2.1 Programmable processor concept

Programmable processor overview

A ***programmable processor*** carries out desired functionality by executing instructions from an instruction memory. Unlike a typical circuit that carries out the same functionality repeatedly, a programmable processor can be configured to carry out nearly any functionality by putting different instructions in the instruction memory. Ex: A single programmable processor can be programmed to carry out the functionality of a calculator, a web browser, and a word processor. Storing instructions into an instruction memory is known as ***programming*** the memory, and those instructions are known as a ***program***.

The processor executes one instruction at a time, proceeding to the next instruction when done.

PARTICIPATION ACTIVITY 2.1.1: Simple programmable processor.

1 2 3 4 2x speed

Instruction memory IM

0	Load t0 with DM[5001]
1	Load t1 with DM[5002]
2	Add t5 = t0 + t1
3	Store t5 to DM[5005]
4	Load t4 with DM[5015]
5	Add t5 = t3 + t4

Data memory DM

5000	
5001	20
5002	40
5003	
5004	
5005	

Register file

zero	0
t0	20
t1	40
t2	
t3	
t4	
t5	10
t6	

ALU

CPU

The second instruction loads t1 with the value located at 5002 from the data memory.

Captions

1. The first instruction loads t0 with the value located at 5001 from the data memory.
2. The second instruction loads t1 with the value located at 5002 from the data memory.
3. The next instruction adds t0 + t1, and puts the sum in t5.
4. The next instruction stores t5's value into data memory location 5005.

Feedback?

A programmable processor includes:

- ***CPU***: A ***central processing unit*** executes instructions by controlling an ALU, register file, and other hardware components.
  - ***ALU***: A component that performs arithmetic and logic operations, like addition or subtraction, on data in the register file. Short for ***arithmetic logic unit***.
  - ***Register file***: A set of registers that holds temporary data accessible by the ALU. A ***register*** is a digital circuit that can store multiple bits, such as 32 bits.
- ***Instruction memory***: A memory that holds instructions.
- ***Data memory***: A memory that holds data used by the instructions.

A ***memory*** is a digital circuit that holds relatively large amounts of data, often organized as bytes with each having a unique ***address***, where each byte can either be read ("load") or written ("store"). Ex: A memory may hold 1024 bytes, with addresses 0, 1, 2, ..., 1023. Common memory sizes range from 1 Kbyte to 4 Gbyte, while typical register files are smaller with perhaps 128 or fewer registers.

PARTICIPATION ACTIVITY 2.1.2: Processor basics.

Refer to the above animation.

1) What is the value in data memory location 5002?

40

Check Show answer

Correct

40

The value in the box next to label 5002 is 40. Thus, data memory location 5002 holds value 40.

2) What is the value in t1 after the instruction Load t1 DM[5002] executes?

40

Correct

40

Check Show answer

The instruction reads the data held in DM[5002], which is 40, and writes that 40 into t1.

3) The first Add instruction adds the values in t0 and t1, and writes the result in what register?

t5

Check Show answer

Correct

t5

The instruction Add t5 = t0 + t1 adds the values in t0 and t1 (so 20 + 40) and writes the result in t5.

4) How many executed instructions copied data from the data memory to the register file during the animation?

2

Check Show answer

Correct

2

The first two instructions are Load instructions, which copy data from data memory to the register file.

5) How many executed instructions used the ALU during the animation?

1

Check Show answer

Correct

1

The Add instruction is the only instruction in this program that uses the ALU. Only one Add instruction was executed.

6) How many total instructions were executed during the animation?

4

Check Show answer

Correct

4

Load, Load, Add, and Store were executed, so 4 were executed. Two more instructions are shown in the instruction memory, but weren't executed in the animation.

7) The CPU contains a register file and what other component?

ALU

Correct

ALU

Check Show answer

The ALU carries out arithmetic and logic operations. ALU stands for "Arithmetic Logic Unit".

