Kabeta Processor Design

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| Date: | April 11, 2018 |
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| Reviewer: | (N/A) |

# Introduction

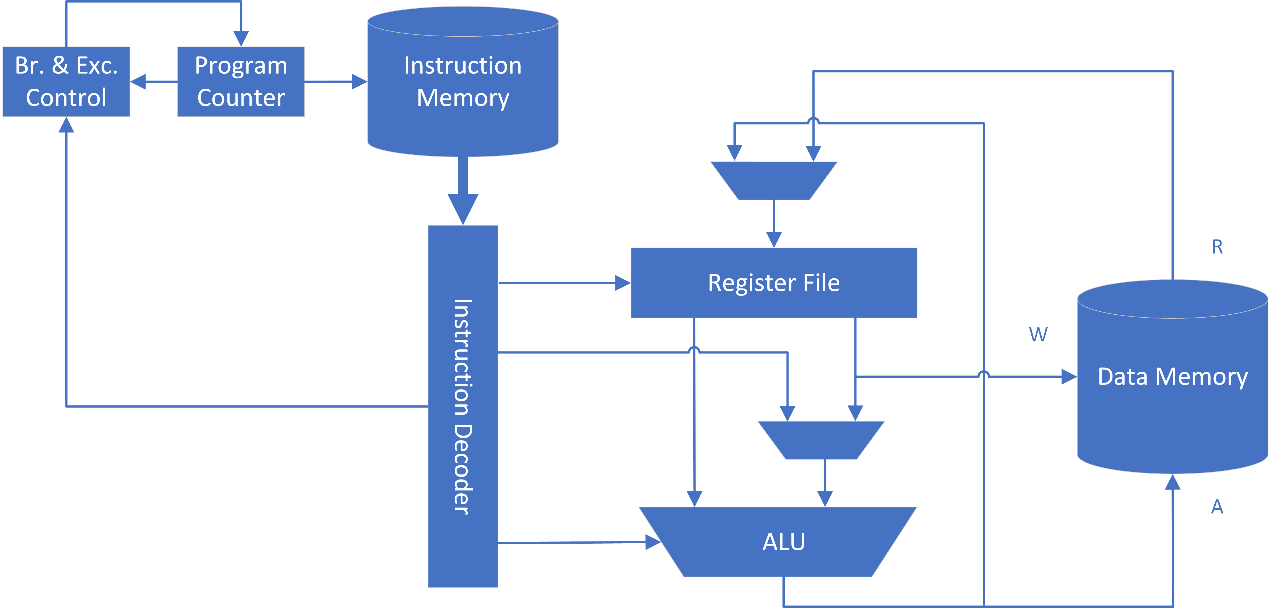
## Description

Kabeta is a RISC processor based on the β Processor of MIT. Its main features and limitations include:

* Typical 5-stage Pipeline with Bypass
* Supervisor and User Modes
* Separate Instruction, Data and I/O Address Spaces
* Synchronous Single-cycle Access on-chip Instruction and Data RAMs

(for the sake of implementation in FPGA)

## Components



Kabeta mainly consists of Register File, Arithmetic and Logic Unit, Instruction Registers and Decoders, Branch and Exception Control, Program Counter, on-chip Data Memory and Instruction Memory.

## Block Diagram

[Click Here to Open Detailed Block Diagram](Design%20Diagrams%20-%20Detailed%20Block%20Diagram.png)

**NOTES:**

* ALU in the diagram should contain an output register.
* Read-while-write behavior of Register File should be write-through, i.e. the output data should be the data to be written.

