20 (this uses **memory direct** addressing method).

CPU INSTRUCTIONS IN MEMORY (RAM)		
PAdd	LAdd	Instruction
<input type="checkbox"/> 0100	0000	STB #65, 20

2. Move number 51 into register R04. Use the store instruction to **store** the contents of R04 in program data memory location 21 (this uses **register direct** addressing method).

<input type="checkbox"/> 0100	0000	MOV #51, R04
<input type="checkbox"/> 0106	0006	STB R04, 21

3. Move number 22 into register R04. Use this information to indirectly **store** number 59 in program data memory (hint: you will need to use the '@' prefix for this – see the list of instructions in appendix) - (this uses **register indirect** addressing method).

<input type="checkbox"/> 0100	0000	MOV #22, R04
<input type="checkbox"/> 0106	0006	MOV #59, R00
<input type="checkbox"/> 0112	0012	STB R00, 0

4. Locate the instruction that **loads** a byte from program data memory into a register. Use this to load the number in memory address 22 into register R10.

CPU INSTRUCTIONS IN MEMORY (RAM)		
PAdd	LAdd	Instruction
<input type="checkbox"/> 0100	0000	MOV #22, R04
<input type="checkbox"/> 0106	0006	MOV #59, R00
<input type="checkbox"/> 0112	0012	STB R00, 0
<input type="checkbox"/> 0118	0018	LDB @22, R10

5. Write a loop in which 10 numbers from 41 to 50 are written in program data memory starting from memory address 24 (hint: use **register indirect** addressing where register R04 indirectly represents memory address to write to and increment it to address increasing memory locations).

CPU INSTRUCTIONS IN MEMORY (RAM)		
PAdd	LAdd	Instruction
<input type="checkbox"/> 0100	0000	MOV #9, R06
<input type="checkbox"/> 0106	0006	MOV #41, R07
<input type="checkbox"/> 0112	0012	MOV #24, R08
<input type="checkbox"/> 0118	0018	STB R07, @R08
<input type="checkbox"/> 0123	0023	ADD #1, R08
<input type="checkbox"/> 0129	0029	ADD #1, R07
<input type="checkbox"/> 0135	0035	SUB #1, R06
<input type="checkbox"/> 0141	0041	CMP #0, R06
<input type="checkbox"/> 0147	0047	JGT 18
<input type="checkbox"/> 0151	0051	HLT

6. Manually initialise part of program data memory starting from address 40 with string "CPU INSTRUCTIONS RULE" (see section D above on how to do this). Write a loop in which this string is copied to another part of the program data memory starting from address 64.

CPU INSTRUCTIONS IN MEMORY (RAM)			DATA MEMORY										
PAdd	LAdd	Instruction	PAdd	LAdd	B0	B1	B2	B3	B4	B5	B6	B7	Data
<input type="checkbox"/> 0100	0000	MOV #22, R00	<input type="checkbox"/> PAGE 0										
<input type="checkbox"/> 0106	0006	MOV #40, R01	<input type="checkbox"/> ----	0000	00	00	00	00	00	00	00	00
<input type="checkbox"/> 0112	0012	MOV #64, R02	<input type="checkbox"/> ----	0008	00	00	00	00	00	00	00	00
<input type="checkbox"/> 0118	0018	LDBI @R01, R05	<input type="checkbox"/> ----	0016	00	00	00	00	00	00	00	00
<input type="checkbox"/> 0123	0023	STB R05, @R02	<input type="checkbox"/> ----	0024	00	00	00	00	00	00	00	00
<input type="checkbox"/> 0128	0028	ADD #1, R02	<input type="checkbox"/> ----	0032	00	00	00	00	00	00	00	00
<input type="checkbox"/> 0134	0034	SUB #1, R00	<input type="checkbox"/> ----	0040	03	43	50	55	20	49	4E	53	.CPU INS
<input type="checkbox"/> 0140	0040	CMP #0, R00	<input type="checkbox"/> ----	0048	54	52	55	43	54	49	4F	4E	TRUCTION
<input type="checkbox"/> 0146	0046	JGT 18	<input type="checkbox"/> ----	0056	53	20	52	55	4C	45	00	00	S RULE..
<input type="checkbox"/> 0150	0050	HLT	<input type="checkbox"/> ----	0064	03	43	50	55	20	49	4E	53	.CPU INS
			<input type="checkbox"/> ----	0072	54	52	55	43	54	49	4F	4E	TRUCTION
			<input type="checkbox"/> ----	0080	53	20	52	55	4C	45	00	00	S RULE..

Part D: Instructions for calling subroutines and passing parameters to subroutines:

1. Add the following code and run it starting from the first MOV instruction (to do this you need to first select this instruction and then click on the RUN button).