8) A typical register file has 1G or more registers. Type true or false.

false

Check Show answer

Correct

False

A register file should be small to fit next to an ALU and thus support fast accesses (among other reasons). A typical register file has fewer than 128 registers, perhaps just 32 registers for example. 1G (1 billion) is more appropriate for memory.

Feedback?

Note that when the processor reads data from the data memory or register file, the data is copied, not removed.

Instructions

A processor executes instructions in sequence, one at a time. The instruction order thus matters.

PARTICIPATION ACTIVITY 2.1.3: Instruction order.

1) Complete the following instruction sequence to add the values in registers t0 and t1 and store the result in DM[5007].

Correct

The add instruction calculates the sum of t0 and t1, and writes the result in t6. Finally, the store instruction copies the value in register t6 to DM[5007].

_____
Store t6 to DM[5007]

- ○ Add t2 = t0 + t1
- ◉ Add t6 = t0 + t1
- ○ Add t6 = t0 + t2

2) Complete the following instruction sequence to add the values in registers t2 and t6 and store the result in DM[5007].

Add t3 = t2 + t6

_____

- ○ Store t6 to DM[5007]
- ○ Store t3 to DM[5000]
- ◉ Store t3 to DM[5007]

Correct

The store instruction copies the value in t3 to data memory element at location 5007.

3) Select the instruction sequence that calculates the sum of register t1 and DM[5000], and writes the sum in register t5.

- ◉ Load t4 with DM[5000]
Add t5 = t1 + t4
- ○ Add t5 = t1 + t4
Load t4 with DM[5000]

Correct

DM[5000] is loaded into register t4. Then, the add instruction adds the values in register t4 and t1, and writes the result in t5.

4) Select the instruction sequence that calculates the sum of t0 and t1, and stores the results to DM[5001].

- ○ Store t2 to DM[5001]
Add t2 = t0 + t1
- ◉ Add t2 = t0 + t1
Store t2 to DM[5001]

Correct

The Add instruction adds t0 and t1, writing the result into t2. Then, the Store instruction copies register t2's value to DM[5001].

Feedback?

A processor may support hundreds of possible instruction types. Those instruction types can usually be classified into three categories:

- A ***data transfer instruction*** copies data among the data memory and register file.
- An ***ALU instruction*** operates on data.
- A ***branch instruction*** specifies the location of the next instruction to execute, being different from the next instruction in instruction memory.

PARTICIPATION ACTIVITY 2.1.4: Instruction type categories.

Indicate the category for the instruction.

1) Load t0 with DM[5255]
   - (•) Data transfer
   - ( ) ALU
   - ( ) Branch

Correct

A data transfer instruction copies data among the data memory and register file. This instruction copies data memory location 5255's value to register t0.

2) Jump to instruction 90
   - ( ) Data transfer
   - ( ) ALU
   - (•) Branch

Correct

The instruction indicates that the next instruction to execute should be the instruction at location 90 in instruction memory.

3) Subtract t6 = t1 - t4
   - ( ) Data transfer
   - (•) ALU
   - ( ) Branch

Correct

An ALU instruction performs an arithmetic or logical operation on data. Subtract is one such arithmetic operation.

Feedback?

Each instruction typically is encoded into a limited number of bits, such as 32 bits. Using a small limited number of bits per instruction ensures more instructions can fit into the memory, and keeps the processor's circuit simple and fast. Some bits may represent the instruction type (like Load or Add), other bits may indicate the registers involved (like t0 or t1), and others a data memory address (like 5005). As such, the number of instruction types is limited. Ex: If the instruction type is represented in 8 bits, then only $2^8 = 256$ instruction types are possible.

Thus, a processor's instruction types are limited and kept basic, like the basic Add, Store, and Load instructions seen above. A programmer must achieve desired functionality using just those relatively-few instruction types.