## References

* [MIT β Processor Specification](MIT6_004s09_lab_beta_doc.pdf)
* [MIT β Processor Summary](MIT6_004s09_lab_beta_summary.pdf)
* [Lecture Notes](https://ocw.mit.edu/courses/electrical-engineering-and-computer-science/6-004-computation-structures-spring-2009/lecture-notes/) of [MIT 6.004 Computation Structures](https://ocw.mit.edu/courses/electrical-engineering-and-computer-science/6-004-computation-structures-spring-2009/) ([L14](MIT6_004s09_lec14.pdf), [L22](MIT6_004s09_lec22.pdf), [L23](MIT6_004s09_lec23.pdf))

# Instruction Extension

## No Operation -- NOP (1A)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 31 26 | 25 21 | 20 16 | 15 1 | 0 |
| **01**1010 | Rc | 00000 | 000000000000000 | E |

E: Exception Status

* Normal NOP

E == 0, Rc == 31

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 31 26 | 25 21 | 20 16 | 15 1 | 0 |
| **01**1010 | 11111 | 00000 | 000000000000000 | 0 |

* Exceptional NOP (Internal Use Only)

E == 1, Rc == XP (30)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 31 26 | 25 21 | 20 16 | 15 1 | 0 |
| **01**1010 | 11110 | 00000 | 000000000000000 | 1 |

**NOTE:** NOP instruction does not cause exceptions.

## System Service -- SVC (1C)

|  |  |  |  |
| --- | --- | --- | --- |
| 31 26 | 25 21 | 20 16 | 15 0 |
| **01**1100 | 00000 | 00000 | SVC\_ID |

**NOTE:** This instruction will cause System Service Trap.

## Input/Output Read -- IOR (08)

|  |  |  |  |
| --- | --- | --- | --- |
| 31 26 | 25 21 | 20 16 | 15 0 |
| **00**1000 | Rc | Ra | Offset (two’s complement) |

Reg[Rc] ← IO[Reg[Ra] + SExt(Offset)]

**NOTE:** This is a privileged instruction.

## Input/Output Write – IOW (09)

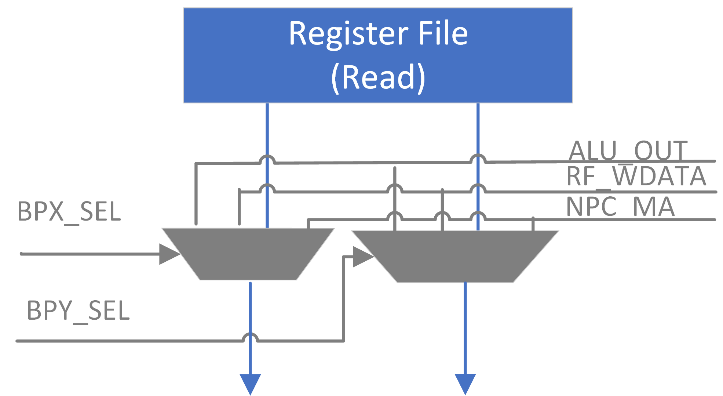
|  |  |  |  |
| --- | --- | --- | --- |
| 31 26 | 25 21 | 20 16 | 15 0 |
| **00**1001 | Rc | Ra | Offset (two’s complement) |

IO[Reg[Ra] + SExt(Offset)] ← Reg[Rc]

**NOTE:** This is a privileged instruction.

# Bypass

## Bypass Paths



## Control Signals

* Port X

ALU\_OUT\_SELX = (IR\_EX.Opcode in {OP, OPC, LD, ST, JMP, B, IOR, IOW})

&& (IR\_EX.Ra != 31)

&& (IR\_EX.Ra == IR\_MA.Rc) && (IR\_MA.Opcode in {OP, OPC})

NPC\_MA\_SELX = (IR\_EX.Opcode in {OP, OPC, LD, ST, JMP, B, IOR, IOW})

&& (IR\_EX.Ra != 31)

&& (IR\_EX.Ra == IR\_MA.Rc) && (IR\_MA.Opcode in {JMP, B, NOP})

RF\_WDATA\_SELX = (IR\_EX.Opcode in {OP, OPC, LD, ST, JMP, B, IOR, IOW})

&& (IR\_EX.Ra != 31)

&& (!ALU\_OUT\_SELX && !NPC\_MA\_SELX)

&& (IR\_EX.Ra == IR\_WB.Rc)

&& (IR\_WB.Opcode in {OP, OPC, LD, LDR, JMP, B, NOP, IOR})

