# Designing the processor

## Datapath and Control Signals

* [Click here](https://drive.google.com/file/d/1rPPUsLKs8p134EQi3qqJmZcQUA2audfj/view?usp=sharing)

## Instruction Set

There are 31 instructions that can be used by the assembly programmer. Some instructions have a 16-bit operand, and most instructions are zero operand instructions. 8 bits are used for opcode. Following table explains the operations of each instruction.

|  |  |  |  |
| --- | --- | --- | --- |
| Instruction | Opcode | Operand (16 bit) | Operation |
| loadac | 0000 0100 | - | ac <= DM[ac] |
| movacr | 0000 1000 | - | r <= ac |
| movacr1 | 0000 1001 | - | r1 <= ac |
| movacr2 | 0000 1010 | - | r2 <= ac |
| movacr3 | 0000 1011 | - | r3 <= ac |
| movacr4 | 0000 1100 | - | r4 <= ac |
| movacr5 | 0000 1101 | - | r5 <= ac |
| movacdar | 0000 1110 | - | dar <= ac |
| movrac | 0000 1111 | - | ac <= r |
| movr1ac | 0001 0000 | - | ac <= r1 |
| movr2ac | 0001 0001 | - | ac <= r2 |
| movr3ac | 0001 0010 | - | ac <= r3 |
| movr4ac | 0001 0011 | - | ac <= r4 |
| movr5ac | 0001 0100 | - | ac <= r5 |
| movdarac | 0001 0101 | - | ac <= dar |
| stac | 0001 0110 | - | DM[ac] <= ac |
| add | 0001 1001 | - | ac <= ac + r |
| sub | 0001 1011 | - | ac <= ac – r |
| lshift | 0001 1101 | - | ac <= r << ac |
| rshift | 0001 1111 | - | ac <= r >> ac |
| incac | 0010 0001 | - | ac <= ac + 1 |
| incdar | 0010 0010 | - | dar <= dar +1 |
| incr1 | 0010 0011 | - | r1 <= r1 +1 |
| incr2 | 0010 0100 | - | r2 <= r2 +1 |
| incr3 | 0010 0101 | - | r3 <= r3 + 1 |
| loadim | 0010 0110 | imm | ac <= imm |
| jumpz | 0010 1001 | imm | if z == 1, go to instruction IM[imm] |
| jumpnz | 0011 0000 | imm | if z == 0, go to instruction IM[imm] |
| jump | 0011 0001 | imm | go to instruction IM[imm] |
| nop | 0011 0010 | - | no operation |
| endop | 0011 0011 | - | end process |

## Microinstructions

These microinstructions are used for finite state machine in the control unit. one microinstruction can be operated in one clock cycle. Following table explains operations of each microinstruction.