The set of instruction types supported by a particular processor is called the processor's ***instruction set***. A program written using a processor's instructions is called an ***assembly***

language program, in contrast to programs written in higher-level languages like C, C++, Java, or Python.

PARTICIPATION ACTIVITY 2.1.5: Using limited instruction types.

Assume a processor's only instruction type available for adding is:
Add regA = regB + regC
where regA, regB, and regC each is any register.

1) Which computes t5 = t1 + t3?

   - (●) Add t5 = t1 + t3
   - ( ) Add t1 = t5 + t3

Correct

The processor's available Add instruction perfectly matches the desired operation of adding two registers and putting the result into a third register.

2) Assume the following initial values: t1 = 7, t2 = 6, t3 = 8. What is in t5 after the following:

   Add t0 = t1 + t2
   Add t5 = t0 + t3

   - ( ) 13
   - ( ) 3
   - (●) 21

Correct

The first Add puts 7 + 6 or 13 into t0. The second Add puts 13 + 8 or 21 into t5.

3) Assume the following initial values: t1 = 7, t2 = 6, t3 = 8. What is in t5 after the following:

   Add t3 = t1 + t2
   Add t5 = t3 + t3

   - (●) 26
   - ( ) 21

Correct

The first Add puts 7 + 6 or 13 into t3. The second Add puts 13 + 13 or 26 into t5. The first add overwrote t3's original value of 8.

4) Which computes t0 = t1 + t2 + t3?

   - ( ) Add t3 = t1 + t2
Add t0 = t3 + t3
   - (●) Add t4 = t1 + t2
Add t0 = t4 + t3

Correct

The first instruction puts (t1 + t2) into t4. The second instruction puts (t1 + t2) + t3 into t0.

5) Which computes t0 = t1 + t2 + t3 + t4?

- Add t4 = t1 + t2
Add t0 = t4 + t3
- Add t5 = t1 + t2
Add t6 = t3 + t4
Add t0 = t5 + t6 (selected)

Correct

The last instruction computes t0 = (t1 + t2) + (t3 + t4), because the first instruction put (t1 + t2) into t5, and the second put (t3 + t4) into t6.

6) Can t4 = t3 + t2 + t1 + t0 be computed in two instructions?

- Yes
- No (selected)

Correct

Three instructions are needed. Many possibilities exist, such as:
Add t5 = t3 + t2
Add t6 = t5 + t1
Add t4 = t6 + t0

Feedback?

Register file

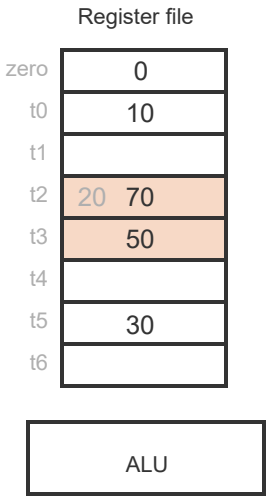
Each register in the register file has a name. The ***zero register*** is a read-only register that always holds the value 0. In the animation above, t0 ... t6 refer to the register file's next seven registers, which can be read and written by instructions.

An ALU instruction may read a register's value and write the operation's result into that very same register.

PARTICIPATION ACTIVITY 2.1.6: Register file: Reading and writing.

1 2 2x speed

Add t2 = t2 + t3



The result overwrites the value in t2 with 70.

Captions

1. The instruction adds the values located at t2 and t3.
2. The result overwrites the value in t2 with 70.

Feedback?

PARTICIPATION ACTIVITY 2.1.7: Registers.

1) Assume the following initial values: t0 = 7, t1 = 5, and t2 = 3. What is in t2 after the following:

Add t2 = t2 + t1

- 3
- 8
- 12

Correct

The Add instruction adds the values in t2 and t1, and writes the result 8 into t2. The value previously held in t2 is thus replaced by the Add instruction.