* Port Y

ALU\_OUT\_SELY = **(**(IR\_EX.Opcode in {OP}) && (IR\_EX.Rb != 31)

&& (IR\_EX.Rb == IR\_MA.Rc) && (IR\_MA.OpCode in {OP, OPC})**)**

|| **(**(IR\_EX.Opcode in {ST, IOW}) && (IR\_EX.Rc != 31)

&& (IR\_EX.Rc == IR\_MA.Rc) && (IR\_MA.OpCode in {OP, OPC})**)**

NPC\_MA\_SELY = **(**(IR\_EX.Opcode in {OP}) && (IR\_EX.Rb != 31)

&& (IR\_EX.Rb == IR\_MA.Rc)

&& (IR\_MA.Opcode in {JMP, B, NOP})**)**

|| **(**(IR\_EX.Opcode in {ST, IOW}) && (IR\_EX.Rc != 31)

&& (IR\_EX.Rc == IR\_MA.Rc)

&& (IR\_MA.Opcode in {JMP, B, NOP})**)**

RF\_WDATA\_SELY = **(**(IR\_EX.Opcode in {OP}) && (IR\_EX.Rb != 31)

&& (!ALU\_OUT\_SELY && !NPC\_MA\_SELY)

&& (IR\_EX.Rb == IR\_WB.Rc)

&& (IR\_WB.Opcode in {OP, OPC, LD, LDR, JMP, B, NOP, IOR})**)**

|| **(**(IR\_EX.Opcode in {ST, IOW}) && (IR\_EX.Rc != 31)

&& (!ALU\_OUT\_SELY && !NPC\_MA\_SELY)

&& (IR\_EX.Rc == IR\_WB.Rc)

&& (IR\_WB.Opcode in {OP, OPC, LD, LDR, JMP, B, NOP, IOR})**)**

# Pipeline Stall

Stall the pipeline when one of the source registers of the instruction at RR-Stage coincides with the target register of the load/read instruction at EX-Stage.

## Control Signals

STALL = **(**(IR\_RR.Opcode in {OP, OPC, LD, ST, JMP, B, IOR, IOW}) // Read Ra

&& (IR\_RR.Ra != 31)

&& (IR\_RR.Ra == IR\_EX.Rc) && (IR\_EX.Opcode in {LD, LDR, IOR})**)**

|| **(**(IR\_RR.Opcode in {OP}) // Read Rb

&& (IR\_RR.Rb != 31)

(IR\_RR.Rb == IR\_EX.Rc) && (IR\_EX.OpCode in {LD, LDR, IOR})**)**

|| **(**(IR\_RR.Opcode in {ST, IOW}) // Read Rc

&& (IR\_RR.Rc != 31)

&& (IR\_RR.Rc == IR\_EX.Rc) && (IR\_EX.Opcode in {LD, LDR, IOR})**)**

NOTE: Stall the pipeline as early as possible to disable less components.

## Implementation

Inject a Normal NOP instruction into EX-stage and disable Register File read, PC\_RR, IR\_RR, PC\_IF and Instruction Memory.

**NOTE:** This implementation is a bit different with MIT β Processor.

## Mitigation

When writing programs, put an instruction independent of the data following the load/read instruction to eliminate pipeline stall.

# Exception

## Reference

Refer to Section 6. Extensions for Exception Handling in [MIT β Processor Specification](file:///F:\Workspace\Kabeta\doc\MIT6_004s09_lab_beta_doc.pdf)

## Supported Exceptions

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Name** | **Code** | **Type** | **Source** | **Priority** | **Exc. Vector** |
| Reset | 000 | Reset | RST Pin | 0 (highest) | 8000\_0000 |
| System Service | 001 | Trap | RR-Stage | 3 | 8000\_0004 |
| Illegal Instruction | 010 | Fault | RR-Stage | 8000\_0008 |
| Invalid Operation | 011 | Fault | EX-Stage | 2 | 8000\_000C |
| Invalid D-Address | 100 | Fault | MA-Stage | 1 | 8000\_0010 |
| Invalid I-Address | 101 | Fault | IF-Stage | 4 | 8000\_0014 |
| Interrupt 0 | 110 | Interrupt | IRQ Pin | 5 (lowest) | 8000\_0018 |
| Interrupt 1 | 111 | Interrupt | IRQ Pin | 8000\_001C |

**NOTES:**

1) The MSBs of exception vectors indicate that the exception handlers will executed in the Supervisor Mode.