|  |  |  |  |
| --- | --- | --- | --- |
| Instruction (8bits) | Opcode  (decimal) | Microinstruction (6bits) | Operation |
| idle  (internal) | - | idle | goto fetch1 if status == 1 else idle |
| fetch  (internal) | - | fetch1 | read IMEM |
| write ir |
| goto fetch2 |
| fetch2 | read IMEM |
| write ir |
| goto fetch3 |
| fetch3 | read IMEM |
| goto ir[5:0] |
| loadac | 4 | loadac1 | read ac |
| write dar |
| goto loadac2 |
| loadac2 | read ac |
| wrirte dar |
| goto loadac3 |
| loadac3 | read DMEM |
| write ac |
| goto loadac4 |
| loadac4 | read DMEM |
| write ac |
| increment pc |
| goto fetch1 |
| movacr | 8 | movacr | read ac |
| write r |
| increment pc |
| goto fetch1 |
| movacr1 | 9 | moveacr1 | read ac |
| write r1 |
| increment pc |
| goto fetch1 |
| movacr2 | 10 | moveacr2 | read ac |
| write r2 |
| increment pc |
| goto fetch1 |
| movacr3 | 11 | moveacr3 | read ac |
| write r3 |
| increment pc |
| goto fetch1 |
| movacr4 | 12 | moveacr4 | read ac |
| write r4 |
| increment pc |
| goto fetch1 |
| movacr5 | 13 | moveacr5 | read ac |
| write r5 |
| increment pc |
| goto fetch1 |
| movacdar | 14 | moveacdar | read ac |
| write dar |
| increment pc |
| goto fetch1 |
| movrac | 15 | moverac | read r |
| write ac |
| increment pc |
| goto fetch1 |
| movr1ac | 16 | mover1ac | read r1 |
| write ac |
| increment pc |
| goto fetch1 |
| movr2ac | 17 | mover2ac | read r2 |
| write ac |
| increment pc |
| goto fetch1 |
| movr3ac | 18 | mover3ac | read r3 |
| write ac |
| increment pc |
| goto fetch1 |
| movr4ac | 19 | mover4ac | read r4 |
| write ac |
| increment pc |
| goto fetch1 |
| movr5ac | 20 | mover5ac | read r5 |
| write ac |
| increment pc |
| goto fetch1 |
| movdarac | 21 | movedarac | read dar |
| write ac |
| increment pc |
| goto fetch1 |
| stac | 22 | stac1 | read ac |
| goto stac2 |
| stac2 | read ac |
| write dm |
| goto stac3 |
| stac3 | read ac |
| increment pc |
| goto fetch1 |
| add | 25 | add1 | add alu |
| goto add2 |
| add2 | add alu |
| write alu\_to\_ac |
| increment pc |
| goto fetch1 |
| sub | 27 | sub1 | sub alu |
| goto sub2 |
| sub2 | sub alu |
| write alu\_to\_ac |
| increment pc |
| goto fetch1 |
| lshift | 29 | lshift1 | lshift alu |
| goto lshift2 |
| lshift2 | lshift alu |
| write alu\_to\_ac |
| increment pc |
| goto fetch1 |
| rshift | 31 | rshift1 | rshift alu |
| goto rshift2 |
| rshift2 | rshift alu |
| write alu\_to\_ac |
| increment pc |
| goto fetch1 |
| incac | 33 | incac | increment ac |
| incremtnt pc |
| goto fetch1 |
| incdar | 34 | incdar | increment dar |
| incremtnt pc |
| goto fetch1 |
| incr1 | 35 | incr1 | increment r1 |
| incremtnt pc |
| goto fetch1 |
| incr2 | 36 | incr2 | increment r2 |
| incremtnt pc |
| goto fetch1 |
| incr3 | 37 | incr3 | increment r3 |
| incremtnt pc |
| goto fetch1 |
| loadim | 38 | loadim1 | increment pc |
| goto loadim2 |
| loadim2 | read IMEM |
| goto loadim3 |
| loadim3 | read IMEM |
| write ac |
| increment pc |
| goto fetch1 |
| jump | 49 | jump | increment pc |
| goto jumpz2 |
| jumpz | 41 | jumpz1 | increment pc |
| goto jumpz2 if z == 1 else jumpz6 |
| jumpz2 | read IMEM |
| write pc |
| goto jumpz3 |
| jumpz3 | read IMEM |
| write pc |
| goto jumpz4 |
| jumpz4 | read IMEM |
| write ir |
| goto jumpz5 |
| jumpz5 | read IMEM |
| write ir |
| goto fetch3 |
| jumpz6 | goto jumpz7 |
| jumpz7 | increment pc |
| goto jumpz4 |
| jumpnz | 48 | jumpnz1 | increment pc |
| goto jumpz3 if z == 0 else goto jumpz7 |
| endop | 51 | endop | read DMEM |
| goto endop |
| nop | 50 | nop | increment pc |
| goto fetch1 |

## Finite State Machines for Microinstructions

* [Click here](https://drive.google.com/file/d/1sTfO4wpmlyjbBeBT12DA6SesE3SfmX9s/view?usp=sharing)

## Modules and Components

### Machine

There are three phases in this machine.

1. Load the image – Phase 1
2. Processing – Phase 2
3. Get the processed image – Phase 3

In phase 1, we have to give the image data to data\_in and memory address to data\_addr\_in. Then processing will be done. After phase 2 is done, end\_process will be asserted. In phase 3, we can get the output image data from the data\_out.

Diagram, schematic

Description automatically generated

|  |  |
| --- | --- |
| Inputs | Outputs |
| clk – clock | **end\_process** – signal that indicate process has ended |
| status – control signal for change phases (input image data, process data, output data) | **data\_out** – ouput image data |
| data\_in – input image data |  |
| data\_addr\_in – input data memory address |  |

|  |  |  |  |
| --- | --- | --- | --- |
| status | 10 | 01 | 11 |
| phase | 1 – load image | 2 – process | 3 – output image |

### Chart, diagram Description automatically generatedInside of the machine

### Processor

Diagram

Description automatically generated

|  |  |
| --- | --- |
| Inputs | Outputs |
| clk – clock | **end\_process** – signal that indicate process has ended |
| status – control signal for change phases (input image data, process data, output data) | **dm\_en** – data memory write enable signal |
| dm\_out – output of data memory | **im\_en** – instruction memory write enable signal |
| im\_out – output of instruction memory | **pc\_out** – instruction memory address |
| data\_in – input image data | **dar\_out** – data memory address |
| data\_addr\_in – input data memory address | **bus\_out** – data output for data memory |

* Inside of the Processor – [Click here](https://drive.google.com/file/d/19FY7MgWt2P39a2HArgFuCaK_7dW6WJbC/view?usp=sharing)