2) Assume the following initial values: t0 = 2, t1 = 5, and t2 = 4. What is in t0 after the following:

Add t0 = t0 + t1
Add t0 = t0 + t2

- 2
- 7
- 11

Correct

t0 initially holds the value 2. After the first Add instruction, the sum 7 (2 + 5) is written into t0. So, the result of the second Add instruction is 11 (7 + 4), is written into t0.

3) Assume the following initial values: t2 = 7, t3 = 1, and t4 = 9.
What is in t4 after the following:

Add t3 = t3 + t2
Add t4 = t4 + t3

- 9
- 10
- 17 (selected)

Correct

After the first Add instruction, t3 holds 8, which is then added to t4. The result 17 is written back into t4.

4) Complete the following instruction sequence to add the values in registers t3, t4, and t5, and store the result in DM[1007].

Add t6 = t4 + t5
____
Store t6 to DM[1007]

- Add t6 = t6 + t3 (selected)
- Add t6 = t6 + t4
- Add t6 = t4 + t3

Correct

After the first Add instruction, t6 holds the sum of t4 and t5. The second Add instruction adds t6 with t3, and writes the sum in t6. t6 then holds the sum of t3, t4, and t5.

Feedback?

Reset

*A **reset** is an input that when asserted causes a circuit to enter a known state. A processor's reset causes 0's to be written to all registers, including the register file and program counter. So, after the reset, the processor executes the instruction at address 0. A **power-on-reset** circuit resets the processor when power is first applied.*

Register file and data memory

When displaying data values in registers or memory, this material may show: 1) a 0 for register if the register is known to be 0, such as on reset, 2) a blank location if the value is unknown, such as memory location that has not yet been written, or 3) a grayed value representing a previous value for a register or memory location that has been written a new value. Additionally, all registers within the register file may not be shown, instead showing only those registers that are relevant for each example.

Register file with zero and nonzero values

zero	0
t0	20
t1	17
t2	85
t3	36
t4	40
t5	5208
t6	5200

Register file with blank entries

zero	0
t0	
t1	
t2	
t3	
t4	40
t5	50
t6	5000

Register file with grayed value

zero	0
t0	20
t1	17
t2	10
t3	70 75
t4	256
t5	6000
t6	6008

Register file with a subset of registers

t0	20
t1	17
t2	85
t3	36

MIPS

MIPS is a processor that was popular in various computers in the 1990's, and is found in some embedded computing devices today. MIPS is presently one of the most popular processors for learning assembly language programming, and also for learning processor design. MIPS is known for having a simple and elegant instruction set, which in turn enables simple and fast processor designs.

MIPS' instruction set has just over 100 instructions, and each instruction is 32 bits. The MIPS register file has 32 registers, each being 32 bits. Memory addresses are 32 bits. Memory can be accessed by words (4 bytes), half words (2 bytes), or bytes.

For educational purposes, this material teaches a greatly-simplified version of MIPS, known as ***MIPSzy***, using a small subset of the MIPS instruction set, and using a register file with only 8 primary registers. MIPSzy only allows memory to be accessed by words (4 bytes).

PARTICIPATION ACTIVITY 2.1.8: MIPS and MIPSzy.

1) MIPS is the most popular processor in commercial products today.

- ○ True
- ◉ False

Correct

MIPS is popular in education due to having a relatively straightforward instruction set, enabling students to focus on important concepts rather than tedious non-essential details.

2) The register file in MIPS has 32 registers.

- ◉ True
- ○ False

Correct

The 32 registers have names like $s0 and $t5 that will be introduced later.

3) The register file in MIPSzy has 32 registers.

- ○ True
- ◉ False

Correct

Unlike MIPS, which has 32 registers, MIPSzy has only 8 primary registers in the register file (plus a couple special purpose registers, to be described later). Having fewer registers eases the learning of how processors work and are built. A real processor needs more registers for faster program execution.

Feedback?

Exploring further:

- MIPS Processor
- Computer Organization and Design (6e) - Interactive Version (MIPS)

How was this section? **Provide section feedback**