2) If instructions at multiple stages have caused exceptions simultaneously, only the exception in the highest priority should be processed.

3) Pay attention to the suppression of exceptions by the branch instruction in EX-Stage, refer to Section 6.2.

## Exception Conditions

|  |  |
| --- | --- |
| **Name** | **Condition** |
| Reset | External reset signal (active LOW) |
| System Service | SVC instruction |
| Illegal Instruction | Undefined opcodes (6’b010\_xxx) in both modes, privileged opcodes (6’b00x\_xxx) in User Mode, or undefined privileged opcodes in Supervisor Mode. |
| Invalid Operation | Undefined Operate Class Opcodes, MUL/MULC, or DIV/DIVC |
| Invalid D-Address | Out of data memory address range |
| Invalid I-Address | Out of instruction memory address range |
| Interrupt 0/1 | External interrupt signal |

## Interrupt Request and Acknowledge

* External interrupts are level triggered.
* Interrupt number is read from IID pin.
* Acknowledge is a pulse of one clock cycle’s duration.

**NOTE:** The above signals (IRQ, IID and IACK) cross clock domains.

## Implementation

When an Exceptional NOP instruction arrives at WB-Stage, write register XP = PC\_WB, which is the instruction address plus 4.

### Pipeline Control Signals

|  |  |
| --- | --- |
| **Name** | **Signals to Assert** |
| Reset | (None) |
| System Service | ExcRR, FlushIF, FlushRR |
| Illegal Instruction |
| Invalid Operation | ExcEX, FlushIF, FlushRR, FlushEX |
| Invalid D-Address | ExcMA, FlushIF, FlushRR, FlushEX, FlushMA |
| Invalid I-Address | ExcIF, FlushIF |
| Interrupt 0/1 | ExcEX, FlushIF, FlushRR, FlushEX |

### Reset Processing

* Reset all Instruction Registers (i.e. load Normal NOPs).
* Reset all Program Counters (i.e. load 32’h0000\_0000 address).
* Set ExcAddr = reset exception vector, and select ExcAddr as next PC value.

**NOTE:** Synchronization of external RST signal is necessary.

### Trap and Fault Processing

When a trap or fault occurs:

* Replace the instruction which has caused the exception with an Exceptional NOP instruction.
* Replace the later instructions in the pipeline with Normal NOP instructions (i.e. flush the pipeline).
* Jump to the exception handler.

**NOTE:** Traps and Faults could be nested, as long as XP is stored onto stack in the exception handlers.

### Interrupt Processing

When an interrupt occurs:

* Wait until Supervisor bit is cleared (i.e. PC\_IF.S == 0).
* Replace the instruction at EX-Stage with an Exceptional NOP instruction.
* Replace the instructions at IF-Stage and RR-Stage with Normal NOP instructions (i.e. flush the pipeline).
* Jump to the exception handler.

**NOTE:** Interrupts could not be nested with other exceptions.

# Branch

## Branch Delay Slots

There are 2 branch delay slots. The instructions in the branch delay slots will be flushed by asserting *FlushIF* and *FlushRR*, and corresponding PCs will be replaced with PC\_EX (i.e. the address of the branch instruction plus 4) by asserting *ReplicatePC*, if the branch is not taken.

## Exception Suppression

When branch instruction is at EX-Stage and branch is to be taken, the Traps and Faults caused by the instructions in the branch delay slots will be ignored.

## Supervisor Mode

Only the JMP instruction is allowed to clear the Supervisor bit but not set it, and no other instructions may have any effect on it.

# Appendix A: Document Version History

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| --- | --- | --- | --- | --- |
| **Version** | **Date** | **Editor** | **Reviewer** | **Comment** |
| 1.0 | April 11, 2018 | K. White | (N/A) | Initial version. |