### Modules Inside the Processor

**Arithmetic & Logic Unit (ALU)** – Do arithmetic and logic operations in the processor

**Control Unit** – Do all the controlling in the processor. Implemented as a finite state machine.

**Special purpose registers**

* + Accumulator (ac) – input for the ALU, store ALU output
  + Program counter (pc) – directed to the next instruction to be fetched
  + Instruction register (ir) – store the instruction fetched from the instruction memory
  + Data address register (dar) – keep the address of the store location of the data memory. Loading from data memory and storing to data memory are being done using this address
  + r register – one of the inputs for the ALU

**General purpose registers**

* + r1, r2, r3 – general purpose registers which can be incremented
  + r4, r5 – general purpose registers which cannot be incremented

### ALU

ALU is responsible for all the arithmetic and logic operations. Inputs are taken from ac and r registers and output is stored in ac register. We are using 3-bit alu\_op even though there are only four operations since it is better to have some improvement capabilities. z will be 1 if the alu\_out is zero. z will be 0 if the alu\_out is nonzero.

A picture containing text, antenna

Description automatically generated

|  |  |  |
| --- | --- | --- |
| alu\_op | Operation | Description |
| 001 | Addition | Alu\_out <= in1 + in2 |
| 010 | Subtraction | Alu\_out <= in2 – in1 |
| 011 | Left shift | Alu\_out <= in1 << in2 |
| 100 | Right shift | Alu\_out <= in1 >> in2 |

### Control Unit

Control Unit is responsible for all the control signals in the processor. Here we are implemented this using a finite state machine.

Diagram, schematic

Description automatically generated

|  |  |
| --- | --- |
| Inputs | Outputs |
| clk – clock | **end\_process** – signal that indicate process has ended |
| status – control signal for change phases (input image data, process data, output data) | **read\_en** – 4 bit read enable signal |
| instruction – instruction from the instruction register | **write\_en** – 16 bit write enable signal |
| z – z output from the alu | **inc\_en** – 8 bit increment enable signal |
|  | **alu\_op** – ALU opcode |

#### Read Enable – read\_en

read\_en is the control signal that is responsible for all the readings in the processor. Read values are written to the data bus. We cannot read from multiple registers and write them to the same bus. Hence, we are using 4 bit signal such that only one register can be read at one time.

|  |  |
| --- | --- |
| Decimal Value | Register |
| 0 | - |
| 1 | dar |
| 2 | ac |
| 3 | r |
| 4 | r1 |
| 5 | r2 |
| 6 | r3 |
| 7 | r4 |
| 8 | r5 |
| 9 | DM |
| 10 | IM |

#### Write Enable – write\_en

write\_en is the control signal that is responsible for all the writings in the processor. Unlike the reading, we can write data to multiple locations at the same time. Therefore, we are using 16-bit signal and each bit has assigned to separate location. We can write those location by setting those bits to 1.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Bit 15  N/A | Bit 14  N/A | Bit 13  alu to ac | Bit 12  IM | Bit 11  DM | Bit 10  r1 | Bit 9  r2 | Bit 8  r3 | Bit 7  r4 | Bit 6  r5 | Bit 5  r | Bit 4  ac | Bit 3  ir | Bit 2  dar | Bit 1  pc | Bit 0  N/A |

#### Increment Enable – inc\_en

inc\_en is the control signal that is responsible for all the increments in the processor. Same as the writing, we can increment multiple registers at the same time.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Bit 7  N/A | Bit 6  r3 | Bit 5  r2 | Bit 4  r1 | Bit 3  dar | Bit 2  ac | Bit 1  pc | Bit 0  N/A |

### Accumulator

Accumulator is a special purpose register which has two data inputs. One is from the data bus and the other one is from the ALU output. There are two write enable signals to indicate from which input the writing should be done. This is one of the inputs to the ALU.

Diagram

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### Register Which Can Be Incremented

Diagram, schematic

Description automatically generatedpc, dar, r1, r2, r3 are registers of this type. The values in those registers can be incremented without using the ALU.

### Register Which Cannot Be Incremented

Diagram, schematic

Description automatically generatedir, r, r4, r5 are registers of this type. The values in those registers cannot be incremented without using the ALU.

### Data Bus

This is a 16-bit path which connects all the necessary components that needed to the data flow.

Diagram

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### Data Memory

This is the main memory which data is stored. The image should be stored here before the processing begins. This memory contains 65536 locations of 8 bits long. Since we are using 256\*256 image, 65536 pixel values are needed to be stored and that is why 65536 locations. Since the pixel value range is 0-255, we need 8-bit long memory to store that.

Diagram, schematic

Description automatically generated

### Instruction Memory

This is for storing the instructions. This is a read only memory. The processor cannot write into instruction memory during the processing. This can be written only when we need to load a new programme.

Diagram, schematic

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