NOTE:

Ask your tutor how to add labels to your code. A Label represents the address of the instruction immediately following it. For example, 'Label2' below represents the address of the MOV instruction following it. Labels are used by the jump instructions by putting a '\$' in front of the label name, e.g. the 'JMP \$Label2' instruction will jump to the instruction at address represented by the label 'Label2'.

```
Label2
MOV #16, R03
MOV #h41, R04
Label3
STB R04, @R03
ADD #1, R03
ADD #1, R04
CMP #h4F, R04
JNE $Label3
HLT
```

NOTE:

This code stores numbers hex 41 to hex 4F starting from program memory address 16. These numbers are ASCII codes for displayable characters of the alphabet. **You need to understand how this is done by this code in order to benefit from these exercises.**

- a. Make a note of what you see in the program's data area after the program stops running:

DATA MEMORY											
PAdd	LAdd	B0	B1	B2	B3	B4	B5	B6	B7	Data	
<input type="checkbox"/> ----	0016	41	42	43	44	45	46	47	48	ABCDEFGH	
<input type="checkbox"/> ----	0024	49	4A	4B	4C	4D	4E	00	00	IJKLMN..	

- b. Suggest what the significance of @ in @R03 might be:

Indicate address value in R03

2. Add the following subroutine calling code but do **NOT** run it yet:

```
MSF
CAL $Label2
HLT
```

Now convert the code in (1) above into a subroutine by simply replacing the **HLT** instruction with the **RET** instruction.

- a. Make a note of the contents of the **PROGRAM STACK** after the instruction **MSF** is executed (you can execute this instruction by simply double-clicking on it):

PROGRAM STACK (RAM)			
	Pos	Val (D)	Addr
<input type="checkbox"/> TOS->	1	0	0039
<input type="checkbox"/> BOS->	0	0	0039

- b. Make a note of the contents of the **PROGRAM STACK** after the instruction **CAL** is executed (you can execute this instruction by simply double-clicking on it):

PROGRAM STACK (RAM)			
	Pos	Val (D)	Addr
<input type="checkbox"/> TOS->	1	44	0039
<input type="checkbox"/> BOS->	0	0	0039

- c. What is the significance of the additional information on the stack after executing the **CAL** instruction?

Used to call the specified subroutine

3. Let's make the above subroutine a little more flexible. Suppose we wish to change the number of characters stored when calling the subroutine. Modify the calling code in (2) as below:

```
MSF
PSH #h60    ← puts the number hex 60 on top of the stack
CAL $Label2
HLT
```

- a. Now modify the subroutine code in (1) as below and run the above calling code (starting from the **MSF** instruction). Pay particular attention to the behaviour of the stack:

```
Label2
MOV #16, R03
MOV #h41, R04
POP R05     ← puts the number on top of the stack in R05

Label3
STB R04, @R03
ADD #1, R03
ADD #1, R04
CMP R05, R04 ← compares R05 with R04
JNE $Label3
RET
```

- b. Add a second parameter to the above code that can provide different starting addresses for the data transfer to memory and test it on the simulator. Write the modified code below:

CPU INSTRUCTIONS IN MEMORY (RAM)				
	PAdd	LAdd	Instruction	Base
<input type="checkbox"/>	0000	0000	label2:	000
<input type="checkbox"/>	0000	0000	POP R06	000
<input type="checkbox"/>	0003	0003	MOV R06, R03	000
<input type="checkbox"/>	0008	0008	MOV #h41, R04	000
<input type="checkbox"/>	0014	0014	POP R05	000
<input type="checkbox"/>	0017	0017	label3:	000
<input checked="" type="checkbox"/>	0017	0017	STB R04, @R03	000
<input type="checkbox"/>	0022	0022	ADD #1, R03	000
<input type="checkbox"/>	0028	0028	ADD #1, R04	000
<input type="checkbox"/>	0034	0034	CMP R05, R04	000
<input type="checkbox"/>	0039	0039	JNE Slabel3	000
<input type="checkbox"/>	0043	0043	RET	000
<input type="checkbox"/>	0044	0044	MSF	000
<input type="checkbox"/>	0045	0045	PSH #h60	000
<input type="checkbox"/>	0049	0049	PSH #16	000
<input type="checkbox"/>	0053	0053	CAL Slabel2	000
<input type="checkbox"/>	0057	0057	HLT	000

4. Write a subroutine that takes two numbers as parameters, adds them and returns the result in register R00, i.e. when the subroutine is exited the result is available in R00 to the rest of the program. Test it on the simulator by writing the calling instructions that include passing two numbers on the stack. Copy the code below (including the calling instructions):

CPU INSTRUCTIONS IN MEMORY (RAM)			Cache - Pipeline		Executing		SPECIAL CPU REGISTERS		GENERAL PURPOSE CPU REGIS			
	PAdd	LAdd	Instruction				PC	SR	Reg	Val (D)	C	V
<input type="checkbox"/>	0100	0000	main:				25	0	R00	25		
<input type="checkbox"/>	0100	0000	POP R00				SP	8096	R01	15		
<input type="checkbox"/>	0103	0003	POP R01						R02	0		
<input type="checkbox"/>	0106	0006	ADD R01, R00						R03	0		
<input type="checkbox"/>	0111	0011	RET						R04	0		
<input type="checkbox"/>	0112	0012	MSF						R05	0		
<input type="checkbox"/>	0113	0013	PSH #15						R06	0		
<input type="checkbox"/>	0117	0017	PSH #10						R07	0		
<input type="checkbox"/>	0121	0021	CAL Smain						R08	0		
<input checked="" type="checkbox"/>	0125	0025	HLT						R09	0		

5. Write a subroutine that takes two numbers as parameters, compares them and returns the higher of the two as the result in register R00 (consider what should happen if the two numbers are the same). Test it on the simulator by writing the calling instructions that include passing two numbers on the stack. Copy the subroutine code alone below:

The screenshot displays a computer simulator interface with several panels:

- CPU INSTRUCTIONS IN MEMORY (RAM):** A table listing instructions with their Program Address (PAdd), Link Address (LAdd), and Instruction text. The instruction at PAdd 0144 is highlighted in red and is `HLT`.
- Cache - Pipeline:** A panel with tabs for 'Cache - Pipeline' and 'Executing'. It includes options for 'Pipeline' (Single, Select), 'Cache' (Select cache, Data), and buttons for 'SHOW PIPELINE...' and 'SHOW CACHE...'.
- SPECIAL CPU REGISTERS:** A panel showing values for PC (44), SP (8096), SR (0), BR (100), IR (HLT), MAR (144), and MDR (HLT). It also includes status flags (Z, N, O) and a 'CPU Mode' selector (User, Kernel).
- PROGRAM LIST:** A table with columns 'Name', 'Base', and 'Start'. It lists 'lab1' with Base 0100 and Start 0000.
- PROGRAM STACK (RAM):** A table with columns 'Pos' and 'Val (D)', currently empty.
- GENERAL PURPOSE CPU REGISTER:** A table with columns 'Reg', 'Val (D)', 'C', and 'V'. It lists registers R00 through R16. R00, R01, and R02 are highlighted in blue, with R00 and R01 having a value of 40.

***** End of Exercises *****

Appendix – CPU Simulator Instruction Sub-set

Inst.	Description
Data transfer instructions	
MOV	Move data to register; move register to register e.g. MOV #2, R01 moves number 2 into register R01 MOV R01, R03 moves contents of register R01 into register R03
LDB	Load a byte from memory to register e.g. LDB 1022, R03 loads a byte from memory address 1022 into R03 LDB @R02, R05 loads a byte from memory the address of which is in R02
LDW	Load a word (2 bytes) from memory to register Same as in LDB but a word (i.e. 2 bytes) is loaded into a register
STB	Store a byte from register to memory STB R07, 2146 stores a byte from R07 into memory address 2146 STB R04, @R08 stores a byte from R04 into memory address of which is in R08
STW	Store a word (2 bytes) from register to memory Same as in STB but a word (i.e. 2 bytes) is loaded stored in memory
PSH	Push data to top of hardware stack (TOS); push register to TOS e.g. PSH #6 pushes number 6 on top of the stack PSH R03 pushes the contents of register R03 on top of the stack
POP	Pop data from top of hardware stack to register e.g. POP R05 pops contents of top of stack into register R05 Note: If you try to POP from an empty stack you will get the error message "Stack underflow".
Arithmetic instructions	
ADD	Add number to register; add register to register e.g. ADD #3, R02 adds number 3 to contents of register R02 and stores the result in register R02. ADD R00, R01 adds contents of register R00 to contents of register R01 and stores the result in register R01.
SUB	Subtract number from register; subtract register from register
MUL	Multiply number with register; multiply register with register
DIV	Divide number with register; divide register with register

Control transfer instructions	
JMP	Jump to instruction address <u>unconditionally</u> e.g. JMP 100 unconditionally jumps to address location 100 where there is another instruction
JLT	Jump to instruction address if less than (after last comparison)
JGT	Jump to instruction address if greater than (after last comparison)
JEQ	Jump to instruction address if equal (after last comparison instruction) e.g. JEQ 200 jumps to address location 200 if the previous comparison instruction result indicates that the two numbers are equal, i.e. the Z status flag is set (the Z box will be checked in this case).
JNE	Jump to instruction address if not equal (after last comparison)
MSF	Mark Stack Frame instruction is used in conjunction with the CAL instruction. e.g. MSF reserve a space for the return address on program stack CAL 1456 save the return address in the reserved space and jump to subroutine in address location 1456
CAL	Jump to subroutine address (saves the return address on program stack) This instruction is used in conjunction with the MSF instruction. You'll need an MSF instruction before the CAL instruction. See the example above
RET	Return from subroutine (uses the return address on stack)
SWI	Software interrupt (used to request OS help)
HLT	Halt simulation
Comparison instruction	
CMP	Compare number with register; compare register with register e.g. CMP #5, R02 compare number 5 with the contents of register R02 CMP R01, R03 compare the contents of registers R01 and R03 Note: If R01 = R03 then the status flag Z will be set, i.e. the Z box is checked. If R01 < R03 then none of the status flags will be set, i.e. none of the status flag boxes are checked. If R01 > R03 then the status flag N will be set, i.e. the N status box is checked.

Input, output instructions	
IN	Get input data (if available) from an external IO device
OUT	Output data to an external IO device e.g. OUT 16, 0 outputs contents of data in location 16 to the console (the second parameter must always be a 0)
